**NIST Grant/Contractor Report
NIST GCR 25-062**

Economic Benefits of the Global Positioning System (GPS)

Alan C. O'Connor
Michael P. Gallaher
Kyle Clark-Sutton
Daniel Lapidus
Zack T. Oliver
Troy J. Scott
Dallas W. Wood
Manuel A. Gonzalez
Elizabeth G. Brown

RTI International

June 2019

NIST | NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

June 2019

Economic Benefits of the Global Positioning System (GPS)

Final Report

Prepared by

RTI International
Alan C. O'Connor
Michael P. Gallaher
Kyle Clark-Sutton
Daniel Lapidus
Zack T. Oliver
Troy J. Scott
Dallas W. Wood
Manuel A. Gonzalez
Elizabeth G. Brown
Joshua Fletcher
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

RTI Project Number 0215471

⊿RTI
INTERNATIONAL

ECONOMIC BENEFITS OF THE
GLOBAL POSITIONING SYSTEM (GPS)

FINAL REPORT

by Alan C. O'Connor

Michael P. Gallaher

Kyle Clark-Sutton

Daniel Lapidus

Zack T. Oliver

Troy J. Scott

Dallas W. Wood

Manuel A. Gonzalez

Elizabeth G. Brown

Joshua Fletcher

Contents

Figures

Tables

Acknowledgments

Executive Summary

The Global Positioning System (GPS) delivers an extremely precise positioning, navigation, and timing signal to users around the world. Originally launched for U.S. military use, in the years since its signal was made available to the private sector, it has enabled innovators to develop a host of applications, services, and products. These advances have led to substantial gains in productivity, efficiency, and personal enjoyment.

From people driving to some place new to multinational corporations coordinating complex logistics networks, hundreds of millions of users rely on GPS every day for navigation and positioning. Its precision timing capability supports industries as diverse as finance, electricity, and telecommunications. Even the term *GPS* has entered the popular vernacular to mean one's specific location at a specific point in time.

For the United States alone, we estimate that GPS has generated roughly $1.4 trillion in economic benefits (2017$) since it was made available for civilian and commercial use in the 1980s. Because of the likelihood of measurement error, we recommended interpreting this estimate as a rough order of magnitude. Most benefits have accrued in the last 10 years following rapid gains in information technologies, miniaturization and commoditization of powerful devices, and the availability of robust wireless services.

ES.1 Background

The ability to measure time intervals and frequencies extremely precisely is what allows GPS users to pinpoint their location anytime, anywhere in the world. The launch of Sputnik in 1957 and the resulting space race led the United States to accelerate scientific efforts deemed essential for national security and spaceflight capability, including the creation of what is today the Defense Advanced Research Projects Agency.

An important breakthrough occurred when U.S. researchers discovered they could discern the location of ground-receiving stations based on Sputnik's radio transmissions and accurately determine the satellite's orbit. That realization catalyzed research and development programs within the U.S. national laboratories, the military, and contractors in the private sector to develop satellite systems to further American geopolitical and defense interests. Programs from the 1950s and 1960s were combined in 1973 to form what is the GPS program today.

ES.2 Analysis Scope and Overview

The focus of our analysis was on the estimation of the economic benefits of GPS to the U.S. private sector. We provide estimates from two perspectives. First, we quantified the value of GPS relative to alternative technologies and systems for the period from 1984 to 2017. Second, we estimated what the potential impacts would be if a GPS outage were to occur today.

Our analysis combined insights from nearly 200 experts in the use of GPS for specific applications, surveys of professional surveyors and smartphone users, economic modeling tools, and national statistics.

Benefits comprise productivity gains from new and existing products and services, improvements in quality, increases in personal enjoyment, and environmental and public health impacts.

ES.3   Economic Benefits of GPS to the U.S. Private Sector, 1984 through 2017

Table ES-1 summarizes the benefits we quantified. Certainly, other industries use GPS, but the industries in this table have a particular need for GPS's precision that technology alternatives cannot meet. Benefits are largest for telecommunications, telematics (e.g., fleet management, logistics), and location-based services (LBS) (e.g., location features of smartphones and other personal devices). Relative to total industry size, GPS was particularly transformative for the professional surveying sector. Other industries, such as finance, leverage GPS because of its reliability and ubiquity, although the precision they are afforded is far greater than what is required. Alternatives are or would have been readily available for them.

The magnitude of benefits for telecommunications, telematics, and LBS warrants additional explanation. Precision timing has a critical role in synchronization of telecommunications networks, enabling service providers to more efficiently use available spectrums and deliver high-speed wireless services. Given American society's intensive use of wireless technologies, it is perhaps not surprising that benefits related to telecommunications are substantial.

Table ES-1. Summary Economic Benefits of GPS for Private-Sector Use, 1984 to 2017

Sector	Specific Analytical Focus	Benefits ($ million)
Agriculture	Precision agriculture technologies and practices	$5,830
Electricity	Electrical system reliability and efficiency	$15,730
Location-based services	Smartphone apps and consumer devices that use location services to deliver services and experiences	$215,702
Mining	Efficiency gains, cost reductions, and increased accuracy	$12,350
Maritime	Navigation, port operations, fishing, and recreational boating	Negligible
Oil and gas	Positioning for offshore drilling and exploration	$45,922
Surveying	Productivity gains, cost reductions, and increased accuracy in professional surveying	$48,124
Telecommunications	Improved reliability and bandwidth utilization for wireless networks	$685,990
Telematics	Efficiency gains, cost reductions, and environmental benefits through improved vehicle dispatch and navigation	$325,182
Total		**$1,354,830**

Note: Economic benefits were measured relative to a counterfactual that specified that preexisting positioning, navigation, and timing (PNT) systems continued to be available in the absence of GPS. Thus, the relative benefit for some sectors is negligible but substantial for those with applications that have a requirement for GPS's accuracy and precision. We recommend interpreting the $1.4 trillion estimate as a rough order of magnitude. The range of benefits to date is estimated to be between $903 billion and $1.8 trillion.

Benefits relating to telematics and LBS have significant positive externalities beyond productivity impacts: improved navigation and fleet management reduces miles driven, generating environmental and public health benefits through reduced fuel combustion. And, of course, Americans enjoy all the location and navigation features of their personal devices.

In looking across the many sectors and applications that require GPS's accuracy and precision, it becomes clear that GPS has some attributes of a utility. The signal is a public good and service provided by the U.S. government that enables productivity, quality, and efficiency benefits that would not otherwise be possible.

The economic significance of GPS is growing. About 90% of GPS's benefits have accrued since 2010 (Figure ES-1). Long technology life cycles in some sectors, such as electric utilities, mean that although GPS-enabled equipment has been installed, legacy equipment is still in place. This suggests that the full potential of GPS functionality has yet to be realized.

Figure ES-1. Time Series of GPS's Economic Benefits for the Private Sector

ES.4   Potential Impact of a GPS Outage

The question of the potential impact of a 30-day GPS outage was added to our study scope. The duration was specified by the Department of Commerce, and it is not known whether a severe space weather event or nefarious activity by a bad actor would or could cause such a long disruption. Our analysis assumed that other global satellite navigation systems (e.g., GLONASS [Russia], Galileo [Europe], BeiDou [China]) would be disrupted as well. Although many systems relying on GPS can retain, or "hold over," timing precision for a period of time before drifting, eventually those systems do drift. Drifting would affect productivity and efficiency more as the outage wore on. Industries relying on precision positioning and navigation would be affected immediately.

We estimate that the loss of GPS service would have a $1 billion per-day impact. If the outage were to occur during the critical planting season in April and May and lasted multiple weeks, the impacts could be as much as 50% higher because of the widespread adoption of GPS-enabled precision agriculture technologies by American farmers.

Some sectors adopted GPS not because they needed it, but because it was simple, convenient, and ubiquitous. The maritime sector, for example, had technologies and systems available that complemented mariners' skills. A system known as Loran once provided a two-dimensional positioning signal, but the signal was turned off in favor of GPS. This means that although the historical benefits relative to technology alternatives are negligible, the consequences for maritime industries would be significant in the event of an outage, particularly for port operations and the safety of recreational boating.

ES.5   Concluding Remarks

An important observation from assessing the benefits of GPS is the relationship between science investments, private-sector innovation, and time. GPS was fully operational in 1995. It was used by several industries for positioning in the 1980s and 1990s, but the majority of benefits began to accrue during the technology boom starting in the late 1990s. The availability of a reliable, accurate, and extremely precise timing signal meant that innovators had one less barrier to their development of the technologies and applications that are pervasive today and that generate the lion's share of GPS's economic benefits. GPS was a resource whose quality was known, and it took time for innovators to leverage the service. The combination of rapid advances in information technology and GPS was clearly transformative. Excellent examples are telematics and LBS.

GPS is not just a service; it is also a platform for innovation. With the support of federal agencies, private enterprise has leveraged GPS to deliver value through precision agriculture, advanced logistics and route optimization, high-speed wireless services, and a host of other applications. For most Americans, the impact of GPS is as near as their smartphone. Using maps and navigation, social networking, shopping, dating, and relationships are all supported by their phones' location services. GPS is a link between innovation within the national lab system, technology transfer to the private sector, and the tools of their everyday lives.

1. Introduction

The Global Positioning System (GPS) is a network of monitoring stations and satellites that distributes a signal used for positioning, navigation, and timing (PNT). This signal is free, ubiquitous, reliable, accurate, and extremely precise. These attributes make GPS a platform for innovation.

Originally launched for military use, in the years since it was made available for private-sector use, it has enabled innovators to develop a host of applications, services, and products, increasing efficiency, productivity, and personal enjoyment. From people driving to some place new to multinational corporations coordinating complex logistics networks, hundreds of millions of users rely on GPS every day for navigation and positioning. Its precision timing capability supports industries as diverse as finance, electricity, mining, and telecommunications. Even the term *GPS* has entered the vernacular to mean one's specific location at a specific point in time.

The focus of this report is on the valuation of the economic benefits of GPS since it was first made available for private-sector use. GPS has been widely adopted by many industries, including 14 of the 16 industries deemed to be critical infrastructure ("Presidential Policy Directive," 2013). Benefits were measured relative to a counterfactual in which GPS was not available and existing PNT systems and technologies continued to be used. Setting aside for the moment questions of cost, quality, and availability, where a technology alternative could have met a particular need, our valuation approach means that for that application the benefits of GPS are negligible. Where needs could not have been met, the incremental precision and accuracy provided by GPS were critical and benefits were quantified. Netting out value that could have been delivered by GPS alternatives prevents gross overestimation of benefits.

The important role GPS plays in the U.S. economy has given rise to questions about service disruptions and available alternatives. In consultation with other federal agencies, the sponsor of this work, the National Institute of Standards and Technology (NIST), expanded the initial scope of this study to add an additional research question: what is the potential impact of a 30-day disruption of GPS service? A 30-day disruption seems unlikely, the impact of a disruption certainly differs on Day 1 than on Day 30, and devices capable of receiving GPS signals are also capable of acquiring signals from other GPS-like satellite constellations. However, from a policy and planning perspective, understanding the relative magnitude of potential impacts is important for making informed decisions about investments in back-up systems and contingency plans.

This report also charts the evolution of GPS's development, including its emergence from technologies and concepts pioneered in U.S. national laboratories and the role of different agencies and laboratories in working with different industries to take advantage of GPS's potential.

1.1 Defining Positioning, Navigation, and Timing

The ability to measure time intervals and frequencies extremely precisely is what allows GPS users to pinpoint their location anytime, anywhere in the world. The launch of Sputnik in 1957 and the resulting space race led the United States to accelerate scientific efforts deemed essential for national security and

spaceflight capability, including the creation of what is today the Defense Advanced Research Projects Agency (DARPA).

An important breakthrough occurred when U.S. researchers discovered they could discern the location of ground-receiving stations based on Sputnik's radio transmissions and accurately determine the satellite's orbit. That realization catalyzed research and development programs within the U.S. national laboratories, the military, and contractors in the private sector and academia to develop satellite systems to further American geopolitical and defense interests.

The comparison of multiple timing signals allows three general applications.

- Position applications leverage the ability to determine the precise location of a feature or object.
- Navigation is the comparison of current to desired position and the ability to apply necessary course, altitude, and speed corrections to bring an object into a desired position.
- Timing is the ability to acquire and maintain accurate and precise time.

Although the position and navigation aspects are perhaps GPS's best known uses, they are enabled by GPS's timing attribute. The timing attribute of the GPS signal is used for precision timing services by a variety of industries. For example, the telecommunications sector relies on GPS to synchronize the flow of data and voice traffic across the network (see Section 4), financial markets use GPS to timestamp transactions for high-frequency trading (see Section 7), and electric utilities use GPS to increase the efficiency of the transmission grid (see Section 6).

1.2   How GPS Works

The current GPS infrastructure involves three segments: space, control, and user. The space segment currently consists of more than 30 satellites in multiple orbital planes. GPS satellites complete orbits every 12 hours. Each satellite contains four atomic clocks, a radio transmitter, and at least two antennas to communicate with ground control stations (Federal Aviation Administration [FAA], 2014a).

Table 1-1.   Defining Positioning, Navigation, and Timing (PNT)

Position	The ability to accurately and precisely determine one's location and orientation referenced to a standard geodetic system
Navigation	The ability to determine current and desired position (relative or absolute) and apply corrections to course, orientation, and speed at various altitudes
Timing	The ability to acquire and maintain accurate and precise time from a standard (Coordinated Universal Time, or UTC), anywhere in the world and within user-defined timeliness parameters; includes time transfer

Source: U.S. Department of Transportation.

Each satellite's transmitter broadcasts a PNT message. The message contains location, status, and a highly precise timestamp of when the message was transmitted. All GPS satellites are synchronized to Coordinated Universal Time (UTC),[1] which allows messages from different satellites to be reliably compared.

The U.S. Air Force operates and maintains the GPS system through the Global Positioning Systems Directorate, a unit within the Space and Missile Systems Center, Air Force Space Command, at Los Angeles Air Force Base. The directorate is responsible for the acquisition, development, and production of GPS satellites, ground systems, and military user equipment. In 2004, President George W. Bush directed the establishment of an interagency board to provide "guidance and implementation actions" for space-based PNT "programs, augmentations, and activities for the U.S. national and homeland security, civil, scientific, and commercial purposes" (GPS.gov, 2004). Figure 1-1 presents the current structure.

The control segment consists of 15 global monitoring stations, including a Master Control Station located at Schriever Air Force Base in Colorado Springs. Six monitor stations are managed by the Air Force and nine by the National Geospatial Intelligence Agency. The master control station is responsible for the overall management of the monitoring station system. The individual monitoring stations continually check the altitude, position, speed, and operational health of the satellites and feed this information to the master control station (FAA, 2014b).

Figure 1-1.   U.S. Organizational Structure for GPS Governance

Source: GPS.gov (2016d).

---

[1] UTC is the international time standard that is maintained by the Bureau International des Poids et Mesures. UTC is based on International Atomic Time, which is an average of over 300 atomic clocks at 60 timing laboratories where the clocks are weighted based on stability. GPS's primary signal distributes UTC, which enables networks to stay in sync across wide geographic areas (NIST, 2016).

GPS relies on precise, synchronized time to provide accurate PNT. The U.S. Naval Observatory is tasked with maintaining the time and frequency standard for all Department of Defense (DoD) activities, including GPS.[2] A secondary master clock is located at Shriever Air Force Base. The master clocks incorporate multiple cesium atomic clocks (described later) and hydrogen masers.

The user segment consists of GPS receivers used in myriad military, government, commercial, and civilian applications. To pinpoint location, GPS receivers use messages from a minimum of four satellites.[3] By measuring and comparing the timestamps on messages from multiple satellites, the GPS receiver can determine its position in three dimensions. See Figure 1-2 for an illustration of this concept. Basic, unassisted GPS service is accurate to roughly 8 meters 95% of the time anywhere on or near the Earth's surface. However, augmentation techniques such as Assisted GPS (A-GPS), Wide Area Augmentation Service (WAAS), and Real-Time Kinematics (RTK) can acquire greater precision from the GPS signal and improve performance in other ways.

1.3 Analysis Scope and Objectives

To better understand the value of GPS for the private sector, the National Institute of Standards and Technology (NIST) sponsored this analysis. It had three major objectives:

- Present a detailed qualitative and quantitative analysis of the retrospective economic impacts resulting from the availability of the GPS signal for use by the private sector.

- Present a detailed qualitative and quantitative analysis of the potential economic damages resulting from a 30-day GPS outage.

- Identify and characterize the federal research and technology transfer activities that supported the development and deployment of GPS.

As mentioned above, this study initially began as a retrospective analysis to estimate the economic benefits of GPS relative to other sources of position and timing information. The potential impact of a 30-day outage was later added to the scope following discussions with several federal agencies about industries' reliance on GPS and potential significant economic impacts resulting from natural disruptions (such as solar flares) or nefarious activities by bad actors. The 30-day outage period was set by this study's sponsor in consultation with other parties within the Department of Commerce.

---

[2] Directed by DoD, the U.S. Naval Observatory is tasked with maintaining the time and frequency standard for all DoD activities. The primary "master clock," which provides the time standard for GPS and all other DoD timing needs, is managed by the U.S. Naval Observatory in Washington, DC. A secondary master clock is located at Shriever Air Force Base. The master clocks incorporate multiple cesium atomic clocks and hydrogen masers. GPS time differs slightly from UTC in that it is not corrected to match the rotation of the Earth. UTC does this by periodically adding leap seconds and making other corrections. In addition to GPS time, the GPS signal distributes the correction between GPS time and UTC (NIST, 2016).

[3] One can think of the four satellites as providing the information to solve for four unknowns: longitude, latitude, altitude, and the timing error of the receiving source.

Figure 1-2.   How GPS Works

Source: National Air and Space Museum, Smithsonian Institution. (2012). Time and Navigation. How does GPS work?
   Retrieved from https://timeandnavigation.si.edu/multimedia-asset/how-does-gps-work

We selected industries by determining those whose use of GPS provides them with benefits that could not have been met by other technologies or that would not have received the same level of benefits. Before GPS was made available for commercial use, the Loran system (as reviewed later in this report) delivered a signal that was readily available, if not as robust or precise. If GPS had not been made available for commercial and civilian use, Loran likely would have been expanded over time as technological advances required greater access to more precise sources of position and timing information. Thus, not only did we measure benefits relative to a counterfactual in which other technologies would have been available, but we also only included industries that developed a reliance on the incremental precision offered by GPS. Ten industries were included in this analysis.

As we review later in the methodology section, we considered several others, but it was determined that these did not have the need for the precision delivered by GPS over and above what was available from other technologies. Of course, if they are using GPS today and an outage were to occur, they could be adversely affected. A limitation from our initial scope definition means that such industries are not included. This also means that the summary results for the 30-day outage scenario should be interpreted as an underestimate of likely impacts.

Because of this limitation, the Department of Homeland Security (DHS) provided additional funding for the maritime sector to be included in our 30-day outage analysis. DHS is completing a technical assessment of GPS vulnerabilities and available back-up systems and is leveraging the results of this economic analysis. GPS's simplicity and ubiquity have led to widespread use in the maritime sector. Although the benefits of GPS relative to what mariners used to use are not great, mariners have migrated to its use. Thirty-day outage impacts could be significant. The maritime sector is an excellent example of this study's limitations. All benefits monetized and presented here may be underestimates as a consequence.

Table 1-2. Industry Sector Coverage

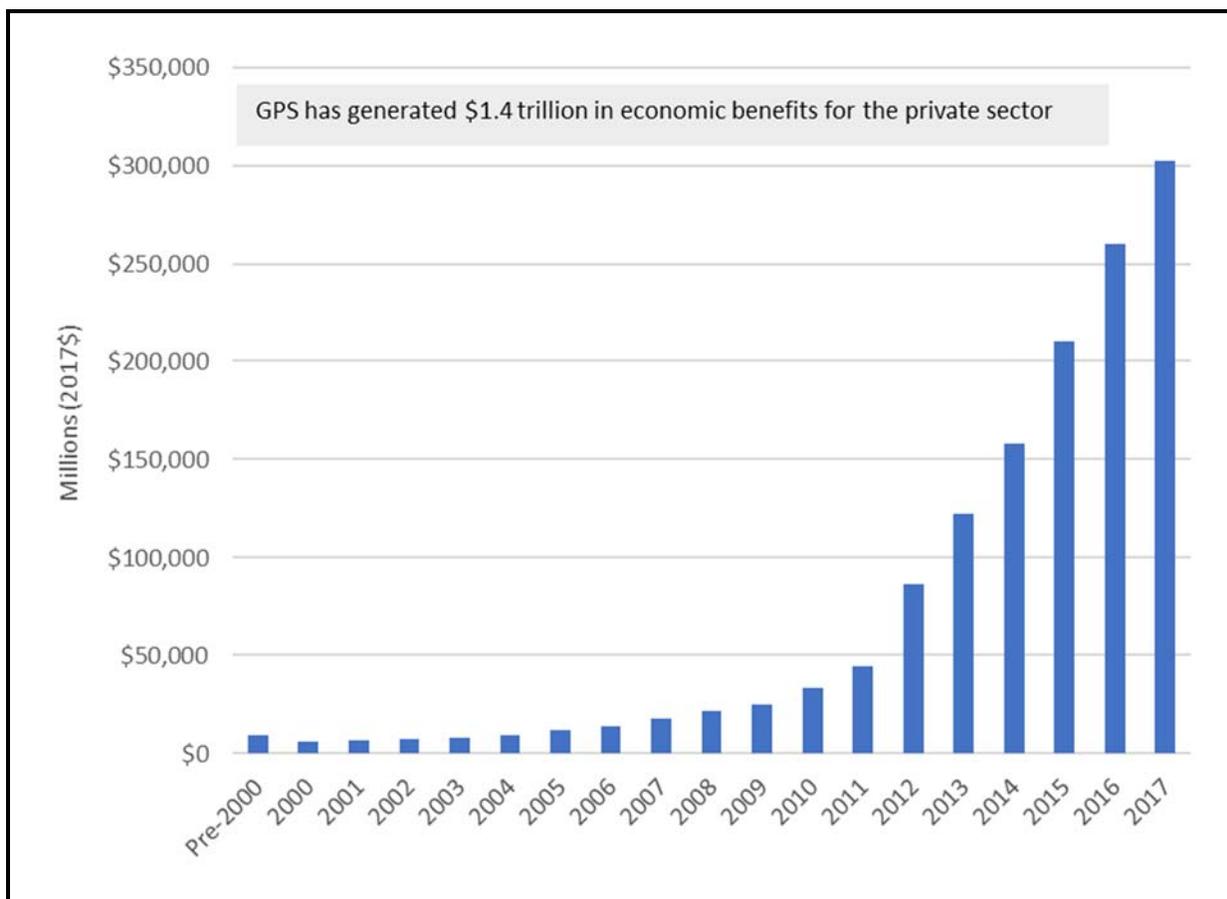| Sector	Specific Analytical Focus
Agriculture	Precision agriculture technologies and practices
Electricity	Electrical system reliability and efficiency
Finance	High-frequency trading
Location-based services	Smartphone apps and consumer devices that use location services to deliver services and experiences
Mining	Efficiency gains, cost reductions, and increased accuracy
Maritime	Navigation, port operations, and recreational boating
Oil and gas	Positioning for offshore drilling and exploration
Surveying	Productivity gains, cost reductions, and increased accuracy in surveying
Telecommunications	Improved reliability and bandwidth utilization for wireless networks
Telematics	Efficiency gains, cost reductions, and environmental benefits through improved vehicle dispatch and navigation

1.4   Approach Overview

Our approach brought together information about the prevalence of GPS's use by industry, its adoption history, industry trends, and available alternatives. We interviewed almost 200 experts in industry, academia, and government and conducted two surveys. The first survey was fielded to surveyors with the support of the National Society of Professional Surveyors. The second was fielded to a representative sample of American smartphone users to understand the extent to which they rely on their phones' location services for emergency services, navigation, games, check-ins, and other activities.

Although other studies have quantified impacts associated with GPS, they either were specific to an application (e.g., precision agriculture [Schimmelpfennig, 2016]), or they were generalizations that relied on desk research to assess impacts (e.g., Leveson, 2015; Pham, 2011). Note that we do not assess the geopolitical and national defense value of GPS. Our scope was civilian and commercial use, with an emphasis on the role GPS plays in meeting private-sector needs for precision PNT information.

We present the results for each industry as a separate case study. How GPS adds value differs by industry, as does the method used to quantify that value. Providing a case study for each industry ensures that each industry's use was appropriately contextualized and described.

1.5   Report Organization

This report is organized as follows:

- Section 2 provides an overview of GPS and the history of innovation in the national laboratories that led to the its development.
- Section 3 presents an overview of our methodology that complements the industry-specific approaches detailed within each case study.
- Sections 4 through 13 provide background information, methods, and estimates of the economic impact of GPS on the 10 different industries and sectors listed in Table 1-1.
- Section 14 concludes the study.

2. The History of GPS Technology: National Laboratory Innovation and Technology Transfer

The technology comprising today's GPS has progressed through multiple technology life cycles over the past 60 years. Military objectives drove the initial development of space-based navigation systems, and as such, the national laboratories with Department of Defense (DoD) support took the lead role in research and development of enabling technologies. For example, research at the Naval Research Laboratory (NRL) and Air Force Research Laboratory (AFRL) established satellite orbital planes, discovered passive ranging techniques to account for signal delays, and performed R&D and testing procedures for critical equipment designed for space travel. Multiple early systems saw the underlying technologies and infrastructure be developed and proven, moving capabilities from two-dimensional (latitude and longitude) to three-dimensional (adding altitude) positioning. In 1973, NAVSTAR integrated existing programs to produce the more accurate and robust system in use today.

The network of technology developers ultimately included the labs, government agencies, research universities, and private-sector contractors. Once selective availability was turned off in the mid-1990s, the private sector took the lead in developing the technologies needed for most of today's commercial applications, building on the base of technology from earlier years. The timeline in Table 2-1 illustrates how research objectives and the roles of government and industry have evolved over time.

This section describes how today's GPS system evolved from national laboratory technologies and programs. Our focus is on noting key programs and milestones; many comprehensive histories of GPS's development exist. For reference, Table 2-2 presents a timeline of significant milestones.

2.1 Project Vanguard

The International Geophysical Year (IGY)—from July 1957 to December 1958—was an international cooperative engagement to study the geophysical properties of Earth. The Naval Research Laboratory established Project Vanguard in 1955 to represent the United States in the IGY. On December 6, 1957, Project Vanguard's first satellite launch failed, resulting in a near-immediate explosion at Cape Canaveral, Florida. The failed launch, dubbed "Flopnik," was carrying Satellite TV3 (Test Vehicle 3), the purpose of which was to conduct an orbital analysis and collect other information on the environmental (radiation) effects on TV3. Four months later, Project Vanguard successfully launched a replacement satellite into orbit. The following year, Vanguard 1—the first solar-powered satellite in space—was successfully launched. Vanguard 1 ultimately met the project's goals by collecting valuable information on Earth's physical, atmospheric, and environmental properties. Project Vanguard ended with the launch of Vanguard 3 in 1959.

Table 2-1.   U.S. Satellite Navigation Systems, Programs, and Manufacturers

Program	Owner	Years Active	Key Technology Capabilities
Vanguard	U.S. Navy	1955–1959	Used solar cells to power radio transmitter, collected novel information about satellite orbits as well as geophysical characteristics of Earth
Transit	U.S. Navy	1959–1996	Established orbital patterns and predictions
System 621B	U.S. Air Force	1963–1973	Developed "pseudo-random noise" signal to resist jamming
Timation	U.S. Navy	1964–1973	Developed passive-ranging technique using high-stability clocks and time reference for positioning
NAVSTAR GPS	U.S. Air Force, JPO	1973–present	Installed atomic clocks onboard GPS satellites; delivered civil and military signal; ground, control, and space segments maintain timing integrity

GPS Satellite Block	Manufacturer	Launch Period	Key Technology Capabilities/Improvements
I	Rockwell International (Boeing)	1978–1985	Design life of 5 years, two L-band navigation signals, served as concept testing series
II	Rockwell International (Boeing)	1989–1990	Nuclear detection sensors, designed to operate for 14 days without contact from control segment
IIA	Rockwell International (Boeing)	1990–1997	Durability improvements, designed to operate for 180 days without contact from control segment; 7.5-year design lifespan
IIR	Lockheed Martin	1997–2004	Replacement satellites for Block II, 7.5-year design lifespan
IIR-M	Lockheed Martin	2005–2009	Included military signal (M-code) and new civil signal (L2C), 7.5-year design lifespan
IIF	Boeing	2010–2011	Included third civil signal (L5), inertial navigation systems, 12-year design lifespan
IIIA	Lockheed Martin	2014 onwards	Include a fourth civil signal (L1C), higher broadcasting power, navigation enhancements, improved interoperability, greater jamming resistance, 15-year design lifespan

Source: Whitlock, R.R. & McCaskill, T.B. (2009); Pace, S. (1995); GPS.gov (2017b).

Table 2-2.   Notable Milestones in the Development of GPS

Year	Achievement
1954	The utility of space-based satellites is in review by various scientific agencies; a study is proposed to NSF
1955	DoD recommends the Naval Research Laboratory Scientific Satellite Program—which became Project Vanguard
1957	Soviet Union launches Sputnik I and II satellites
	Attempt to launch Project Vanguard's first satellite (TV3) is unsuccessful
1958	United States launches first satellite into orbit—Explorer 1—under the direction of the Army Ballistic Missile Agency
	Project Vanguard successfully launches Vanguard 1 satellite
1959	Transit satellite navigation system developed at Johns Hopkins Applied Physics Laboratory

Table 2-2. Timeline of GNSS Development (continued)

Year	Achievement
1963	System 621B, a navigation system developed by Air Force, is established
1964	Timation is established by the Naval Research Laboratory and led by Roger Easton
1968	DoD establishes steering committee—NAVSEG (Navigation Satellite Executive Steering Group)—to coordinate satellite navigation efforts
1973	In April, DoD further pushes for coordination, naming the Air Force to lead a new initiative called the Defense Navigation Satellite System (DNSS). DNSS was overseen by the Joint Program Office (JPO). NRL is still involved.
	In December, the NAVSTAR GPS concept is approved by the Defense System Acquisition and Review Council (DSARC).
	Phase 1 of the GPS program begins; intended to confirm the concept of space-based navigation.
1974	First NAVSTAR satellite—Navigation Technology Satellite (NTS)—is launched. It was a refurbished Timation satellite built by the NRL. It used the first atomic clock in space—a rubidium atomic standard.
	NRL expands cesium clock development for use on future satellites.
1977	NTS-2 satellite is launched carrying first cesium atomic clock into space.
1978	First of 11 Block I satellites launched between 1978 and 1985.
1983	After a Korean plane was accidentally shot down by the Soviet Union, President Reagan announces his intentions to make GPS available to civilian aircraft for free when the system is operational.
1989	The U.S. Coast Guard assumes responsibility as the lead agency for the Civil GPS Service within the Department of Transportation.
	The first five GPS Block II satellites are launched; From 1989 to 1997, 28 satellites are launched, including the last 19 being updated versions (Block IIA).
1991	First combat use of GPS is used in the Persian Gulf War, enabling U.S. military forces to validate its usefulness in the featureless Iraqi desert.
1994	GPS is announced as operational and integrated into the U.S. air traffic control system.
	FAA announces implementation of the WAAS to improve GPS integrity and availability for civil users in all phases of flight.
1996	Transit satellite system ceases operation on December 31 at 2359 GMT.
2001–2003	Combat following 9/11 attacks and during Operation Iraqi Freedom further demonstrates the precision of GPS in military conflict.
2005	First "modernized" GPS satellite is launched (IIR-M) that transmits a second civilian signal for enhanced performance.
2008	U.S. Air Force announces award to Lockheed Martin for the development and production of GPS III satellites.
2010	Russian GLONASS system completes constellation of 24 satellites, becomes fully operational.
	U.S. Air Force announces award to Raytheon to development next-generation Operation Control System (OCX).
2012	BeiDou reaches regional Asia-Pacific coverage.
2016	The EU's Galileo achieves Early Operational Capability with 18 satellites in orbit.

Sources: Pace, S. (1995); Whitlock, R.R. & McCaskill, T.B. (2009); GPS World. (2014).

2.2   Transit

Transit was initially developed to accurately provide navigation data for Polaris missile submarines and other ships at the ocean surface. After the unexpected launch of Sputnik 1, researchers studied the satellite's radio signals and eventually could determine the satellite's location in orbit (Guier & Weiffenbach, 1998). This research contributed to Transit's development in 1958 through a joint effort between DARPA and Johns Hopkins Applied Physics Laboratory (Aerospace Corporation, 2010). After a failed satellite (Transit 1A) launch in 1959, the second attempt in launching a Transit satellite (Transit 1B) was successful. In 1964, the system was transitioned to the Naval Research Laboratory.

By 1968, Transit was fully operational with 36 satellites in orbit. Transit operated for 28 years until 1996, when the Defense Department replaced it with the current GPS system. Transit was initially designed to provide accuracy within about 0.5 nautical miles (926 meters) but eventually reached a level of accuracy of 0.1 nautical miles (185 meters) ("Transit—US Navy Navigation Satellite System," n.d.). The system was two dimensional and thus did not measure altitude.

Transit was significant in proving space-based navigation was possible and provided technical contributions to later navigation systems through the orbits and orbital prediction methods.

2.3   System 621B

System 621B originated at the Aerospace Corporation and was supported by the U.S. Air Force. It was the first satellite navigation system to feature three-dimensional navigation, which was needed to monitor aircraft positioning ("Evolving Solutions," n.d.). Another contribution of 621B was that it used a signal called pseudo-random noise to resist jamming. The signal was tested on aircraft between 1968 and 1971 and was ultimately verified in 1972 at White Sands Proving Ground in New Mexico (Stanford, 1995). System 621B's signal structure and frequency were ultimately used in the first iteration of GPS (Pace, 1995).

2.4   Timation

Timation (short for Time and Navigation) was a program developed by the Naval Research Laboratory in 1964. This program was instrumental in the history of navigation systems because of its emphasis on precision time references to provide accurate positioning. Although atomic clocks were not yet employed in satellites, Timation satellites used high-stability clocks that were regularly updated and synchronized with a master clock on the ground (Beard, Murray, & White, 1986). The program proved three-dimensional navigation (latitude, longitude, and altitude) was possible through its "passive ranging" technique. The U.S. Naval Observatory was also involved in developing the timing equipment used in Timation satellites and was active in research toward atomic time standards.

The Timation program launched only two satellites—in 1967 and 1969—but was instrumental in the use of time references to pinpoint locations on Earth ("Navigation Technology Satellites," n.d.). In 1973, the program merged with System 621B, and its third satellite (Timation III) was redesigned under the new NAVSTAR program and launched in 1974.

2.5   Atomic Clock Development

The most accurate clocks rely on some source of frequency. The frequency needs to have an oscillation period that is well characterized, resistant to external disrupters, and highly stable (Lombardi et al., 2007). Mechanical clocks used pendulums that swung at relatively constant rates to measure time to within up to one-hundredth of a second per day. In 1927, a breakthrough in time keeping was developed using the frequency provided by quartz crystals. The quartz clock's accuracy exceeded the pendulum-driven clocks because of the piezoelectric properties of the crystal, which vibrates at a precise frequency when jolted with electricity. Quartz clocks are still abundantly available today in watches, clocks, and appliances. This concept of frequency remains true even in the most advanced clocks.

The development of advanced atomic clocks by NIST (then called the National Bureau of Standards [NBS]) and the UK's National Physical Laboratory provided one of the most critical technology components of satellite navigation. In 1949, the NBS built the world's first atomic clock using ammonium absorption. However, this clock was primarily experimental and was never used for practical purposes. "Atomic," in more recent terms, refers to the use of measuring the electron frequency of an atom—cesium or rubidium, most commonly—for timekeeping. In 1955, researchers at the National Physical Laboratory in the UK built the first cesium atomic clock. Although early research was performed at national laboratories, private companies innovated and improved the atomic clock for practical purposes, such as space-compatible clocks to be launched aboard satellites.

In 1974, the first atomic clock (NTS-1) was launched aboard a GPS satellite. This was followed by continued research to improve timing standards and develop a series of new atomic clocks, which were incorporated into the GPS system as it evolved. Table 2-3 presents the noteworthy timeline of atomic clock development.

Table 2-3.   Notable Milestones in Precision Timing

Year	Achievement
1949	World's first atomic clock is built by NIST (then the NBS)—it used ammonia absorption.
1951	Cesium atomic beam device is completed at NBS with Office of Naval Research funding.
1952	First atomic clock using cesium atoms for frequency is built by NIST, named NBS-1, although not accurate enough to be a time standard.
1955	▪ Louis Essen at the UK's National Physical Laboratory built the first atomic clock accurate enough to be a time standard. ▪ ONR contracts the National Company, Malden, Massachusetts, to produce a military atomic clock based on that of Jerrold R. Zacharias of MIT, with engineering characteristics set forward by the Navy Bureaus of Ships and Aeronautics and the Naval Research Laboratory.
1956	The National Company produces Atomichron, the first commercial cesium atomic beam clock.
1958	Commercial cesium clocks become available, costing $20,000 each, developed by The National Company.
1959	NBS-1 becomes NIST's primary frequency standard.
1960	▪ First atomic hydrogen maser (or frequency standard) was built at Harvard. ▪ NBS-2 is developed at NIST's laboratories in Boulder, Colorado.
1963	NBS-3 is developed and offers improved accuracy and stability.

(continued)

Table 2-3. Developments in Precision Timing (continued)

Year	Achievement
1964	Cesium atomic beam tubes are developed by Varian Associates for Hewlett Packard.
1967	The 13th General Conference on Weights and Measures defines the second as the vibrations of the cesium atom, which replaced astronomical timekeeping.
1968	NBS-4 is developed as the world's most stable clock, used into the 1990s as part of the NIST time system.
1972	NBS-5 is developed and serves as the new primary standard.
1975	NBS-6 is developed; it is accurate to within 1 second in 300,000 years.
1993	NIST-7 is developed and is 20 times more accurate than NBS-6.
1999	NIST-F1 begins operation—it is accurate to 1 second in 20 million years.
2014	NIST launched NIST-F2, an atomic clock accurate to 1 second in 300 million years.

Source: Pace, S. (1995); Whitlock, R.R. & McCaskill, T.B. (2009); Bhaskar et al. (1996); Lombardi, M.A. (2012).

The atomic clock has become perhaps the most critical technology component of satellite navigation because of the level of precision required. The signals sent and received by satellites, ground stations, and GPS receivers rely on coordinated time standards so that accurate positioning is maintained. If there is lack of timing coordination or if timing standards were less accurate by some orders of magnitude, then the positioning errors of meters to hundreds of meters could likely result. Given that four satellites need to be simultaneously visible to provide location information, it is critical that timing and signal delivery from satellite to ground-based clocks and receivers are synchronized to support today's applications (Piester et al., 2011).

The Time and Frequency Division at NIST, through Defense Advanced Research Projects Agency (DARPA) funding and collaboration, developed the chip-scale atomic clock (CSAC), which is now being developed and marketed by private companies. Weighing just 35 grams and consuming 115 mW of power, the CSACs enable portable applications for military and commercial uses (Fetter, 2013). For military uses, the CSAC's low size, weight, and power consumption complement other gear required in the field such as improvised explosive device jammers. Its highly accurate timing synchronization also helps to prevent self-jamming and can track GPS signals more quickly and with less visibility (i.e., a minimum of three satellites in view versus the normal four). Unmanned aerial vehicles also benefit from CSAC's small physical properties as well as its ability to improve signal detection and jamming resistance ("Quantum SA.45s CSAC," 2016).

Since the Unites States' primary civilian time and frequency standard, NIST-F2, was initiated in 2014, NIST researchers have already been developing significantly more precise atomic clocks. Although the Naval Observatory oversees GPS time, NIST manages civilian timing applications, and its R&D activities contribute to GPS timing and frequency standards in the future. In 2015, the strontium lattice atomic clock demonstrated that it would "neither lose nor a gain one second in some 15 billion years." For comparison, this level of performance is 50 times more precise than the NIST-F2 cesium fountain atomic clock. An example of the strontium atomic clock's practical application is measuring gravitational shift based on marginal changes in altitude—as marginal as 2 centimeters (NIST, 2015). Additional research at

NIST has combined two experimental atomic clocks based on the frequency of ytterbium atoms. The double clock has further increased precision and stability by eliminating a distortion in laser frequency that synchronizes that atoms (NIST, 2016a). Like the potential new applications and discoveries made possible through the strontium atomic clock, the double clock could improve the current performance of PNT as well as enable new capabilities.

2.6   NAVSTAR GPS

With Navy and Air Force satellite-based navigation programs advancing in parallel and limited by the availability of resources, the DoD designated that the existing systems be consolidated into one comprehensive system led by the Air Force (Pace, 1995). In December 1973, the Joint Program Office (JPO) approved the concept of NAVSTAR (Navigation System with Timing And Ranging) GPS and incorporated the best features of Transit, Timation, and System 621B (Rip & Hasik, 2002).

The new GPS system launched its first satellite in July 1974, designated Navigation Technology Satellite 1 (NTS-1), which was a refurbished Timation satellite. NTS-1 carried the first atomic clock into orbit—a rubidium frequency standard. The second (and last) of the NTS series carried the first cesium atomic clock into space (Pace, 1995).

GPS was originally planned as a constellation of 24 satellites, which were to be launched in phases, or "Blocks." Eleven Block I satellites—launched between 1978 and 1985—were launched as the initial developmental satellites to establish feasibility ("Global Positioning System," n.d.). The Block II satellites were designed and launched to establish operational capacity. The first Block II satellite was launched in February 1989 and featured significant improvements over the Block Is including radiation-hardened electronics, selective availability and anti-spoofing capabilities, and automatic error detection for certain conditions (Pace, 1995). Between 1989 and 1996, 27 Block II and Block IIA (Advanced) satellites were launched. Figure 2-1 presents the number and timeline of GPS satellite launches by Block. All satellites launched before 1996 are now retired.

GPS provides two levels of service that operate on different frequencies: 1) the PPS frequency restricted to U.S. Armed Forces, federal agencies, and selected allied armed forces and governments and 2) the SPS available for civil and commercial use (NASA, 2012).

The first military test of GPS was carried out during Operation Desert Storm during the Persian Gulf War in 1990. In the vast expanse of the Iraqi desert, military personnel used GPS to navigate the featureless terrain (Space and Missile Systems Center, 2016). Their weapons' precision and movement capabilities were considered crucial to success in the conflict. Not only did GPS prove to be valuable for military purposes, it began to be used in humanitarian operations, such as delivering relief supplies through air drops.

In 1996, President Clinton made good on President Reagan's promise to make GPS available for civilian use at no cost after Korean Air Lines Flight 007 was shot down in 1983 after flying too close to Soviet airspace ("Korean airliner 'shot down'," n.d.). The system's availability for civilian use sparked new industry segments and applications. Select availability was turned off in 2000.

Figure 2-1.   Timeline of GPS Satellites in Orbit

Source: GPS World (2016)

3. Methodology Overview

The methodology for valuing the economic benefits of GPS's provision of spaced-based positioning, navigation, and timing (PNT) signals will be specific to each industry sector included in the study. This methodology overview discusses our general approach, common assumptions, and areas of overlap. Then, each sector has a stand-alone case study with methodological notes specific to the valuation of the benefits GPS delivers to it.

To reiterate a point made in the introduction, our goal is not to value PNT services themselves, but to value PNT as it is delivered by the GPS system. This framing allows us to consider other PNT delivery systems as potential alternatives to GPS when developing counterfactual scenarios for benefits estimation. When GPS became available, a variety of delivery systems were in place that provided PNT services, including NIST time, Loran-C, and OMEGA.

3.1 Conceptual Approach to Valuing Economics Benefits

The economic assessment characterizes the benefits of GPS by how it improves production methods, improves product attributes, or both. To illustrate these distinctions, consider the following three technology examples:

1. Improved production: A mining company uses GPS positioning to increase the efficiency of its transportation and hauling activities. The process now produces an identical commodity at a lower cost.

2. Improved product: The telecommunications industry uses GPS precision timing to synchronize its towers. This reduces/eliminates dropped calls and increases the bandwidth, enabling more advanced networks such as 4G LTE and 5G.

3. Both improved: The electricity industry uses GPS frequency to synchronize its phase measurement units, which in turn reduce transmission and distribution losses (improved production of electricity) and increase system reliability (improved product).

Figure 3-1 provides a simple graphical depiction of the three scenarios, illustrating how the market impacts of these technology innovations differ. In the first example, production costs have lowered, shifting the supply (marginal cost) curve to the right. In the second example, the net benefit to consumers is now greater, shifting the demand curve to the right. In the final example, both curves have shifted to the right: we refer to this sort of technological innovation as a "market-spanning" innovation; it changes both the supply and demand curves in the market.

Each of the three chosen examples increases total welfare, measured by the area above the supply curve and below the demand curve. Thus, conceptually the benefit of GPS is measured by the incremental welfare area generated by the shift in the curves.

The graphs in Figure 3-1 illustrate improvements in production and/or in quality for an existing product or service. For example, prior to GPS the United States had a highly functional electricity system serving all customers. GPS then lowered the cost and increased the quality of electricity service.

Figure 3-1.   Three Scenarios of Consumer and Producer Surplus Expansion

However, in some instances, it can be claimed that certain products or services would not be possible or would not have been developed without GPS. For example, most of the location-based apps popular with consumers today would not exist without the free and ubiquitous precision location capabilities provided by GPS. In this instance, the entire welfare triangle above the supply curve and below the demand curve can be attributed to GPS.

As we have already noted, the exact method for quantifying the benefits of GPS will be different for each sector and may also differ for specific products and services within a given sector. Thus, each sector chapter will have its own economic benefits methodology section.

3.2   Counterfactual A: In the Absence of the Availability of GPS for Civilian Use

Economic impacts are measured relative to a counterfactual scenario that describes what otherwise would have been in place or would have occurred in the absence of the technology being analyzed. For this study, developing a counterfactual means answering two key questions:

1.   What did each sector of interest use before GPS was available (if anything)?

2.   In the absence of GPS, are there other technologies that would have evolved or been invented to provide some of the same services that GPS provides?

To answer these questions, we conducted research and scoping interviews with sector-specific GPS experts to understand the technology landscape in the late 1980s and early 1990s when the private sector first began leveraging GPS for commercial applications. In general, the feedback was that some industries (e.g., agriculture) would have continued using the same technologies for their PNT needs that had been used before GPS was available. Other sectors (e.g., telecom) were actively exploring alternative technologies at the time when GPS was adopted; both scenarios provide insight into what technologies might otherwise have been used in the absence of GPS.

One such alternative technology is Loran-C, a land-based PNT system that was originally developed for marine navigation purposes (Justice et al., 1993). Additionally, as recently as the 2000s, both government

and the private sector were researching and testing an enhanced Loran system known as eLoran, although it was never made operational. Both Loran-C and eLoran provide the same kind of timing and frequency signal as GPS, but in most cases, Loran is less accurate and precise (see Table 3-1). Additionally, the evolution of Loran-C into eLoran over time would have been different from GPS, potentially affecting the development of some commercial applications.

For most of the sectors, our counterfactual assumption is that in the absence of GPS a Loran-based network (similar to Loran-C) likely would have received more investment to fully cover the U.S. This would have been used for many of the same applications that rely on GPS today. Note that it is possible that many applications across several sectors would be able to leverage a Loran-C signal to achieve the same benefits that are experienced using GPS today, effectively eliminating the benefits of GPS for those applications under this counterfactual scenario.

3.3   Counterfactual B: An Unexpected 30-Day Outage of the GPS System

Under a 30-day outage of GPS scenario, we assumed that neither Loran-C nor eLoran would be available as a backup. Neither one of these systems is operating today, nor could these systems be implemented within the 30-day time window of our analysis. We also assumed that other international global navigation satellite systems (GNSSs), such as GLONASS or Galileo, would also not be available for use within the 30-day time window.

Hence, the counterfactual for the 30-day failure of GPS is simply the quality/reliability of each sector's current backup system. These systems include backup timing systems and the associated level of holdover these clocks/systems may have. For most positioning applications, the location-based GPS functionality would not be possible at all, forcing the sectors to revert to pre-GPS alternative processes.

3.4   Approach for Selecting Industry Sectors

Because of the vast and growing number of applications reliant on GPS, the study needed to down select to the key sectors whose use comprises the bulk of the economic benefits. Our approach to selecting sectors was based on the following criteria:

Table 3-1.   Precision and Accuracy Performance of Loran-C, eLoran, and GPS

	Loran-C	eLoran	GPS
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10–50 ns	10 ns
Positioning (meters)[a]	18–90 m	8–20 m	1.6–4 m

[a] The positioning accuracy of each of these technologies varies widely by type of receiver and augmentations being applied. The accuracy quoted here for GPS is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

Sources: Narins et al. (2012); Curry (2014); Celano et al. (2003); GPS.gov

- **Need for precision:** For both position and timing, the level of precision needed for the GPS application for the industry/sector was ranked as high, medium, or low as follows
  - Position

- High: less than +/− 1 meter

- Medium: +/− 1 meter to 10 meters

- Low: greater than +/− 10 meters

– Timing

- High: less than +/− 1 microsecond

- Medium: +/− 1 meter to 1,000 microseconds

- Low: greater than +/− 1 millisecond

▪ *Alternatives:* In the absence of GPS, are there technology, behavioral, or process options available to achieve the associated function?

– **Yes***:* Alternatives to GPS are available. They might be less efficient, but the industry/sector would not be dramatically affected.

– **No:** The function or application that GPS enables would not be possible.

– **Costly:** Alternatives are available but at significantly higher cost or loss of efficiency/functionality.

▪ *Scale*: What is the size of the industry or market for the GPS applications?

– **Large:** Large industry/application size with significant market penetration.

– **Medium:** Either industry/application size or market penetration is modest.

– **Small:** Both industry/application size or market penetration are modest/small.

Table 3-2 summarizes the assessment of the criteria for the industries with significant GPS applications. This table was based on an assessment and review of available literature, and in some instances individual ranking (high, medium, low) were changed based on further research and scoping interviews.

We finalized the key industries to be included in the detailed analysis and present the methodology for quantifying economic impacts along with detailed counterfactuals for each selected industry. Based on our assessment and discussions with industry and government agencies, the following focus sectors were selected:

▪ agriculture

▪ electricity

▪ financial services

▪ location-based services

▪ maritime

▪ mining

▪ oil and gas

Table 3-2.   Summary of Precision Need, Alternatives and Application Scale by Industry Sector

Industry/Sector	Need for Precision Position	Need for Precision Timing	Alternatives to GPS	Potential Scale of Impacts
Aviation	Low	Medium	Yes	Medium
Maritime transportation	Medium		Yes	Large
Rail transportation	High		No	Medium
Road navigation/telematics	Medium		Yes	Large
Agriculture	High–Medium		No	Large
Conservation	Low		Yes	Small
Forestry	Low		Yes	Small
Surveying	High		Costly	Large
Public safety and disaster relief	Low		Yes	Medium
Mining	Medium		Yes	Medium
Oil and gas sector	Medium		Yes	Medium
Electricity sector		High	Costly	Large
Construction and mining	Medium—low		Yes	Large
Space	Medium		No	Small
Finance		Low	Yes	Large
Telecommunications		High	Costly	Large

- surveying
- telecommunications
- telematics

3.5   Approach for Quantifying Economic Benefits by Sector

Because of the variety of sectors included in the analysis, we employed several different methods to estimate the benefits delivered by GPS. These valuation approaches can generally be grouped into the following categories:

- Changes in production costs: Additional labor, capital, materials, or energy is needed to produce the same product or service. For example, GPS improves vehicle fleet management and logistics, reducing fuel cost and increasing utilization of the existing fleet.

- Changes in productivity and/or revenue: For example, precision agriculture increases crop yield which can be valued at market prices.

- Willingness to pay (WTP): WTP is a stated preference approach where individuals or businesses are asked to value a service, activity, or product attribute. For example, what are consumers willing to pay for location-based services/apps via their smart phones.

Table 3-3 shows the valuation approach we employed for each sector. In almost all sectors GPS helps lower production costs high levels of precision at very low costs. In some sectors GPS enables totally new products and services and can be valued by increased revenue. If it is likely that new services are generating significant consumer surplus above market price, a willingness to pay approach is used. Some sectors (such as maritime) used multiple approaches to value different benefits in different subsectors (commercial fishing: lost revenue, recreational boating: WTP, navigation in seaways: increased operating costs). Details on individual valuation approaches are provided in each sector section.

All dollar values are presented in real, 2017 terms except where noted.

Table 3-3.   Summary of Benefits Valuation Approach by Sector

Sector	Changes in Production Costs	Changes in Productivity and/or Revenue	Willingness to Pay
Agriculture	X	X	
Surveying	X		
Telematics	X		
Location-based services			X
Mining	X		
Oil and gas	X	X	
Telecommunications			X
Electricity	X	X	
Financial services	X		
Maritime	X	X	X

4. Telecommunications Sector

The telecommunications industry relies on continuous, error-free information transfer across a large country and a myriad of independent network operators, all of which requires sophisticated synchronization systems. Today, this synchronization is predominantly accomplished by leveraging precision time and frequency signals from GPS. GPS functions as a common source of synchronization for the entire industry.

Because it was critical to unlocking advanced wireless networks with the implementation of 4G LTE, we estimate the economic impact of GPS to range from $81 billion (based on firms' willingness to pay for spectrum) to $686 billion (based on consumers' willingness to pay for increased bandwidth and speeds). During a 30-day outage of GPS, we estimate the economic loss would range from $5.5 to $14.2 billion.

This analysis considers the role of GPS in both the wireline and wireless telecommunications networks but does not consider other telecommunications services such as home internet services, cable television services, and broadcast radio and television.

4.1 Sector Introduction and Overview

Although telecom network operators have used other sources of precision time and frequency in the past and still use atomic clocks extensively, the network infrastructure has evolved to rely heavily on GPS. GPS is a free, ubiquitous signal that can be captured with relatively inexpensive equipment from anywhere in the world—something that cannot be said for any other source of precision timing.

As the demand for ever more sophisticated and high-performance telecom services has grown, the technology has evolved around GPS. This is especially true in wireless networks, which often do not have access to a precision timing signal from the wireline network. Although other technologies exist to meet the needs of network providers, none are widely implemented or available. The result is a critical infrastructure (telecommunications) that is heavily reliant on a single source of precision timing.

4.1.1 The Role of Precision Timing in Telecom

Precision timing enables a number of telecom services, including the synchronization of traffic between carrier networks and across wide geographic areas, initializing calls between wireless handsets, wireless handoff between base stations, carrier aggregation, directional antennas and adaptive transmission power control, and billing management. On wireless networks, higher levels of precision timing enable service providers to increase bandwidth and handle more devices within the same infrastructure and wireless spectrum as technology evolves. Table 4-1 details the level of precision timing required for both wireline and wireless networks by standard-setting bodies, including the International Telecommunications Union (ITU), the European Telecommunications Standards Institute (ETSI), and the Alliance for Telecommunications Industry Solutions (ATIS).[4]

---

[4] This is an abbreviated version of a table in ATIS (2017), a report that details the timing requirements of the telecom sector and examines the vulnerabilities posed by reliance GPS without a backup system.

Table 4-1.   Timing Precision Requirements in Telecommunications

Application	Precision Needed
Wireline (sources of timing)	
PRTC (primary reference time clock)	±100 ns with respect to Coordinated Universal Time (UTC)
ePRTC (enhanced primary reference time clock)	± 30 ns with respect to UTC
Wireless	
CDMA2000	± 3–10 µs
TD-SCDMA	± 3 µs
WCDMA-TDD (NodeB TDD mode)	± 2.5 µs
W-CDMA MBSFN	± 12.8 µs
LTE MBSFN	< ± 1 µs (spec. still under study)
W-CDMA (Home NodeB TDD mode)	Microsecond-level accuracy
WiMax	± 1–1.43 µs
LTE-TDD (wide area base station)	3 µs (small cell, <3 km radius) 10 µs (large cell, >3 km radius)
LTE-TDD (home area base station)	3 µs (small cell, <500 m radius)
LTE-TDD to CDMA handovers	± 10 µs
IP network delay monitoring	± 100 µs to ± 1 ms

Source: Adapted from ATIS (2017).

Precision requirements characterized in Table 4-1 reflect the requirements of the most advanced wireless technology available today. Previous generations of telecom infrastructure did not require as much precision. However, even in the late 1980s, wireline networks required at least microsecond-level accuracy to maintain reliable synchronization across a wide geographic area (Butterline et al., 1988).

In addition to using receiver equipment to directly access a time signal from GPS, telecom service providers also distribute time over their terrestrial fiber networks using Precision Time Protocol (PTP), which measures the delay between network points to calculate an accurate timing signal. However, while PTP theoretically could be used to distribute time independent of GPS, it typically synchronizes to UTC using GPS, so it does not function as a suitable alternative to GPS in its current implementation. Similarly, telecom network operators use atomic clocks on wireline infrastructure, but the clocks are typically disciplined using GPS.

4.1.2   Historical Context

Prior to GPS' availability, all telecom networks in the United States used analog switching and were synchronized using a precise frequency signal from an ensemble of cesium clocks operated by AT&T in Hillsboro, Missouri, and distributed over a hierarchical network (Butterline et al., 1988). With this system, everything was traceable to a single source. The ensemble of clocks was known as the Basic Synchronization Reference Frequency (BSRF).

At the time, using a single source of precise timing was feasible because network infrastructure was simple compared with today's. However, this changed in the late 1980s as two factors drove increased complexity in the network and more stringent synchronization requirements. First, in 1984, AT&T's monopoly was broken up by the federal government, resulting in seven new large telephone companies providing regional service. Second, the breakup of AT&T also helped accelerate the transition to digital network infrastructure as companies in the long-distance space competed on enhanced quality of service enabled by digital technology (Butterline & Frodge, 2001).

These two trends increased competition and technological evolution but made service delivery more complex, increasing the importance of synchronization and precision timing across the national telecom infrastructure. There was a pressing need to create network standards that would be accepted by all, which resulted in the creation of the Alliance for Telecommunications Industry Solutions (ATIS) in 1983 (Butterline & Frodge, 2001). ATIS is an industry association comprising information and communication technology companies that focuses on resolving shared challenges, including standardization, cybersecurity, and emergency communications infrastructure (ATIS, 2018).

The first standard developed by ATIS was the Synchronization Interface Standard, which set the performance requirement for a Primary Reference Source (PRS) for precision timing. While in the past there was one PRS (the BSRF operated by AT&T), two trends in telecom infrastructure necessitated many PRSs as networks evolved. First, each independent telecom company after the breakup of AT&T preferred to operate its own PRS so that it was not reliant on a competitor to provide precision timing. Second, the complexity of new digital networks necessitated more than one PRS per network, which would need to be synchronized to facilitate data and voice traffic travelling both within and between networks. The exact number per network varied depending on the network design and the operator's risk tolerance (Butterline et al., 1988).

AT&T was a pioneer in developing a PRS-based network; Figure 4-1 provides a representative illustration of AT&T's verifiable digital sync architecture (Butterline et al., 1988). PRSs, called primary nodes in Figure 4-1, were synchronized to UTC time using GPS and distributed precision timing to secondary nodes. Each secondary node was monitored by two PRSs, allowing the system to verify the accuracy of the signal throughout the network. PRSs were also backed up by two rubidium oscillators to provide holdover in the event of an outage of the source of UTC time (see Box 2).

Box 2. What is holdover?

Holdover refers to the operating condition of a clock when it has lost its source of precision timing (i.e., GPS). Most GPS receivers in the telecom infrastructure are supported by at least one oscillator, which is disciplined by GPS and relays the precise timing signal to the network. If the GPS signal is lost, the oscillator will enter holdover, relying on stored data to maintain precise timing. Depending on the quality of the oscillator, holdover may be able to maintain a stable signal for a few hours up to over a month (Butterline & Frodge, 2001).

Figure 4-1. AT&T Verifiable Digital Sync Plan

Legend:
▲ PRIMARY REGIONAL CLOCK NODE
— PRIMARY TIER MONITORING DS1 LINKS
□ SECONDARY TIER BITS-2 CLOCK NODE
—— SECONDARY TIER DISTRIBUTION & MONITORING DS1 LINKS

Source: Reproduced from Butterline et al. (1988).

When ATIS first introduced the Synchronization Interface Standard, only three technologies met the stringent requirements: cesium clocks, Loran-C, and GPS.

Following AT&Ts leadership, the industry largely made the decision to standardize on a regional network of PRSs disciplined by GPS, a decision that was driven by cost, performance, and the importance of interoperability across the industry. Although the telecom industry had a long track record of providing precise timing with cesium, deploying a large number of cesium clocks across the country (as opposed to three clocks in one location) would have been cost prohibitive, particularly for the smaller networks. A cesium clock cost around $40,000 to $60,000 in the 1990s ($65,000 to $97,000 in 2017 dollars), whereas a high-quality receiver for GPS cost approximately $10,000 ($16,000 in 2017 dollars). Furthermore, the cost of GPS equipment fell rapidly because of economies of scale as GPS was adopted for a wide range of uses around the country (Butterline & Frodge, 1999).

Loran-C would have provided an affordable source of precise timing, but at the time the signal was not nationally available, making it unsuitable for national carriers (who wanted to standardize on one source of UTC) and network operators outside of the coverage area of Loran-C. Finally, GPS provided a combination of flexibility and superior performance that made it the dominant choice for most network operators.

By 1990, Loran-C had been expanded to cover the entire continental United States through the Mid-Continent Expansion Project (MEP),[5] which made it feasible as an alternative to GPS or as a backup. However, by 1994, the government's long-term commitment to maintaining Loran-C was in question, which drove telecom operators to increasingly invest in GPS-dependent infrastructure. In 2007, the Loran-C signal was officially turned off; by that time, only a small number of telecom providers advocated for maintaining it because they used it as a backup to GPS.

The value of GPS for telecom increased even more with the advent of wireless networks. Wireless base stations require synchronization (both time and frequency, depending on the wireless technology) to interface with the core wireline network and to communicate between wireless base stations to execute handoffs as a user moves from one base station's range to another.

One of the challenges of implementing wireless communication is that the network must account for many more variables to maintain reliable service, from atmospheric and topographic conditions that may affect a signal to maintaining service with a moving target. Because of these additional complexities, wireless base stations are designed to maintain service under less stringent synchronization requirements than the wireline network. However, this need to maintain service under less stringent requirements does not reduce the reliance on GPS in wireless infrastructure. Because wireless base stations form the "edge" of the telecom network, base stations often do not have access to precise time or frequency from the core network. Instead, they must access GPS directly using on-site receiver equipment. Because there are so many wireless base stations,[6] telecom infrastructure providers are incentivized to provide precise timing as cheaply as possible, meaning that most base stations have relatively low-quality holdover devices, making them more vulnerable to a GPS outage.

4.1.3   *Existing Literature on the Economic Impact of GPS in Telecom*

Although many studies have been conducted to assess the vulnerabilities of GPS and need for a backup source of precision, navigation, and timing, few studies have attempted to quantify the economic benefits of GPS. With respect to the telecom sector, only Leveson (2015) has attempted to quantify the economic value of GPS to the telecom sector.

Leveson (2015) estimates the benefits of GPS to telecom by estimating the cost of developing an alternative to GPS if the system had never been available. Leveson considers two alternative timing and frequency sources—eLoran and a network of four geostationary satellites. He concludes that the average annual avoided cost of maintaining either eLoran or a network of geostationary satellites is $43.8 million in 2013 ($46.1 million in 2017 dollars). For the purposes of this study, we do not consider other space-

---

[5] The Mid-Continent Expansion Project (MEP) was jointly funded by the U.S. Coast Guard and the Federal Aviation Administration. It was initiated as part of the efforts to upgrade and expand Loran-C for use in aviation, which required that Loran-C was universally available across the continental United States. The project was completed in 1990 with the addition of two new Loran-C chains, which are comprised of multiple Loran-C towers.

[6] According to the Cellular Telecommunications Industry Association (CTIA), cited in FCC (2017), there were 308,334 wireless base stations (or cell sites) at the end of 2016. Wireless base stations come in different sizes and different levels of coverage, but all require access to a precision timing signal. Some receive a distributed signal from a larger base station, but GPS is always the original source.

based PNT solutions, but we do discuss the viability of Loran-C and eLoran to provide the required synchronization needs of the telecom industry.

4.2   Methodological Notes

4.2.1   *Counterfactual A: If GPS Were Not Available for Civilian Use*

As described above, the advent of digital networks and a fragmented competitive landscape necessitated a more distributed approach to maintaining synchronization across the telecom infrastructure. In the absence of GPS, two other options would have been available to telecom providers to source their precision timing signal: cesium clocks or Loran-C.

Cesium clocks were considered cost prohibitive, and Loran-C was also discarded as a primary source of precision timing in favor of GPS, though not because it was unsuitable. Indeed, while GPS was more accessible and performed better, Loran-C was used as a backup by some telecom companies, particularly once it became nationally available in 1990. Research suggests that Loran-C would likely have served as a suitable alternative to GPS (Narins, 2004), though the requirements of present-day wireless technology have now surpassed Loran-C's capabilities.

Additionally, throughout the 1990s, the federal government invested in developing and testing eLoran, or Enhanced Loran. With respect to frequency, Loran-C is comparable in performance to eLoran and GPS, but it lacks a time signal, which became increasingly important for digital and wireless networks. Implementing eLoran would have added new features to the Loran signal, one of which was a precise time message. Table 4-2 provides a comparison of the performance of Loran-C, eLoran, and GPS.

The level of investment and interest in advancing Loran technology suggests that it had broad support in the government. Over time, however, interest in supporting Loran-C and developing eLoran waned. In 1994, the U.S. Coast Guard ceased operating the international Loran-C chains, and the 1994 Federal Radionavigation Plan stated that support for the remaining domestic Loran-C chains would end by 2000. The Loran-C signal was officially shut off for good in 2007. Both the literature and experts we spoke with suggested that GPS was a significant factor in the waning interest in maintaining Loran-C (Justice et al., 1993), suggesting that, in the absence of GPS, Loran-C may have remained operational.

Table 4-2.   Performance Capabilities of Loran-C, eLoran, and GPS[a]

	Loran-C	eLoran	GPS
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	N/A	10–50 ns	10 ns

Sources: Narins et al. (2012); Curry (2014); Celano et al. (2003); GPS.gov (n.d.)

[a] The positioning accuracy of each of these technologies varies widely by type of receiver and augmentations being applied. The accuracy quoted here for GPS is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

Considering this historical context, we make the following assumptions about what would have happened if GPS had not been developed:

1. **The telecom industry would have chosen to use Loran-C as its primary source of precision time.** Loran-C was capable of meeting the telecom sector's precision timing needs and, in fact, was used for precision timing by the telecom sector (albeit on a small scale at the end) up until it was turned off in 2007.

2. **In the absence of GPS, Loran-C would have received support to maintain its performance and national coverage.** In the 1990s, the federal government was already making significant investments in improvements to the existing Loran-C service to make it useful for the aviation industry. The absence of GPS would only increase the importance of maintaining and upgrading Loran-C; thus, we consider it reasonable to assume this would have happened.

3. **The federal government would have continued to finance the operation of the Loran signal.** We also consider it reasonable to expect that the federal government would have continued to finance the operation of the Loran signal because it was broadly useful to a wide variety of sectors when it was operational (e.g., maritime, air travel), and a number of critical infrastructure sectors that evolved to use GPS (e.g., electricity, finance) would have potentially used it to meet their precision timing needs as well.

4. **The cost of Loran receiver equipment, at least for telecom sector use, would have benefited from similar economies of scale as GPS did.** Although there are some key differences in the nature of the GPS and Loran signals, the technology required to harness the signal is relatively similar. If Loran adoption increased in the absence of GPS, we expect that the cost of Loran receiver equipment would drop because of economies of scale, thus making it roughly similar in cost to GPS.

5. **With the availability of Loran-C, the wireline infrastructure would have been relatively unaffected in the absence of GPS.** We assumed that the wireline network would be relatively unaffected given that PRSs (see Section 4.1.2) are the primary source of synchronization and could be disciplined through Loran-C.

6. **The absence of GPS would have prevented the development of 4G LTE wireless technology given its more stringent synchronization requirements and its heavier reliance on precision time rather than frequency.** We assumed that the progression of wireless technology would have been unaffected up until the rollout of 4G LTE networks for two reasons. First, the synchronization requirements prior to 4G LTE were much less stringent. Second, the dominant wireless standard around the world was the GSM family of technologies.[7] GSM was predominantly reliant on frequency for synchronization, which could be distributed from the core wireline network or through Loran-C. Even though there was a competing wireless standard (Code Division Multiple Access, or CDMA) that was more reliant on GPS in the United States, in the absence of GPS, it is reasonable to assume that GSM would have been the standard of choice in the United States.

The rollout of 4G LTE technology, which began in late 2009, represented a significant increase in reliance on GPS and time synchronization as wireless network operators sought to meet the demand for faster data speeds and more data usage that was driven by the diverse capabilities of smartphones. Additionally, there were no competing standards akin to GSM that offered a less GPS-dependent alternative. Because of the significant increase in the criticality of GPS for 4G

---

[7] The Global System for Mobile Communications (GSM) "family" of technologies includes GSM, GPRS, EDGE, UMTS, and HSPA, which are all wireless telecommunications standards (4G Americas, n.d.) used by wireless network operators that invested in GSM technology. Each successive standard introduced increased performance for network operators and users. At its peak, GSM held 90% of global wireless subscribers (4G Americas, n.d.).

LTE and the lack of a clear alternative, we assumed that, in the absence of GPS, 4G LTE would have not been implemented.

For the purposes of this analysis, we assumed that eLoran would not have been implemented. While there are many commercial applications for an eLoran signal, investment in PNT infrastructure has historically been driven by a demand from government (usually defense). In the absence of strong evidence or an explicit government need for eLoran, we assumed that Loran-C would have continued to operate, albeit with only minimal performance improvements.

4.2.2   Approach for Quantifying Retrospective Economic Benefits

To estimate the economic impact of 4G LTE not being available in the absence of GPS, we relied on two approaches:

1. using radio spectrum auction data to estimate telecom service providers' minimum willingness-to-pay (WTP) for spectrum to provide 4G LTE and

2. using estimated consumer WTP for broadband speeds enabled by 4G LTE technology

Radio spectrum auction. Radio spectrum is a finite resource in high demand for many purposes, including broadcast television and radio, satellite television, PNT signals like GPS, Wi-Fi, keyless entry for cars, and mobile broadband services (GSMA, 2012b). With respect to wireless telecom service, spectrum access is a prerequisite to providing service. Additionally, the type and amount of spectrum that a provider has access to directly affects their infrastructure costs. Therefore, telecom service providers are highly motivated to invest heavily in securing adequate spectrum to stay competitive.

We used data from spectrum auctions in the United States as a proxy for telecom service providers' WTP for the ability to provide 4G LTE service. We considered this reasonable because similar assumptions have been made in the literature (Mölleryd & Markendahl, 2011). While additional investments in base stations are required once spectrum is secured, we focused on spectrum purchases as a reasonable lower bound for the economic value of 4G LTE service to telecom service providers.

WTP. The second approach used estimated consumer WTP for increased bandwidth enabled by 4G LTE to value the economic impact enabled by GPS. As a foundation, we used WTP estimates from Liu et al. (2018), which estimates household WTP for fixed broadband (i.e., a consumer's home internet connection). WTP for fixed broadband may potentially be different from WTP for mobile broadband, but no recent studies estimate WTP for mobile broadband in the United States.

Figure 4-2 presents WTP estimates from Liu et al. (2018). The left axis indicates WTP per month at a given level of bandwidth in Mbps. The right axis indicates the WTP for an additional Mbps[8] at different levels of bandwidth (i.e., marginal WTP). For example, if a user's internet bandwidth is 20 Mbps, their

---

[8] One Mbps, or megabit per second, is a common unit for representing data transfer rates. One megabit is equal to 1000 kilobits or 1,000,000 bits and 8 bits is equal to one byte, the common base unit for conveying file sizes (1000 bytes is equal to 1 kilobyte)

Figure 4-2.   Willingness to Pay for Fixed Broadband

Source: Liu et al. (2018).

willingness to pay for service is $38.33 per month and they would pay an additional $1.57 for each additional Mbps of bandwidth up to 25 Mbps, at which point their willingness to pay for additional bandwidth drops to $0.57 per additional Mbps. The declining nature of the marginal WTP line indicates that as bandwidth increases, additional (marginal) increases become less valuable to the consumer.

In addition to WTP, we collected data on wireless subscribers and average bandwidth by year in the United States. Figure 4-3 presents this data. The left axis, which is associated with the bars in the figure, quantifies average bandwidth over time as reported by Ookla, a company that provides internet speed testing services and collects data from individual users of the service. To estimate a weighted average bandwidth by year, we weighted download bandwidth data from the top four carriers (AT&T, Verizon, Sprint, and T-Mobile) using market share data from the FCC. The top four carriers account for approximately 90% of all wireless subscribers in the country. Smaller carriers are not included in the calculation because data availability was limited. Data on average bandwidth from Ookla and market share are reported by the FCC Mobile Wireless Competition reports (FCC, 2019). The right axis of Figure 4-3 quantifies wireless subscribership over time as reported by the FCC (2017).

Figure 4-3.   Average Bandwidth and Wireless Subscriptions in the United States, 2010–2017

Table 4-3 presents data from both Figures 4-2 and 4-3. Using estimated WTP from Liu et al. (2018), we calculated the annual value of increases in average bandwidth from 2010 to 2017 per wireless subscriber. We then scaled the value by the number of wireless subscribers in the United States. Note that Liu et al. (2018) does not place a WTP value on bandwidth levels lower than 4 Mbps; we use their estimated WTP value for 4-10 Mbps. This assumption is likely conservative given that bandwidth increases at such a low level of bandwidth would likely be valued higher by users than bandwidth increases at higher level of bandwidth. This is supported by the Liu et al. (2018)'s research, which shows a declining marginal WTP at higher starting levels of bandwidth.

Table 4-3.   Average Bandwidth, WTP, and Mobile Subscribership in the United States

Year	Average Bandwidth (Mbps)	Change Over 2009 Levels (Mbps)	WTP ($/Mbps) for additional bandwidth	Wireless Subscribers (mil)
2009	0.9	—	$2.34	285.6
2010	1.0	0.1	$2.34	296.3
2011	1.38	0.5	$2.34	316.0
2012	4.43	3.5	$2.34	326.5
2013	7.48	6.6	$2.34	335.7
2014	9.62	8.7	$2.34	355.4
2015	14.08	13.2	$1.57	377.9
2016	18.72	17.8	$1.57	395.9
2017	22.69	21.8	$1.57	400.2

4.2.3   Counterfactual B: Potential Impacts of a 30-Day GPS Outage

In the event of a 30-day outage of GPS, the precision timing devices on telecom networks would enter holdover mode. The performance of holdover will depend entirely on the sophistication of the holdover device at each point. The most basic holdover devices may maintain a stable timing signal for a few hours, while the most expensive atomic clocks (e.g., rubidium or cesium) may maintain stability from several weeks to over a month.

In general, we assumed that the wireline network would be relatively unaffected by a 30-day outage because of the sophistication of the holdover devices on wireline networks. With respect to wireless networks, we assumed that service quality will be maintained for 24 to 48 hours before it begins to steadily degrade.

4.2.4   Approach for Quantifying Potentials Impacts of a 30-Day Outage

To estimate the economic impact of a 30-day outage of GPS in the context of the telecom sector, we relied on the available literature and the opinion of subject matter experts to help us understand how the impacts of an outage might unfold within the infrastructure of the telecom industry and how the impacts affect the quality of service for users.

We estimated impacts as a percentage of the affected revenue of telecom providers from wireless users, which we used as a proxy for user WTP for wireless service. As discussed in Section 4.5.1, our research and interviews with experts led us to conclude that the wireline network would be relatively unaffected during a 30-day outage of GPS.

Data on average revenue per user (ARPU), a common metric in the telecom industry, are available from the FCC's annual Wireless Competition Report (FCC, 2017). Although average cost per month to subscribers would be a more appropriate proxy because it includes taxes and fees, these data were not available.

In 2016, the latest year of data available, ARPU was $41.50 per user per month or $1.36 per user per day. In 2017, there were approximately 400.2 million mobile connections. Using these two data points, we estimated wireless service revenue to be $546.3 million every day (FCC, 2017).

Using the estimated revenue per day as a proxy for consumer WTP for wireless service, we estimated the economic loss associated with a 30-day outage by scaling down the daily revenue based on the condition of the wireless infrastructure in a given day during the 30-day outage. As the network degrades, the loss of value increases in proportion.

For the purposes of the 30-day outage, we considered all impacts in the context of 4G LTE networks.[9] Over 99% of the U.S. population is covered by at least one carrier that supports LTE (FCC, 2017). While

---

[9] Within LTE technology, two types of LTE exist—Frequency Division Duplex (FDD) and Time Division Duplex (TDD). True to the name, LTE-FDD networks leverage a frequency signal and require less stringent precision time. LTE-TDD, however, relies more heavily on precision time rather than frequency to enable higher speeds and other network features and is therefore more vulnerable to a GPS outage. However, while data on the exact distribution between LTE-FDD and LTE-TDD base stations are not available, the general consensus of our subject matter experts is that the telecom infrastructure in the United States is

legacy standards are still supported on wireless networks, they are used primarily as backup networks if a device cannot establish a 4G LTE signal. Furthermore, data on the amount of usage that travels over legacy standards (e.g., GSM or CDMA) compared with LTE are not available.

4.2.5 Interviews with Sector-Specific GPS Experts

Table 4-4 details the distribution of experts contacted and interviewed for this study. RTI leveraged several resources to develop a list of subject matter experts to contact for this study:

- literature review
- speaker lists for industry events, including major conferences such as the Workshop on Synchronization and Timing Systems and the International Timing and Sync Forum
- referrals from NIST
- referrals from individuals who participated in interviews

In total, RTI contacted 39 subject matter experts and conducted interviews with 21. The largest stakeholder group represented was the private sector, which was predominantly made up of experts from companies that develop and market precision timing and GPS receiver equipment for telecom and other sectors. Likely a result of the proprietary nature of their work, any requests for interviews with current employees of telecom network operators were declined or ignored. While we do not believe this makes it impossible for us to reach reasonable conclusions about the impact of GPS on the telecom sector, lack of access to the telecom sector does increase the uncertainty of our results.

Table 4-4. 4G LTE-Related Spectrum Auction Revenues

Auction[a]	Year	Frequencies Offered[b]	Total FCC Revenue from Auction ($billion nominal)	Total FCC Revenue from Auction (2017$ billion)
FCC Auction 66 (AWS-1)	2006	1700 MHz 2100 MHz	$13.70	$16.66
FCC Auction 73	2008	700 MHz	$18.96	$21.59
FCC Auction 97 (AWS-3)	2015	1700 MHz 2100 MHz	$41.33	$42.74
Total			**$73.99**	**$80.99**

[a] Auction revenues are reported in nominal dollars here to preserve traceability to the source data. Values reflect net bids for each auction.
[b] Auction data from FCC (2006), FCC (2008), and FCC (2015), respectively.

---

mostly operating LTE-FDD wireless base stations. Thus, we did not attempt to distinguish between the impact of an outage on LTE-FDD versus LTE-TDD base stations.

4.3   Retrospective Economic Benefits Analysis

In speaking to experts about how telecom infrastructure might have evolved in the absence of GPS, we were able to construct the important historical context already discussed in previous sections. As mentioned previously, most experts believe that the telecom sector would have continued to advance at a similar pace by adopting another source of precision timing. To paraphrase one expert, the telecom industry did not *need* GPS, but it was there, and it was cheap, so they used it. At the same time, a key caveat to note alongside these examples of alternatives is that not all of them were mature technologies when the telecom industry began adopting GPS. The Synchronous Ethernet (SyncE) standard, as one example, was not introduced until 2007.

In addition, all experts agreed that any alternative source of precision timing would have been more expensive and difficult to implement than GPS, with the exception of Loran-C, which had similar adoption costs to GPS and was already being used widely in the telecom sector. The added expense of other alternatives, according to three experts from private-sector telecom companies, made it more likely that the industry would have relied more heavily on Loran-C to provide precision timing services to infrastructure given that it was readily available and was similar to GPS in implementation.

As detailed in Section 4.2.1, we employed two approaches for valuing the retrospective economic impact of GPS in telecom under the assumption that 4G LTE technology would not have been feasible in the absence of GPS if Loran-C was the predominant alternative source of synchronization.

First, to build up our estimates of carriers' WTP for spectrum, we identified spectrum auctions in which carriers bought spectrum to be used for 4G LTE implementation. FCC Auction 73 in 2008, which auctioned off spectrum in the 700 MHz band, is the most important because this is the primary band on which AT&T and Verizon have built their 4G LTE network. In addition, 4G LTE networks operate on the 600 MHz, 1,700 Mhz, and 1,900 Mhz bands. Table 4-5 summarizes details of all the auctions included in our estimate. In total, we estimated a minimum carrier WTP for 4G LTE-related spectrum of $81 billion. This is likely conservative because it does not capture all of the spectrum used for 4G LTE.

Second, we estimated consumer WTP for increased bandwidth. As described previously, we assumed that in the absence of GPS, 4G LTE would not have been implemented. Based on the methodology described in Section 4.2.1, we estimated that from 2010 through 2017, GPS generated $686 billion in economic value that would not have occurred in the absence of GPS. This value represents the upper bound of our conservative estimates of the retrospective economic impact of GPS in telecom.

In summary, we estimate the economic impact of GPS in telecom to ranges from $81 billion to $686 billion between 2010 and 2017.

Table 4-5. Estimated Consumer WTP for Bandwidth Enabled by 4G LTE

Year	Average Bandwidth (Mbps)	Change over 2009 Levels (Mbps)	WTP for additional bandwidth ($/Mbps/ month)[a]	Annual WTP per Subscriber ($)	Wireless Subscribers (Million)	Annual National WTP ($ million)
2009	0.9	—	$2.34	—	285.6	—
2010	1.0	0.1	$2.34	2.8	296.3	$832
2011	1.38	0.5	$2.34	13.5	316	$4,259
2012	4.43	3.5	$2.34	99.1	326.5	$32,363
2013	7.48	6.6	$2.34	184.8	335.7	$62,026
2014	9.62	8.7	$2.34	244.9	355.4	$87,022
2015	14.08	13.2	$1.57	340.6	377.9	$128,721
2016	18.72	17.8	$1.57	428.1	395.9	$169,496
2017	22.69	21.8	$1.57	502.9	400.2	$201,270
Total						**$685,990**

[a] Liu et al. (2018) estimates that WTP decreases from $2.34 to $1.57 above 10 Mbps. To account for this, we valued all increases in bandwidth below 10 Mbps at $2.34 per Mbps and any increases above 10 Mbps at $1.57 per Mbps.

4.4   Potential Impacts of a 30-Day Outage

To construct a timeline of how a 30-day outage would affect telecom networks, we asked subject matter experts to qualitatively describe what they think would happen. In addition to asking for qualitative descriptions, we asked experts to review Tables 4-6, 4-7, and 4-8, which were reproduced from Curry (2010), and agree or disagree with its characterization of the holdover capability of different configurations. Table 4-6 describes the holdover capability for wireline networks. Tables 4-7 and 4-8 describe the holdover capabilities on LTE-FDD and LTE-TDD networks.

Table 4-6.   Telecom Wireline Network Traffic Timing—Holdover Capability

Telecom Network Traffic Timing	3 Mins	3 Hrs	3 Days	3 Wks	3 Mos	3 Yrs	>3 Yrs
TCXO	X	X	X	X	X	X	X
Low spec OCXO	●	○	X	X	X	X	X
High spec OCXO	●	●	○	X	X	X	X
Low spec Rb	●	●	●	○	X	X	X
High spec Rb	●	●	●	●	○	X	X
1:1 system OCXO and Rb	●	●	●	●	○	X	X
1:1 system + backup timing	●	●	●	●	●	○	○
1:1 system + 24 x 365 support	●	●	●	●	●	●	●
1:1 system + backup + support	●	●	●	●	●	●	●

Source: Curry (2010).

X Failure of GPS would cause failure within the indicated time period.

○ Failure of GPS may cause degradation of service within the indicated time period.

● Failure of GPS would not affect service within the indicated time period.

Table 4-7.   Wireless Base Station Timing—Holdover Capability (FDD Systems)

Mobile Base Station Timing	3 Min	3 Hrs	3 Days	3 Wks	3 Mos	3 Yrs	>3 Yrs
TCXO	X	X	X	X	X	X	X
Low spec OCXO	●	○	X	X	X	X	X
High spec OCXO	●	●	○	X	X	X	X
Low spec Rb	●	●	●	○	X	X	X
High spec Rb	●	●	●	●	○	X	X

Source: Curry (2010).

X Failure of GPS would cause failure within the indicated time period.

○ Failure of GPS may cause degradation of service within the indicated time period.

● Failure of GPS would not affect service within the indicated time period.

Table 4-8.   Wireless Base Station Timing—Holdover Capability (TDD Systems)

Mobile Base Station Timing	3 Min	3 Hrs	3 Days	3 Wks	3 Mos	3 Yrs	>3 Yrs
TCXO	X	X	X	X	X	X	X
Low spec OCXO	○	X	X	X	X	X	X
High spec OCXO	●	○	X	X	X	X	X
Low spec Rb	●	○	X	X	X	X	X
High spec Rb	●	○	X	X	X	X	X
Lo spec OCXO with PTP backup	●	○	○	○	○	○	○
Hi spec OCXO with PTP backup	●	●	●	●	●	●	●

Source: Curry (2010).

X Failure of GPS would cause failure within the indicated time period.

○ Failure of GPS may cause degradation of service within the indicated time period.

● Failure of GPS would not affect service within the indicated time period.

The most important qualifier in this analysis is that there is a large degree of uncertainty around the impact of a 30-day outage for two reasons. First, such a catastrophic failure has never happened before, making the outcome unpredictable. Second, the resilience of different parts of the network will vary because the GPS receiver and holdover equipment installed varies depending on several factors, including

- the network operator's risk tolerance,
- the criticality of maintaining service in some areas (e.g., New York City vs. a remote desert region), and
- the vintage of the receiver and holdover equipment.

Despite the uncertainties, some key areas of agreement emerged among the subject matter experts. First, 62% of experts who responded to questions about a 30-day outage agreed that the wireline network would remain largely unaffected by a GPS outage. GPS is used in the wireline infrastructure primarily to discipline cesium and rubidium clocks. Although rubidium clocks cannot supply holdover for a full 30 days, all cesium clocks can provide well over 30 days of holdover. Additionally, according to industry

estimates, 95% of GPS receiver equipment installed on telecom networks supports wireless infrastructure rather than wired infrastructure (ATIS, 2017). Because we expect that the wireline network will be mostly unaffected, we excluded it from our analysis of the economic impact of a 30-day outage.

The second key area of agreement is that most wireless infrastructure is equipped with oscillators with sufficient holdover to run for 24 hours unaffected by a GPS outage. This is necessarily a generalized conclusion—the exact timing control algorithms and equipment employed are typically proprietary and closely guarded by telecom network operators (ATIS, 2017). The exception to this general conclusion is if a wireless base station is operating LTE-TDD, which is more heavily reliant on GPS and may begin to degrade more quickly. As mentioned previously, reliable data on LTE-TDD penetration is unavailable, but subject matter experts felt that LTE-TDD makes up a relatively small portion of the infrastructure.

A third area of agreement is in how the impacts early on in the outage would manifest. After the first 48 hours, all of our subject matter experts agreed that wireless base stations would see a degradation in quality of service characterized by

- failure of handovers from one base station to another,

- increased call drops and lost frames in video, and

- a general slowdown in data speeds as base stations cope with a degrading timing signal and mobile handsets can no longer draw data from two base stations to increase bandwidth speeds.

All experts agreed that, eventually, all handovers would fail and a user would have to remain stationary to have any hope of maintaining a connection (albeit still degraded). Handovers rely on two base stations being able to agree on the precise time to complete a successful handoff. Finally, after some time of steady degradation of quality of service, wireless service would cease to function altogether.

Perhaps the most significant area of uncertainty and disagreement after the first 24 hours of an outage is the pace at which the wireless service would degrade over the remainder of the 30-day outage and whether the wireless service would fail altogether before or after the 30-day mark. One expert thought that wireless networks would fail completely after about 2 weeks, while several others thought that some service (most likely voice and text service only) would still remain at the end of 30 days.

To translate qualitative descriptions of what might happen to wireless networks in the event of a 30-day outage into something useful for making quantitative estimates of economic impact, we took the following steps:

1. Seven of the individuals we interviewed were willing to offer opinions on what might happen in the event of a 30-day outage. For each of these, we mapped their qualitative inputs to individual curves representative of the condition or functionality of the wireless network as a percentage of normal service levels over the 30-day period.

2. We averaged the resulting curves together to derive an average estimate of the impact of a 30-day GPS outage on wireless networks.

3. We calculated one standard deviation above and below the average to represent the range of uncertainty across the subject matter experts that offered opinions.

Figure 4-4 illustrates how we expect the impact to progress over the course of the outage period on average. The shaded area on either side of the bold line represents the range of uncertainty in our analysis. On average, we expect very few impacts on wireless infrastructure for the first 48 hours, after which service quality will degrade quickly as handovers become less reliable and data speeds continue to drop. After approximately 4 days, we expect service to continue to degrade, albeit at a slower pace.

It is important to reiterate that these findings are highly uncertain estimates of what might happen in the event of a catastrophic outage that has never happened before. We made every attempt to represent the range of uncertainty when possible, and results should be treated cautiously.

We used average revenue per wireless user as a proxy for WTP for wireless, estimating that wireless telecom providers earn $552.3 million in revenue every day. Using this data point, we estimated the economic loss associated with a 30-day outage of GPS by reducing the expected daily revenue based on the estimated functionality of the network, which we describe in Section 12.5.1.

Table 4-9 presents the estimated damages per day over the outage period. Figure 4-5 graphically represents the same data in cumulative form. Measured by ARPU as a proxy for WTP, a GPS outage would result in damages of $5.5 to $14.2 billion in damages.

Figure 4-4.   Impact of 30-Day GPS Outage on Wireless Network Functionality (based on expert qualitative opinion)

Source: RTI estimates

Table 4-9.   Estimated Economic Damages in Telecom due to 30-Day Outage

Day	Damages per Day (million)		
	Low	**Average**	**High**
1	$0.0	$37.3	$108.0
2	$0.0	$61.3	$143.4
3	$36.1	$151.5	$266.9
4	$41.3	$221.9	$402.6
5	$62.3	$234.2	$406.2
6	$82.3	$246.5	$410.7
7	$101.2	$258.8	$416.4
8	$118.9	$271.1	$423.3
9	$135.2	$283.4	$431.7
10	$149.9	$295.7	$441.5
11	$163.1	$308.0	$453.0
12	$174.6	$320.3	$466.0
13	$184.6	$332.6	$480.7
14	$193.0	$344.9	$496.9
15	$200.0	$357.2	$514.4
16	$211.3	$364.3	$517.3
17	$221.7	$371.3	$520.9
18	$231.3	$378.4	$525.5
19	$239.9	$385.4	$531.0
20	$247.5	$392.5	$537.4
21	$254.2	$399.5	$544.8
22	$260.0	$406.6	$553.1
23	$264.8	$413.6	$562.4
24	$268.7	$420.7	$572.6
25	$272.4	$422.3	$572.2
26	$276.1	$424.0	$571.9
27	$279.7	$425.7	$571.7
28	$283.2	$427.3	$571.5
29	$286.6	$429.0	$571.4
30	$290.0	$430.7	$571.3
Total	**$5,529.90**	**$9,816.21**	**$14,156.66**

Source: RTI analysis

Figure 4-5.   Estimated Economic Damages in Telecom due to 30-Day Outage

Source: RTI analysis

As discussed earlier, telecommunications is considered a general purpose technology with broad applicability across the economy that unlocks significant productivity gains. Thus, it is reasonable to expect that the loss of such services would result in a significant negative economic impact.

4.5   Future Applications

The telecom industry is currently in the middle of early-stage implementation of the next generation 5G wireless network standard. The first spectrum auctions were scheduled for the end of 2018, and the first commercially available 5G-capable mobile devices are expected in 2019.

5G technology marks a significant advancement in the performance and underlying structure of the wireless telecommunications networks in the United States. 5G will leverage higher density placement of smaller cells operating at high frequencies to maximize the bandwidth availability. To coordinate an increasing number of base stations and make efficient use of spectrum, 5G networks will require even more stringent precision timing and will continue to reduce wireless networks' use of frequency and increase its reliance on precision time.

4.6   Concluding Remarks

GPS came along at a time of significant evolution in the telecom sector and played a critical role in the digitization of telecom infrastructure and the advent of wireless technology. We estimate the economic impact of GPS in the telecom sector to be $81 billion to $686 billion. In the event of a 30-day outage, our research suggests that while the wireline networks would remain largely unaffected, wireless networks

would quickly begin to degrade in quality of service and would result in anywhere from $5.5 to $14.2 billion in damage over the course of 30 days.

Looking forward, wireless technology continues to evolve in ways that increase its reliance on highly precise timing, which in turn increases reliance on GPS. Multiple technological trends—from autonomous cars to the internet of things—will be stretching wireless technology to new limits in the coming years; recognizing the role that precision timing plays in enabling the next decade of technological development in telecom highlights just how important the reliability and security of GPS is.

5. Precision Agriculture

The agricultural sector uses the precision location information provided by GPS to improve agricultural mechanization and efficiency. In agriculture, efficiency refers to the ability to produce more food, feed, and fiber per unit of labor and other inputs (e.g., seeds, chemicals).

Precision agriculture, abbreviated as PA in this case study, is a concept that refers to the ability for farmers to conduct site-specific management—to observe, measure, and respond more precisely to inter- and intrafield variability in crops. Before GPS was available for commercial use, farmers had few technologies that allowed them to proactively manage their fields according to the fields' spatial characteristics. GPS played an essential role in the advent and continued adoption of PA technologies and methods. The retrospective impact of GPS, net of adoption costs, is conservatively about $5.8 billion.

If GPS were not available for civilian use, farmers would have continued managing their operations as before, planting and harvesting as they have done historically without the benefit of automated steering or the ability to make decisions based on site-specific information. This counterfactual is not entirely speculative; many farmers today do not use GPS and still farm this way. An alternative system with less accuracy, such as eLoran, could have helped farmers take advantage of some PA technologies such as aerial spraying, coarse yield and soil mapping, or certain kinds of variable-rate technologies (e.g., applying fertilizer to more precisely meet site-specific crop needs), but without GPS these would have been less effective and provided fewer benefits. These technologies would also likely have taken longer to develop.

The proportion of farmers using PA technologies has increased steadily over the last three decades, and these technologies are now used on the majority of U.S. farmland. In the event of a 30-day failure of GPS today, there would be a significant planting delay and adverse impact on yields for many farmers, especially the large, mechanized farmers that have fully embraced PA. Many tractors, combines, and other equipment have GPS technologies integrated into their systems. These farmers would face a steep learning curve and significant efficiency losses trying to either retrofit or operate this equipment without GPS, or they would return to earlier ways of applying inputs.

The impacts would be highly dependent on the time of year, with the largest impacts expected during planting seasons. We estimate that in a worst case scenario the economic loss would be more than $15 billion if it occurred during the planting season.

5.1 Sector Introduction and Overview

GPA-assisted PA technologies allow farmers to manage inputs such as seeds, agrochemicals, and fuel more efficiently, increase yields, and reduce farmworker fatigue and errors. The three most common categories of these technologies are yield and soil mapping, machinery guidance and control systems, and variable-rate technologies (see Table 5-1).

Table 5-1. Three Most Common Categories of GPS-Enabled Precision Agriculture Technologies

Application	Precision Needed	Co-technologies	Benefits: Qualitative Description	Counterfactual	Technical Impact Metric	Economic Value Metric	Potential Magnitude of Impacts
Yield and soil mapping	10 m	GPS + combine yield monitor GPS + soil sampling data GPS + mapping software	Helps farmers more intensively manage their fields; allows farmers to make more informed planting and input application decisions, including how much and where to apply agrochemicals, plant seeds, and irrigate	Collecting yield data using sensors and without mapping or mapping using alternatives to GPS.	Changes in crop yield, input costs (e.g., seeds, fertilizer), and overhead costs (e.g., labor, capital). Environmental benefits include reductions in greenhouse gas (GHG) emissions and nutrient loads in waterways.	Additional net returns on adoption vs. nonadoption on area where the technology was applied. Value of ecosystem services from applying less agrochemicals.	Medium
Tractor and combine guidance system	5 cm–1 m depending on use	GPS + navigation tool (e.g., parallel swathing)	Allows farmers to more precisely apply inputs and harvest crops while reducing overlap and/or skips within a field. Also reduces machine operator error, operator time, operator fatigue, and multitasking	Manual steering of tractors and combines. Apply inputs manually based on markers such as a mechanical marker on a planter or harvester or foam marker on a sprayer.	Changes in crop yield, input costs (e.g., seeds, fertilizer), and overhead costs (e.g., labor, capital). Environmental benefits include reductions in GHG emissions and nutrient loads in waterways.	Value of additional net returns on adoption vs. nonadoption area. Value of ecosystem services from applying less agrochemicals.	Medium
Variable-rate technology	10 cm–1 m depending on use	GPS + variable-rate planter drive GPS + variable-rate spreader drive GPS + variable-rate applicator	Allows farmers to apply inputs (e.g., seeds, agrochemicals) at predetermined rates at different locations in a farmer's field	Adjust inputs manually or apply at one rate throughout the field.	Changes in crop yield, input costs (e.g., seeds, fertilizer), and overhead costs (e.g., labor, capital). Environmental benefits include reductions in GHG emissions and nutrient loads in waterways.	Additional net returns on adoption vs. nonadoption on area where the technology was applied. Value of ecosystem services from applying less agrochemicals.	Medium

- ***GPS-assisted yield and soil mapping*** quantifies and maps information pertaining to yield and/or soil variability throughout a field. Farmers can use this information along with other farm-specific information (e.g., soil, climate, pests) to diagnose issues within the field and respond proactively.

- ***GPS-assisted machinery guidance and control systems*** automatically steer farm equipment in a predetermined path to help farmers reduce overlaps or skips or have built-in input control valves to avoid applying inputs where they are not needed (e.g., headlands). Aerial spraying, or crop dusting, is another GPS-assisted technology that has transformed the way that agrochemicals are applied to agricultural fields.

- ***GPS-assisted variable-rate technologies*** enable farmers to vary the timing and rate at which they apply inputs such as seeds and agrochemicals to more precisely meet their crops' needs.

Many different technologies fall into one of these three broad categories. These categories are also not mutually exclusive; farmers also frequently employ these techniques in combination with each other.

PA in large-scale farming in the United States became possible when the NAVSTAR GPS system became available for civilian use in the early 1990s. The development of the first PA technologies preceded the civilian availability of GPS, but they were limited to small field boundaries marked with posts or flags. For a short time before GPS, radar positioning systems were used as location devices for agricultural applications (mostly for research), but the systems were cumbersome and needed radar posts to function (Tillett, 1991).

When GPS became available for civilian use, there were some limits to its precision. Fortunately, differential GPS (DGPS) was introduced in the late 1990s, which improved location accuracy, thereby paving the way for increased precision in agrochemical application and enabling automated steering in farm vehicles. Because some applications require higher precision than others (Table 5-1), DGPS became essential to the widespread adoption of PA.

The annual PA dealership surveys of crop input dealers, sponsored by *CropLife* and Purdue University, detail the current state and trends of the industry (Erickson et al., 2017). Retailers expect their market areas to expand for all PA uses (Table 5-2); they expect some categories of technologies to expand more than others including variable-rate technologies and some new and emerging GPS-enabled technologies such as unmanned aerial vehicles, satellite or imagery, and data storage and analysis (Table 5-2).

Table 5-2.   Producer Use of Precision Technologies, Current and Projected Market Area

		Estimated Market Area, %		
Precision Agriculture Technologies	**Category**	**2017**	**2020**	**Projected 3-Year Growth**
Guidance/autosteer	Tractor and combine guidance system	60	72	**20**
Field mapping	Yield and soil mapping	45	61	**36**
Grid or zone soil sampling	Yield and soil mapping	45	62	**38**
VRT lime application	Variable-rate technology	40	51	**28**

(continued)

Table 5-2.   Producer Use of Precision Technologies, Current and Projected Market Area (continued)

Precision Agriculture Technologies	Category	Estimated Market Area, %		
		2017	2020	Projected 3-Year Growth
VRT fertilizer application	Variable-rate technology	38	54	**42**
Planter adaptations to improve precision	N/A	22	37	**68**
Satellite or aerial imagery	Yield and soil mapping	19	33	**74**
Cloud storage of farm data	N/A	14	32	**129**
Variable down pressure on planter	Variable-rate technology	14	28	**100**
Variable-rate technology seeding	Variable-rate technology	13	30	**131**
Any data analysis service	N/A	13	30	**131**
Soil electrical conductivity mapping	Yield and soil mapping	9	17	**89**
Variable hybrid placement within fields	Variable-rate technology	7	19	**171**
UAV or drone imagery	Yield and soil mapping	6	22	**267**
Y drops on fertilizer applicator	N/A	6	16	**167**
Telematics	N/A	5	12	**140**
VRT pesticide application	Variable-rate technology	3	13	**333**
Chlorophyll/greenness sensors for Nitrogen management	Variable-rate technology	3	10	**233**

Source: Adapted from Erickson et al. (2017).

The U.S. Department of Agriculture's (USDA's) Agricultural Resource Management Survey (ARMS) has been surveying farmers about PA adoption for several major crops since 1996 and is the best source of data for tracking national-level PA technology adoption rates over time.

The most comprehensive study to quantify the net benefits of adopting PA across the United States was conducted by USDA's Economic Research Service (ERS) (Schimmelpfennig, 2016). This study used national-level data from ARMS to calculate the net benefits of the three categories of PA technologies, finding that net returns for corn and soybean farmers increased by 1 to 2% with the introduction of PA, depending on the technology (Table 5-3).

Table 5-3.   Percentage Change in Profits from Adopting Specific Technologies

Technology	GPS Soil/Yield Mapping	Guidance Systems	Variable-Rate Technologies
Net returns (including overhead) impact of precision technology	1.8%	1.5%	1.1%
Operating profit impact including farm size scale effect	2.8%	2.5%	1.1%

Source: Schimmelpfennig (2016).

Another ERS study from the same year used ARMS data to estimate savings in variable production costs from PA. This study estimated variable per-acre cost savings of variable-rate technologies from $13 to $21 depending on the scenario, but these effects did not take into account the capital investment costs or yield effects (Schimmelpfennig & Ebel, 2016). Other studies have quantified the benefits of PA in specific regions or with respect to crops in different time periods.[10]

Other studies of economic impacts are extrapolated from site-specific data. Recent estimates of GPS's impact on the commercial agricultural sector include Pham (2011) and Leveson (2015); the former estimated that GPS provided the agricultural sector benefits of $19.9 billion per year in 2010, and the latter estimated a range from $10 to $17.7 billion in 2013, both extrapolating from other original data collection efforts. Both studies are countrywide, but neither study accounted for investment costs, which are significant. Also, at the time that these studies were developed, no comprehensive analyses or models of adoption across the United States existed, so both studies had to use simplified assumptions derived from a range of studies from different sources based on various time ranges, crops, and geographic contexts.

5.2   Sector Applications

PA technologies are often used in conjunction with each other. Farmers use soil and yield mapping to gain insights on the relationship between soil and land characteristics and yields to make decisions about their input use for the following season. This technology is sometimes used in conjunction with variable-rate technology and/or equipment auto-guidance systems to vary input rates according to spatial characteristics and to automate their application.

The market penetration rates of the three categories of PA adoption based on ARMS data and Schimmelpfennig (2016). These rates are shown in the addendum to this section and can be summarized as follows:

- Guidance systems are used on 45 to 50% of acres for all crops surveyed except cotton and winter wheat, making it the GPS application with the widest adoption.[11]

- Yield mapping has been adopted on 30% or more of cropland acres for corn and soybeans as of 2012[12], although it is 20% or lower for peanuts, rice, spring wheat, and cotton. Soil mapping has been highly variable over time, with adoption mostly decreasing from 2000 to 2005, only to increase again from 2005 to 2013.[13]

- VRT adoption was above 20% for corn, soybeans, and rice in the most recent survey years but lower for peanuts, spring wheat, winter wheat, and cotton.

---

[10] A compilation and analysis of 108 research studies found that 63% of precision farming applications had positive net returns, 11% had negative returns, and 26% had mixed results (Lambert & Lowenberg-DeBoer, 2000).
[11] Based on data available from 2007-2013. It is likely that guidance systems were applied to more than 45% of acres for all crops after 2014 based on extrapolated ARMS data, Erickson et al. (2017) and stakeholder interviews.
[12] Based on extrapolated ARMS data.
[13] ARMS tracks adoption of yield and soil mapping separately, but Schimmelpfennig (2016) categorizes them together and calculates their net benefits conjunctively.

Figure 5-1 shows adoption on planted acres over time for corn and soybeans for the three high-level categories of GPS-assisted technologies: GPS-enabled soil and yield mapping, guidance or autosteer, and VRT, as reported by the USDA's ARMS survey. Farmers have increased adoption over time. Guidance systems were the most widely adopted GPS-enabled PA technology used, followed by yield and soil mapping and variable-rate technology.

5.3   Methodological Notes

To quantify the economic impacts of GPS for the agricultural sector, we first quantified the additional net benefits that GPS-assisted technologies provide to adopters vs. nonadopters and applied those benefits to the percentage acreage where PA has been applied over space and time. The approach is relatively straightforward because there are many PA adopters and nonadopters in the United States, and USDA has recently compared the net returns between the two groups.

Figure 5-1.   Adoption Rates of Precision Agriculture Technologies in Corn and Soybeans

Note: Data past vertical blue line (2010) are extrapolated for corn; data past vertical orange line (2012) are extrapolated for soybeans (a value of 30% was used for soybean yield mapping as depicted in Figure 3 of Schimmelpfennig [2016]). Linear extrapolation was used, although capped at the highest recent estimated use of PA technologies based on either ARMS or Erickson et al. (2017, Figure 9). Yield and soil mapping are shown separately in the figure but combined into one category for the economic analysis to be consistent with the way that Schimmelpfennig (2016) report PA impacts on profits.

5.3.1   Approach for Quantifying Retrospective Benefits

The counterfactual for this scenario is to assume that without GPS PA would have only progressed marginally with Loran, but it would have been much more limited in its scope of applications compared with GPS. We assumed that in the absence of GPS farmers would primarily continue to farm using currently available technologies in the way that nonadopters do today.

Note that we do not value benefits for PA technologies that do not rely on GPS or require the high levels of precision accuracy that GPS offers.[14] Also, because a counterfactual technology would have had time to evolve in the absence of GPS, we assumed no increase in price volatility or disruption in global agricultural markets. However, it is likely that reduced yields could have led to higher bulk commodity prices and an associated decrease in consumer welfare.

The USDA's ERS commissioned the first study that used an empirical model to estimate the net returns and operating profits of PA from a nationally representative sample of corn farms (Schimmelpfennig, 2016). They used a robust model that considers total net returns, including overhead costs, input costs, and yield changes of PA adopters vs. nonadopters. They found that the additional net returns to three PA technologies, namely GPS soil/yield mapping, guidance systems, and variable-rate technologies, were 1.8%, 1.5%, and 1.1%, respectively for 2010 corn (see Table 5-3 above).[15]

The use of GPS for agricultural applications has steadily increased over time as the technologies have improved and farmers have benefitted from adopting them. Because the USDA ERS net benefits are specific to 2010 corn, we surveyed agricultural experts on how these percentages have changed by crop and over time. We then scaled these net benefits (as well as net returns by crop) using the historical adoption rates of PA technology by crop. We used historical data on adoption rates from the ARMS database[16] and historical net returns from agricultural census data published by USDA's National Agricultural Statistical Service (NASS). These data were aggregated into a spreadsheet model that included a time series of PA adoption by crop and by year, as well as net returns by crop and by year. Table 5-4 summarizes the data sources used for the analysis.

---

[14] Some sensor-based technologies, such as the real-time sense and apply (e.g., GreenSeeker variable-rate technology), miscellaneous laser technologies, and improvements in aerial spraying either do not require accurate positioning or require much less accuracy than GPS offers. These exceptions would have a marginal effect on our results.
[15] These percentages include overhead, labor, and capital costs from investing in GPS technologies.
[16] Accessible at https://data.ers.usda.gov/reports.aspx?ID=17883.

Table 5-4.   Key Data Sources

Variable	Source	Source of Download	Years
Total area harvested by crop	NASS	https://quickstats.nass.usda.gov/. Used USDA/NASS (n.d.) QuickStats, selected: period: all years; geo level: national; state: U.S. total; commodity: select crop. date item: acres harvested; domain: total.	Annually, 1998 to present
PA adoption rates	ARMS	https://data.ers.usda.gov/reports.aspx?ID=17883. Used USDA/ERS (2019b). Selected: report: precision agriculture; filter by all survey states; row group: all farms; subject: commodity; from year: earliest year available; subgroup: all farms.	Variable years (see the addendum to this section)
Net benefits of using PA technologies, 2010	USDA/ERS, Commodity Costs and Returns	https://www.ers.usda.gov/data-products/commodity-costs-and-returns/. Accessed USDA/ERS (2019a) "Recent Costs and Returns" for corn, cotton, peanuts, soybeans, rice, and wheat on 6/25/2018.	Annually, 1998 to present
Net benefits of using PA technologies, scaled up to 2017	Schimmelpfennig (2016) and expert interviews	N/A	Used Schimmelpfennig's net revenues for 2010 and before. Scaled to expert feedback for 2017.

5.3.2   *Approach for Quantifying the Potential Impacts of a 30-Day Outage*

In the case of a 30-day catastrophic failure of GPS, farming operations could experience significant delays, depending on the timing of the outage, but it would not prevent farmers from planting. Given the high learning costs of an alternative, for this aspect of the analysis we assumed that an alternative system to GPS could not be deployed in sufficient time to take its place.

Farming is a seasonal enterprise, so the impact of a GPS failure on the agricultural sector depends on the timing of the failure. A GPS failure during planting season would have a significantly different impact than a failure during the harvesting period or winter months.

Experts in the agricultural industry were unanimous that a 30-day outage of GPS would have severely negative impacts depending on when it occurred, with the most severe impacts occurring during planting season. We asked them about how much a GPS outage would affect revenues if it occurred during spring and fall planting and then modeled how those economic impacts might affect the agricultural sector.

To model the productivity impacts to the agricultural sector, we multiplied experts' estimates of average impacts for a bundle of crops (corn, soybeans, spring wheat, winter wheat, rice, peanuts, and cotton) for a 30-day outage to a 5-year average of the value of the proportion of those crops where PA was adopted. We calculated value by multiplying the total crop production values by the average prices for each crop using NASS data.

$$\text{Agricultural impact} = (Q_c * S_c * A_c) * P_c$$

where

Q_c = Five-year production average (2013–2017), by crop

S_c = Mean 30-day yield impact estimates from experts

A_c = Extrapolated PA adoption by crop, 2017 (ARMS data)[17]

P_c = Five-year price average, by crop

The results give the value of the estimated productivity loss from a 30-day GPS outage for corn, soybeans, spring wheat, rice, peanuts, and cotton, assuming that the outage occurred during the spring planting season when it would have the biggest impacts.

5.3.3   *Expert Interviews*

Expert interviews were critical for obtaining rich descriptive qualitative information on impacts, as well as validating and/or adapting our methodology, data, and sources for estimating impacts. We also used the interviews to solicit both quantitative and qualitative feedback on the impacts of a 30-day disappearance of GPS. Our data collection is somewhat limited in scope because of the wide variety of analysis and data available on PA technologies and adoption.

We interviewed 22 experts total, from six universities (largely land-grant universities), 10 private-sector firms, two government agencies, and an advocacy group. These experts included agronomists, agricultural economists, equipment providers, consultants, and technology developers. Informal conversations were also held at the InfoAg conference held in St. Louis, MO, from July 25–27, 2017. This is a premier event for PA.

5.4   Retrospective Economic Benefits Analysis

PA experts agreed that GPS has become a critical component of modern agriculture in the United States. They indicated that although PA uses many co-technologies that work together with GPS, GPS was the enabling technology that allowed PA to come into existence at scale. They also believe that it would be appropriate to attribute most of the economic benefits of PA to the availability of GPS.

However, respondents disagreed on the extent of those impacts. When presented with ERS's table on the net benefits from 2010 corn, all but one of the respondents felt that the net benefits were lower than what they would have expected, too conservative, and likely had increased significantly since 2010. When asked about present-day net returns, most provided their own estimates for the current net benefits of PA for a bundle of crops (Table 5-5). Experts who worked in the private sector thought that the additional net returns from PA were higher than university researchers or government employees thought.

---

[17] Our analysis used extrapolated values for the highest adoption rates of a PA technology for each crop in 2017, unless the most recent overall PA adoption rate was higher. See also the addendum to this chapter.

Table 5-5.   Expert Estimates on Net Returns from Precision Agriculture

	Guidance Net Return Estimate (N=21)	VRT Net Return Estimate (N=20)	Soil/Yield Mapping Net Return Estimate (N=20)
Mean of expert estimates (standard error)	5.69% (0.0117)	4.85% (0.0114)	5.05% (0.0111)
Minimum of expert estimate	1.5%	1.1%	1.5%
Maximum of expert estimate	20%	20%	20%

Note: Experts were asked to consider corn, soybeans, wheat, cotton, peanuts, and rice.

They also believed that although net benefits could vary significantly from one crop to another they expected the benefits to be higher for higher value crops and lower for lower value crops. Because the crops for which USDA collects adoption rates include a mixture of low- and high-value crops, most experts thought that biases from applying PA net benefits to corn to the other major crops where USDA collects adoption rates (e.g., corn, soybeans, wheat, rice, cotton, peanuts) would be largely offset; therefore, it would be reasonable to apply them similarly across crops in the absence of more specific data.

PA experts also described other benefits that are relevant but challenging to quantify. Some cited health impacts such as reduced stress or physical injuries, and many discussed how PA allows farmers to continue working later into their lives and delay retirement. PA allows farmers to apply inputs more quickly, accurately, and in less time, reducing health impacts related to the long hours of driving and concentration associated with operating large farm machinery.[18] These benefits are likely even higher during a rainy spring planting season, when farmers have less time for planting. GPS-enabled PA, and in particular, automated guidance systems, allows farmers to operate equipment around the clock and plant more quickly than using traditional technologies, which relieves the stress and reduces the risk of missing the planting season window because of extreme or ill-timed precipitation or low temperatures.

Lastly, experts discussed several environmental benefits that PA enables, including using VRT to shut off agrochemical use in environmentally sensitive areas and increasing the efficiency of input use so less fertilizer and other agrochemicals enter the soil, water, and air. Guidance allows farmers to minimize overlaps where agrochemicals are applied on the same area twice, and VRT allows farmers to increase the percentage of fertilizer that is used by the crop rather than lost to the environment. In particular, nitrogen fertilizer is one of the primary direct contributors to GHGs from the agricultural sector, and VRT is one tool that allows farmers to apply it more efficiently, thereby reducing GHG emissions. Experts believed that although the majority of PA benefits will come from the six crops analyzed in this study there are some benefits from PA for higher value horticultural crops. Most experts were reluctant to estimate the

---

[18] The ERS estimates account for the economic impacts of the difference in labor hours and other overhead costs or production differences associated with PA but not for any health impacts, including stress, or the risk avoidance benefits of planting more quickly during an abnormally rainy planting season.

potential impacts of PA on these crops because of the differences between crops and the high spatial and temporal variability as it relates to PA. One expert reported that

> *lettuce in California is probably close to 100% adoption. They started ~ 20 years ago. Open air lettuce around major cities on the East Coast has much lower adoption, since they started 15 years later. How can you compare lettuce in California (3–5 crops/year) with lettuce in the East with one crop per year? And how can you compare kale with tomatoes, onions with carrots?*

Others pointed to specific geographies and crops where farmers are gaining significant profits from using PA, such as wine producers in California that use PA to optimize grape harvesting, maximizing the quality of and selling price for their wine.

One expert argued that the three categories of PA that may be applicable for row crops would not be applicable to horticulture crops:

> *let's not ask about Guidance, Variable Rate and even Yield Mapping. We should be talking about much more rudimentary items—Data Logging, Constant Rate and Real-Time Tracking, as these are the items that will dramatically increase efficiency and productivity while decreasing input costs and management needs.*

We estimate that the total additional net returns since 1998 from adopting PA technologies for corn, soybeans, wheat, rice, peanuts, and cotton are $5.8 billion. This estimate takes into account the adoption of yield and soil mapping,[19] guidance systems, and VRT (see Tables 5-6 and 5-7).

These benefits assume that farmers who applied PA realized the Table 5-3 increase in net benefits from 1998–2010, and then net benefits increased linearly to 2017 until reaching the net benefit percentages reported in Table 5-5. Guidance systems for corn represent the highest single crop/GPS-assisted PA technology combination ($1.3 billion), and corn represents the highest net benefits overall ($2.9 billion), followed by soy ($1.6 billion), spring and winter wheat combined ($927 million),[20] cotton ($224 million), rice ($96 million), and peanuts ($60 million).[21] By technology, guidance systems led to the highest benefits ($2.9 billion), followed by yield and soil mapping ($1.7 billion) and VRT ($1.2 billion).

These totals are lower than previous estimates, but they are net of adoption costs, which is important because PA can be a substantial investment. These estimates build off a national-level peer-reviewed study on the impacts of PA that implicitly consider the counterfactual because it compares adopters with nonadopters.

---

[19] Yield and soil mapping adoption rates were averaged to conform to Schimmelpfennig (2016) PA technologies

[20] Area harvested for spring and winter were pulled separately, but net returns were the same.

[21] Example calculation. *Net returns for corn = $139 per acre. Total acres = 81,446,000. Adoption rate = 45%. Additional % returns for guidance systems (2010) = 1.50%. Change in net returns due to guidance systems for 2010 corn= (139.19*1.50%)*(45.17%*81,446,000) = $76.8 million.* In cases where farmers net returns were negative, the increase in net returns were calculated as being less negative.

Table 5-6.   Net Returns from Precision Agriculture Technologies, by Crop, Since 1998

Crop	Yield and Soil Mapping ($ million)	Guidance Systems ($ million)	Variable-Rate Technology ($ million)	Total ($ million)
Corn	$973.6	$1,342.5	$623.7	$2,939.7
Cotton	$34.2	$162.5	$27.0	$223.7
Peanuts	$12.9	$34.6	$12.3	$59.7
Rice	$19.1	$57.3	$20.0	$96.4
Soybeans	$508.6	$734.2	$340.9	$1,583.7
Spring wheat	$59.1	$215.8	$53.9	$328.8
Winter wheat	$77.2	$364.2	$156.0	$598.3

Table 5-7.   Net Returns from Precision Agriculture Technologies, by Year

Year	Yield and Soil Mapping ($ million)	Guidance Systems ($ million)	Variable-Rate Technology ($ million)	Total ($ million)
1998	$18.4		$8.9	**$27.3**
1999	$41.7		$19.2	**$60.9**
2000	$46.3		$18.6	**$64.9**
2001	$35.8	$7.4	$13.4	**$56.7**
2002	$13.7	$3.1	$6.4	**$23.1**
2003	$12.0	$5.4	$6.0	**$23.4**
2004	$6.9	$9.1	$3.9	**$19.9**
2005	$34.1	$36.5	$16.6	**$87.2**
2006	$25.2	$39.0	$13.1	**$77.4**
2007	$23.0	$31.1	$10.4	**$64.5**
2008	$70.5	$104.9	$34.4	**$209.8**
2009	$31.2	$56.9	$16.4	**$104.4**
2010	$84.7	$124.4	$43.1	**$252.3**
2011	$190.6	$285.9	$112.5	**$588.9**
2012	$216.9	$369.6	$149.8	**$736.3**
2013	$131.4	$246.1	$102.3	**$479.8**
2014	$172.7	$368.5	$146.1	**$687.4**
2015	$148.4	$351.2	$143.1	**$642.7**
2016	$214.3	$475.5	$204.1	**$893.9**
2017	$166.9	$396.6	$166.3	**$729.8**
Total	**$1,684.7**	**$2,911.2**	**$1,234.6**	**$5,830.4**

5.5   Potential Impacts of a 30-Day GPS Outage

The impact of a 30-day outage in the agricultural sector is highly dependent on the time in which it occurs. PA experts mentioned different potential impacts happening at different points in the year. All agreed that the most damaging impacts would occur during planting season because farmers could be so delayed that they could potentially miss the planting window or plant at a suboptimal time, causing significant yield losses. Loss of VRT would affect the ability to apply fertilizer, and planting speeds would have to decrease, causing further delays. Impacts at other times of the year might affect agrochemical application or data collected by yield monitors during the harvest, but these impacts would be much less than those that occur during planting.

Experts also agreed that a 30-day GPS outage during the planting season would be highly damaging or "devastating"; however, most agreed that farmers are quite independent and capable and would eventually figure out how to plant, even if it meant a yield loss and additional input costs.

Experts estimated revenue losses if GPS were to shut off during the planting season. On average, experts estimated 17% with a +/− 6% margin of error for revenue losses across corn, soybeans, wheat, rice, peanuts, and cotton (Table 5-8).

Many large growers that have adopted GPS-assisted PA technologies have adopted larger equipment that is less easy to manage without GPS. Experts discussed how many of the planters are not equipped with markers and are too big for drivers to easily track their rows. In the event of a 30-day outage, it would be very challenging for farmers to retrofit their equipment, and many operators do not have recent experience farming this way, causing numerous overlaps, skips, and over- or underapplying of inputs. Without VRT, farmers would have to return to a single rate application of seeds, fertilizer, and other inputs, increasing operational costs and leading to lower yields.

For many places and crops, there is only a 15-day planting window, and if a farmer plants outside that window, then he will not get optimal yields. In terms of quantity, one expert estimated that farmers lose a bushel per acre when they plant 1 day outside the planting window.

Table 5-8.   Estimated Yield Impacts from Unexpected 30-Day GPS Outage

	Spring Outage Yield Loss (N=22)	Fall Outage Yield Loss (N=18)
Mean of expert estimates	17%	10%
(standard deviation)	(0.14)	(0.07)
Minimum of expert estimate	5%	0%
Maximum of expert estimate	50%	25%

Note: Estimate across corn, soybeans, wheat, rice, peanuts, and cotton.

PA technologies are a nascent industry that depends on building consumer confidence, so it is likely that a 30-day failure would have a negative effect beyond the 30-day time window because farmers would be skeptical of adopting GPS-based systems in the future and would have to invest heavily in backup systems.

Taking the 17% average losses estimated by experts and applying that to the average adoption rates for the six major crops for which PA is applied over time indicates that farmers would lose an average of $15.5 billion in revenue if the outage occurred during the spring planting season (see Table 5-9). The greatest impacts would for corn and soybeans ($8.5 billion and $5.1 billion, respectively), because they represent the highest value crops in the United States, followed by spring wheat, cotton, rice, and peanuts.

These figures assume that the impacts are all related to productivity losses, when in fact revenue losses will most likely come from both lost inputs (e.g., seeds, fertilizer, labor) and losses in yields. They also mask the fact that some farmers might lose their entire crop for the year. Furthermore, unlike some other industries, which might be able to make up some of that lost productivity over time, agriculture is a seasonal enterprise, so any yields (and associated revenue) lost from the agricultural sector would not be possible to recover through increasing productivity in subsequent months.

5.6 Notes on Technology Transfer

Federal and local governments have supported the transfer of GPS technology to the agricultural sector in several ways. The USDA's Agricultural Research Service (ARS) Office of Technology Transfer manages USDA's technology transfer activities with an explicit focus on transferring USDA's agricultural research into the marketplace. This work includes administering patent and licensing information for all intramural research conducted by USDA.

Table 5-9. Revenue Loss If GPS Failed during the Spring Planting Season

Crop	PA Applied (A)	GPS Outage Yield Shock (B)	Overall Yield Shock (A x B = C)	Avg. Annual Value (5-year average production revenues) ($ billion)	Shock Value (C x D = E) ($ billion)
Corn	83%	17%	14%	$60.6	$8.49
Cotton	55%	17%	9%	$5.52	$0.50
Peanuts	69%	17%	12%	$1.35	$0.16
Rice	75%	17%	13%	$2.89	$0.38
Soybeans	73%	17%	12%	$42.5	$5.12
Spring wheat	83%	17%	14%	$3.52	$0.49
Total				**$116**	**$15.1**

One of the public–private partnerships documented during interviews with stakeholders and in the literature was a successful research effort that led to a public–private partnership between USDA/ARS, University of Missouri, and Dupont Pioneer to develop the concept of Environmental Response Units that help farmers "optimize their seed and fertilizer inputs to match production potential within fields" (Bobryk et al., 2016; USDA/ARS, 2016). According to the USDA/ARS Annual Report on Technology Transfer,

> *Soil classification with ERU soil maps better delineates soil and landscape characteristics within fields and can better guide the use of precision agriculture variable-rate technologies. Farmers can use these findings to optimize seed and fertilizer inputs that match production potential within fields. Matching input applications to a better characterized soil resource improves the cost-effectiveness of agricultural production and minimizes field losses of agrichemicals, which furthers production sustainability and natural resource protection.* (USDA/ARS, 2016, p. 295).

Currently USDA/ARS is also using remote sensing technologies (which require GPS) to monitor crop productivity and provide actionable information to farmers. One example is research that enables grape producers to monitor water stress and optimize precision irrigation for their vineyards (USDA/ARS, 2016).

USDA has also supported technology transfer through technical assistance and conservation incentive funding through the Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP). EQIP offers this support in two areas related to precision farming: nutrient management and pest management. EQIP provides technical assistance and financial incentives for variable-rate technologies of fertilizer and for GPS-enabled guidance systems for pesticide application. Through this program, local NRCS conservationists provide technical assistance directly to farmers on how to implement these technologies on their farms. There is no publicly available data on exactly how much technical assistance and funding are provided for precision farming applications, but data show that of the dozens of conservation practices supported by the program the two most widely supported by USDA/NRCS are nutrient management and pest management (USDA, n.d.). The number of supported acres for these practices has steadily decreased over time while PA adoption has increased, perhaps suggesting that farmers have increasingly adopted these technologies over time on their own, obviating the need for additional incentive payments (nutrient management decreased from 1.8 million acres in 2009 to 642,000 acres in 2017).

Although less direct, USDA and many state departments of agriculture provide salary support for university-based agricultural extensionists at land grant universities. Agricultural extension workers provide direct support to farmers to transfer technology and research into practical applications for farmers, including PA. Extensionists have close contact and relationships with farmers, in part through conducting farmer workshops, farmer field days, and farm focused research. As researchers, extensionists strive to provide science-based, unbiased information to farmers, and they are uniquely trusted by farmers. PA involves intensive research on expensive and complex technologies, so this kind of close linkage between university researchers and farmers has been important for the successful transfer of GPS-based technologies, particularly for small- and medium-scale farmers who are less able to take risks on new, sometimes expensive technologies.

PA experts pointed to other examples of federally funded research and infrastructure that has supported GPS technology transfer to the agricultural sector:

- Federally supported infrastructure to test new PA equipment. Multiple stakeholders pointed to the Nebraska Tractor Test Laboratory (https://tractortestlab.unl.edu/), which allows companies to evaluate the performance of new equipment. This service is fee based, but the infrastructure and

capital costs were publicly funded. The lab has been designated by the U.S. Department of Commerce as the Designated Authority responsible for the U.S. tractor test program.

▪ The role of the National Science Foundation (NSF) in funding university programs and curriculum development for degree programs in geospatial technologies in the agricultural sector (particularly in the Midwest).

5.7   Concluding Remarks

GPS enabled the development of PA at scale and has become an integral part of farming in the United States. Almost every new tractor and combine on the market today comes equipped with GPS technology, and precision farming is now widespread. Large commercial farmers heavily rely on GPS to more precisely manage their inputs to increase their yields.

The pervasiveness of PA farming has led to significant monetary benefits for farmers over time, including $5.8 billion in net revenues for six major crops over the period of time from 1998 through 2017. These benefits have accrued over time and represent only a portion of the many benefits that PA has provided to farmers, consumers, and the environment. Farmers who use PA can plant more quickly and avoid the health and stress impacts associated with operating heavy machinery for long hours. Consumers benefit from buying food products at lower prices, and there is less contamination to the environment as farmers limit the amount of agrochemicals that are lost to air and water sources.

However, many farmers have also become reliant on GPS technology and are vulnerable in case there is a disruption or outage to GPS. It would be difficult for these farmers to adjust their farming practices to more traditional techniques in a short period of time. Farmers have relied so much on these technologies that the entire value that GPS has added to the industry could be wiped out if a GPS outage were to occur during the planting season. We estimate that the agricultural industry could lose $15.1 billion across corn, soybean, spring wheat, cotton, and peanuts if such an ill-timed outage were to occur.

Both the monetary benefits of GPS to agriculture and the potential losses in the case of an outage are likely significantly larger because of the role that GPS technology and PA have played in supporting additional crops and farming logistics in recent years. The agriculture industry is generally increasing the adoption of PA, and several experts discussed how they expect GPS to be used more in the future; several pointed toward the potential for better managing logistics and enabling the deployment of autonomous vehicles.

Many horticultural producers have adopted GPS-assisted PA to improve their efficiency, and others have used GPS to better manage their logistics and operations. The adoption rates and benefits in agriculture are very crop, use, and geography specific; as such they are not well suited to generalizable monetization.

Nonetheless, USDA has collected enough data through the ARMS and other sources to allow us to estimate the additional benefits that PA provides to several major crops in the United States. These benefits are significant and are likely to increase in the future as a result of the growing PA industry, growing adoption, and expansion of GPS-assisted PA into additional uses.

Addendum. Historical Adoption of Precision Agriculture Technologies by Crop (Percentage of Crop Planted Acres)

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Yield Mapping																				
Corn	7	12	11	9	12	14	17	19	22	25	28	31	34	37	40	43	46	48	51	54
Cotton	—	—	1	1	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Peanuts	—	—	—	—	—	—	0	1	1	2	3	3	4	5	5	6	7	7	8	9
Rice	—	—	—	—	—	—	—	—	10	11	12	13	14	15	16	18	19	20	21	22
Soybeans	9	9	8	8	8	11	14	17	20	22	24	25	27	28	30	32	33	35	37	38
Spring wheat	2	1	0	2	4	6	9	9	10	11	12	13	14	15	16	17	17	18	19	20
Winter wheat	1	2	2	3	3	3	3	4	4	5	6	6	7	8	8	9	10	10	11	12
GPS Soil Mapping																				
Corn	13	17	22	22	20	18	17	15	16	18	19	21	22	24	25	27	28	30	31	33
Cotton	3	10	13	10	8	5	5	5	5	5	5	5	6	6	6	6	6	6	6	6
Peanuts	—	2	3	3	3	3	3	6	8	10	13	15	17	20	22	24	27	29	31	33
Rice	—	—	—	—	—	—	—	—	8	8	9	10	10	11	12	12	13	13	14	15
Soybeans	12	15	17	13	9	10	11	12	13	14	15	16	17	18	19	21	22	23	24	25
Spring wheat	9	12	15	15	16	16	16	15	14	13	11	10	10	10	10	10	10	10	10	10
Winter wheat	5	8	10	9	7	6	4	5	5	6	6	6	7	7	8	8	8	9	9	10
Guidance and autosteer systems																				
Corn	—	—	—	5	8	10	13	15	21	27	33	39	45	51	57	63	69	75	81	83
Cotton	—	—	—	—	—	11	14	17	20	23	26	30	33	36	39	42	45	49	52	55
Peanuts	—	—	—	—	—	—	4	9	14	19	24	29	34	39	44	49	54	59	64	69
Rice	—	—	—	—	—	—	—	—	26	30	34	37	41	45	49	53	57	61	65	69
Soybeans	—	—	—	—	5	9	13	16	20	24	28	33	37	41	45	50	54	58	62	66
Spring wheat	—	—	—	—	—	—	30	36	41	46	51	57	62	67	72	77	83	83	83	83
Winter wheat	—	—	—	—	—	—	10	15	20	25	30	35	40	45	50	55	60	65	70	75

(continued)

Addendum. Historical Adoption of Precision Agriculture Technologies by Crop (Percentage of Crop Planted Acres) (continued)

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Variable-rate Application Technology																				
Corn	8	12	12	9	10	11	11	12	14	16	18	20	22	25	27	29	31	33	36	38
Cotton	3	4	5	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	5
Peanuts	-	1	2	2	3	3	4	5	7	8	10	11	13	15	16	18	19	21	23	24
Rice	-	-	-	-	-	-	-	-	6	8	10	12	15	17	19	21	23	25	27	29
Soybeans	7	9	7	6	5	6	7	7	8	10	13	15	17	20	22	24	26	29	31	33
Spring wheat	5	3	0	2	5	7	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Winter wheat	2	2	3	4	5	7	8	9	10	11	13	14	16	18	20	23	25	27	30	32

Reported data from Agricultural Resource Management Survey (ARMS) and data from Schimmelpfennig (2016) in blue. Values in green capped due to inappropriateness of linear extrapolation. Extrapolated values in black. ARMS data can be found here: https://data.ers.usda.gov/reports.aspx?ID=17883.

6.   Electricity Sector

The electricity sector uses the precision timing provided by GPS to synchronize electrical waves in the power grid and detect potential problems and faults in the transmission infrastructure. GPS has been a key factor in making phasor measurement units (PMUs) cost-effective and pervasive in the United States' electricity infrastructure.

In the absence of GPS, the electric utility system would likely have continued to rely on its existing supervisory control and data acquisition (SCADA) systems. However, the use of PMUs enabled by GPS has led to a slight (1 to 2%) decrease in the probability and duration of outages and enhanced generation testing/modeling, resulting in economic benefits of approximately $15.7 billion since 2010.

In the event of a 30-day outage of GPS today, a major disruption of the electrical system is unlikely because of safeguards and contingency plans in place. However, the probability of outages might increase. In addition, faults occurring from natural or non-natural events would take longer to identify and repair, increasing the duration of outages. The economic loss is estimated to be approximately $274.8 million from a 30-day GPS outage with little to no physical damage to the system.

6.1   Sector Applications

Electricity suppliers can use the precision timing provided by GPS to monitor the daily operations of the power grid down to the nanosecond. This monitoring is conducted by PMUs, which evaluate electrical waves to detect potential problems and faults in the power distribution infrastructure. To realize this real-time monitoring and analysis, a large number of synchronized PMUs, or synchrophasors, are linked to a common time source that enables them to time stamp the dynamics of the electrical system. The time source is the Coordinated Universal Time (UTC), which is provided via the GPS system (Coppolino, D'Antonio, Elia, & Romano, 2011).

Historically, power systems using SCADA have depended on its *relative time* clock features to perform daily monitoring operations. Relative time refers to the timing of triggering events such as a fault or lightning strike relative to their starting points; that is, the zero point is precisely when the event in question occurred (North America Synchrophasor Initiative [NASPI], 2017). This timing capability allows for SCADA's scan time (frequency of data collection) to range between 1 to 2 seconds and 10 seconds or more (NASPI, 2017). These time scans work well for localized events on small decentralized systems, such as a single generating source supplying a stand-alone grid system. However, they do not work well across a wide-scale interconnected grid system. For many years, it was recognized that the power system data captured by different SCADA systems could be far more valuable if the systems all used a common time standard to "time tag" their measurements.

Beginning in the late 2000s, GPS-based PMUs began to be installed in the electrical system to augment the SCADA-based systems for state estimation. Because PMUs collect data at a much higher sampling rate than SCADA systems, the granularity of the data helps reveal new information about dynamic stability events on the grid.

By 2015, the installed number of PMUs reached approximately 1,800, offering nearly 100% coverage of the transmission system (NASPI, 2017). Figure 6-1 shows current locations of PMUs on the electricity grid. Although the SCADA system is still the backbone of most system applications in the power sector, with GPS supporting ancillary (nonessential) system operations, this is evolving over time and PMUs are likely to be increasingly integrated into system operations, resulting in efficiency and reliability gains.

Synchrophasor technology uses *absolute time* to gauge the state of the system. This timing approach both time-synchronizes and time-stamps data against UTC, or local time, available through GPS (NASPI, 2017). As a result, synchrophasors make possible the monitoring of the electrical grid at 30 to 120 time-tagged samples per second, approximately 100 times faster than SCADA (NASPI, 2017). When data will be used to provide automatic control actions, it is imperative that timing remains as accurate, secure, and reliable as possible (NASPI, 2017). Given that these data must possess an absolute time precision of 1 µs (NASPI, 2017), highly accurate monitoring of the power line dynamics in real time is only attainable by using GPS UTC time stamps.

Figure 6-1.   Phasor Measurement Units in the North American Power Grid

Source: NASPI (2015b).

Today's wide-area grid is highly interconnected. PMUs using GPS have helped make this possible while maintaining resilience. For example, analyses of event observations have shown that during a generator trip situation, frequency is reduced in a proportional way. This reduction, monitored in a certain point, quickly spreads across the transmission lines, thereby showing up in other sites with a certain delay. But with the propagating generator trips evaluation feature of the synchrophasors, the exact location of the event and the power trip misbalancing can be identified, and necessary countermeasures can be subsequently taken. This characteristic allows for the forecasting of serious events such as blackouts and readies the remote power supplier with storage energy sources (Coppolino, D'Antonio, Elia, & Romano, 2011).

6.2   Methodological Notes

Our approach to assessing the economic impacts was to begin by identifying the sector's precision timing and synchronization needs, determining which are currently being provided by GPS, and determining what alternative precision timing systems are, or could be, available. We conducted initial scoping interviews to identify preliminary hypotheses regarding the counterfactual scenarios and the potential technical impacts. The preliminary assessment was then verified and refined based on a more extensive number of interviews with industry experts.

6.2.1   *Precision Timing Needs*

Table 6-1 summarizes the precision timing needs and applications for the electricity sector. Applications range from precision timing needs in the nanoseconds for traveling-wave fault detection milliseconds to less demanding uses. Event reconstruction and system time/frequency are the applications with the greatest precision timing needs.

The precision timing needs for different applications drive the benefits associated with GPS. For example, time-of-use billing requires time stamps, but the level of precision is minimal. In contrast, fault detection requires extremely accurate time stamps because electricity flows at close to the speed of light.

Table 6-1. Electricity Sector Precision Timing Uses and Needs

Application	Precision Needed	Benefits: Qualitative Description	Counterfactual	Technical Impact Metric	Economic Value Metric	Potential Magnitude of Impacts
Event reconstruction	1 ms	Accurate time tags greatly speed up event reconstruction, helping to prevent future events	Manual time stamping and longer event reconstruction time	Frequency, magnitude, and duration of blackouts	Economic impact of outages	High
Phasor measurements	5–6 µs	Monitors grid instability and increases grid efficiency	Less efficient grid system	More efficient dispatch and reduced transmission losses	Fuel and increased capacity requirements	High
System time and frequency	5–50 ms	Line frequency is used by end users as a time standard (clocks in appliances)	Less accurate clocks. Not an issue for appliances but impact other apps.	Increased cost for some applications needing time standards		Low
Billing and power quality incentives	50 ms: Billing 1 ms: Power quality harmonics	Customers typically monitor themselves, and utility bill estimates need to match; thus, accurate time is key	Less reliable M&V for harmonics incentive programs	Impacts due to incentive program (partial attribution)	Value of load shifting and improved power quality	Low
Traveling-wave fault detection	0.1 µs	More precisely locate the point of fault	Longer ground-based search time	Speed time to identifying and fixing faults on large transmission lines (300–500 M spans)	Value of reducing the duration of the outage	High

6.2.2   *Approach for Quantifying Retrospective Benefits*

The most likely counterfactual scenario in which GPS was not made available for civilian use is that the SCADA system would have continued to be used to meet timing needs in the electricity sector. Alternatively, the sector might have migrated to a Loran-based system (if it had been expanded) for some timing needs. In either case, the decrease in precision would have inhibited many of the current applications that rely on GPS.

During our interviews with industry experts, we investigated which system (or combination) would have been more likely to meet timing needs and the potential impact of using that system. Even though SCADA technology has evolved significantly since its conception and is currently capable of providing reliable measurements and results, its readings are not as accurate as those obtained through GPS (North American Electric Reliability Corporation [NERC], 2012) because the measurements that SCADA typically evaluates are not time aligned and are therefore unable to display real-time changes and angle evaluations (Coppolino, D'Antonio, Elia, & Romano, 2011). Highly accurate monitoring of the power line dynamics required in real time is attainable only by using GPS's UTC time stamps. The impact is similar comparing GPS with an expanded Loran system.

Thus, the analytical focus is on the difference in precision timing of GPS compared with the SCADA system or an expanded Loran system. The primary technical impacts associated with the decrease in precision timing are

- a decreased ability to monitor system status and hence a slight increase in the probability of an event/outage;

- increased time to identify, trace, and mitigate/correct faults, leading to longer duration of outages;

- increased cost and downtime for generation model verification;

- a potential increase in transmission line loss; and

- less interconnectivity and hence a less efficient grid system.

Once the technical impact metrics are validated, the next step is to estimate the associated economic impacts. In general, these economic impacts fall into several major categories:

- lost economic activities due to disruptions in the power supply or quality;

- impacts on household welfare in terms of inconvenience or health/injury;

- electricity system costs, including

    – additional costs of operating or switching to a SCADA or Loran system;

    – additional costs associated with identifying, tracing, and fixing system faults;

    – increased generation costs associated with increased line loss; and

    – increased system costs of ensuring reliability and resilience.

The impacts described above are the technical (system) impacts resulting from the loss or unavailability of GPS. The next step is to value these technical impacts to estimate the economic impacts on service providers and their customers. We estimated economic impacts by valuing/monetizing the changes in the cost of service in terms of increased expenditures on labor, capital, and fuel and the quality of service in terms of the cost of increased outages to customers. In most instances, we used the expert interviews to identify and verify technical impacts and then the published literature to calculate the economic impacts.

We estimated a time series of impacts to capture the share of the national electricity grid system using GPS as it was adopted over time. This time series is based on the penetration/installation of PMUs and their pervasiveness throughout the electricity system. Literature suggests that PMUs were initially integrated into the East Coast grid system starting in 2010 and were eventually being used throughout the entire system by 2014 to 2015. As noted below, although PMUs have not replaced the SCADA systems for real-time operation, they do provide ancillary benefits that are valued, and it is these benefits that are scaled to the national level.

6.2.3   Approach for Quantifying the Potential Impacts of a 30-Day GPS Outage

Most published studies conclude that widespread grid failures are not to be expected from a major disruption of the GPS signal (NERC, 2012). The electrical system is highly distributed, and the existing SCADA system could be engaged quickly to serve as an adequate backup system for any GPS-supported functions. This capability reduces the likelihood that a large-magnitude event such as widespread cascading outages would occur.

However, the loss of GPS would affect system monitoring operations and effectiveness, leading to a slightly increased probability of adverse events. The impact would be similar to the retrospective scenario (but more short-lived) and would lead to the following impacts over the 30-day GPS outage period:

- increased time to identify, trace, and mitigate/correct faults;
- increased probability and duration of small-scale outages; and
- increased probability (albeit low) of large-scale blackouts.

Long-term impacts such as infrastructure damage are unlikely.

6.2.4   Interviews with Sector-Specific GPS Experts

We interviewed industry experts with a range of expertise and perspectives. These groups along with key topic areas are summarized in Table 6-2. Electricity sector interviewees were identified through publications, conferences, workshop speaker lists, and referrals.

We identified and contacted 55 experts who specialize in the role of PNT in the electricity sector, and 23 (41%) agreed to participate in the interview process. The largest group interviewed comprised utility and system operators because they were able to provide information on how PMUs are actually being used (as opposed to conceptual benefits).

Table 6-2.   Target Population for the Electricity Sector Interviews

Population Groups	Target Companies/ Organizations	Topic Areas/Questions
Service providers, system operators	▪ Utility operators ▪ Independent system operators	▪ System efficiency gains from GPS's level of timing precision ▪ What are the alternative precision timing systems? ▪ Time series of when PMUs and synchronizers were deployed in different parts of the grid ▪ Holdover and how quickly the system would deteriorate ▪ Capabilities and precision of existing backup systems
Equipment manufacturers, product providers	▪ Synchrophasor manufacturers	▪ Time series of when PMUs and synchronizers were deployed in different parts of the grid ▪ Role of government laboratories in developing and demonstrating PMUs and synchrophasors and promoting their adoption
Regulators and risk assessment experts	▪ Federal Energy Regulatory Commission (FERC), NERC	▪ System efficiency gains from GPS's level of timing precision ▪ Change in the probability of events without GPS
Researchers, universities, government laboratories	▪ Authors of studies ▪ University professors ▪ Engineers and electricity specialists	▪ Costs of blackouts, brownouts, poor power quality ▪ What are the alternative precision timing systems? ▪ Role of government laboratories in developing and demonstrating PMUs and synchrophasors and promoting their adoption
Industry trade associations	▪ Electric Power Research Institute (EPRI), NASPI	▪ System efficiency gains from GPS's level of timing precision ▪ What are the alternative precision timing systems?

After completing the interviews, we compiled and computed all responses to identify the operational activities or applications within the electric utility sector that depend on or benefit from synchrophasor technology. Table 6-3 shows the proportion of experts who highlighted whether synchrophasor technology is used in several electric grid operations.

All experts indicated that PMUs are currently not used in real-time operations because of the reliability of the legacy SCADA systems and the sector's high level of risk aversion. Because the cost of failure is extreme, it will take time to integrate automated PMUs into the system. Research is still ongoing to make sure that using PMUs for real-time operations is safe (having resilient backups, etc.). According to the interviews, the general sentiment among utilities is that "if it is not broken, don't fix it." Along this line, we also heard that no one wants to be responsible for grid failures derived from such significant changes.

Table 6-3. How GPS/Phasor Measurement Units are Being Used in the Electricity Sector and Resulting Benefits (%)

	Real-Time Operations[a]	Situational Awareness[b]	Outages Reduction (probability of an event)	Reduced Outage Duration	Dispatch Efficiency[c]	T&D Losses	Generation and Validation Modeling[d]	Prevention (Planning) and Post–event Analysis	Fault Location
Yes	0	100	83	88	33	0	100	100	100
No	100	0	17	0	33	60	0	0	0
Maybe	0	0	0	11	33	40	0	0	0

[a] The use of PMUs to detect and correct for power/synchronization issued in real time.

[b] Being informed about the behavior of the electric system by visualizing and monitoring its operations.

[c] Increased efficiency by enabling lowest cost dispatch over wide-area interconnected networks.

[d] Ensuring that models accurately represent the nature of the workings, processes, parameters, and behavior of the units or operations for which they were developed. For the purpose of the quantitative analysis in this report, the concept of model validation is applicable to generating units only.

However, experts did provide valuable information for improved situational awareness, which, in turn, leads to reduced frequency of outages. All experts indicated that precise time stamps are essential for fault detection because fault detection decreases the duration of outages. No respondents felt comfortable saying PMUs reduce transmission and distribution (T&D) losses, although some thought it was conceptually possible.

The responses shown in Table 6-3 guided the identification and quantification of benefits discussed in the following sections.

6.3 Retrospective Economic Benefits Analysis

Although not yet used for real-time applications, experts interviewed all agreed that the current applications of PMUs on the electric grid have improved the electricity sector's ability to monitor the behavior of the electric grid and perform post-event analysis. These benefits are realized primarily through PMUs' ability to time tag events to the standard time (UTC). Such features enable better visibility of the grid, increase situational awareness, and enhance post-event analysis, all of which help enhance the operations of the grid. And all experts agreed that the wide-scale adoption of PMUs across the grid was made possible in large part because of the high degree of accuracy and cost-effectiveness of GPS's capability to provide precision timing services. The following presentation of benefits is segmented into qualitative and quantitative findings.

6.3.1 *Qualitative Findings*

Synchronization of Angle Measurements

Industry experts agreed that one of the primary ways in which precision timing became critical for grid operations was in comparing and synchronizing angle measurements. For these operations, time-

synchronized measurements are required to enable the comparison of multiple phasors located in the different parts of the grid. Pointing out the great number of errors inherent to angles, one expert stressed the need to achieve a precision of 1 microsecond or less to perform reliable comparisons between them. GPS made it possible to measure phasor angles with a precision greater than 1 degree, which represents approximately 20 microseconds. The benefits of this precise synchronization become critical in the event of grid isolation or islanding in order to contain an extreme event from cascading throughout the larger system. As stated by a private-sector source:

> *"If the grid separates into islands, and you have PMUs in each island, you can synchronize them together very accurately. And in the event of cyber-attacks, it becomes easier to break the system off into pieces and protect certain parts."*

PMUs have been an enabling technology for synchronizing measurements. As stated by a utility expert,

> *Before they had PMU data, utilities could not do anything meaningful in terms of measurement-based techniques to understand the behavior of the power system because the physics of isolations were faster than what traditional SCADA measurements were able to do.*

Therefore, if GPS had never been deployed or made commercially available, utilities would not have had the capacity to synchronize measurements. Consequently, without GPS, utilities would ultimately revert to a point when, without PMU information, operators had to use their best judgment to figure out what the system was doing.

However, during the interviews, experts also made clear that phase angle measurements still have room for improvement because the measures used to compute phasors may differ across PMU manufacturers. That is, data on frequency and angles do not always have the same default metrics of comparisons, leading to potential discrepancies that reflect interoperability issues between vendors in terms of measurements units.

Although PMU technology does not have the same pivotal role as it does in measuring phase angles, it is employed for power generation dispatch applications. In this regard, a small number of experts highlighted the use of PMU technology in adjusting generation dispatch levels. They stated that even though actual dispatch signals run on standard scans and do not directly rely on GPS the data collected by PMUs help power suppliers plan, with increased accuracy, how much power they may need to generate in a particular time period. As a result of this increased accuracy, suppliers can get closer to supplying the optimum level of generation power needed to satisfy demand.

If GPS had never been developed, wide-area awareness applications would not enjoy the same level of efficiency they currently do. The visibility and behavior of the grid would not be as clear as today's visibility and behavior because of the slower and less frequent wide-area scans made by SCADA technology. Given these limitations, power generation dispatch estimates would be more conservative and further away from the optimum level of generation.

Transmission and Distribution Losses

In contrast to these operational benefits in which GPS plays a clear beneficial role, the performance of other grid operations does not appear to be affected by the deployment of GPS or PMUs. Before we interviewed the experts, we noted that operational data collected by RTI showed a seemingly existing inverse correlation between a reduction in T&D losses and PMU deployment rates since 2009. However, experts with direct knowledge of this operational area of the grid stressed that reductions in T&D losses over the years could not be attributed to PMUs given their nonexistent use for real-time operations. To explain the reduction in T&D losses over the years, they underscored a general trend of efficiency taking place within the electric utility sector before the widespread availability of PMUs. Certainly, starting in the 1980s and well into the 1990s, industry-wide efforts intended to make the grid as efficient as possible with the help of the then-modern electronics and the advent of operational practices such as computer modeling, which were becoming commonplace during that time.

Fault Detection

All experts stated that PMUs help utilities take advantage of GPS location and precision time to obtain wide-area visibility of the grid to pinpoint faults, damages, and failures with more accuracy and in any part of the grid.

Such location and restoration capabilities fall within the broader post-event or forensic analysis category for which utilities have been using PMUs the most thus far, according to all interviewed experts. In essence, given PMUs' capacity to time-stamp events with a microseconds-level of precision, operators rely on the data collected by PMUs to analyze the sequence of events that led to the outage or failure in question. A utility expert explained that "every time abnormalities show up on the data, it means that some type of frequency or phase angle alteration occurred." Once they are aware that something has happened, utilities can find the origin of the event, its location, and the precise time when it occurred because GPS allows the data from all power plants with PMUs to be synchronized to standard UTC time.

As a direct result of this capability, utilities can quickly dispatch a crew to the exact point where repair is needed and restore power more quickly in the event of an outage, regardless of whether it was caused by human error or environmental factors such as lightning strikes, hurricanes, and storms. To illustrate this benefit, a handful of experts stressed that the lengthy and labor-intensive analysis performed after the 2003 Northeast Blackout could have been significantly reduced had PMUs' stage of utilization been more comparable to today's levels. While an admittedly more complicated outage, the 2003 blackout was also harder to analyze because no time-synchronized source was used, which increased the standardization of all data provided by power plants. In addition, there was little expertise on aligned time using GPS time-stamped values. By comparison, experts stated that the 2011 San Diego outage took 2 hours to analyze, concluding that reducing postmortem analysis time of outages from weeks or even months to only hours was made possible by the readily available data provided by PMUs.

Once the data have been collected and analyzed to understand how and why an outage event happened, utilities can create more accurate simulations and models and implement the necessary corrective actions

that enable them to prevent future failures. Specifically, the data help utilities understand critical nodes, thereby reducing the likelihood of a cascade failure.

Model Verification

Other models that benefit from the better and clearer data obtained by PMUs are those used for generators within power plants (see Figure 6-2). Currently, NERC regulations require utilities to validate models of generators with a capacity greater than 20 MVA at least every 5 years. Utilities have been using PMU information to validate their existing models without having to take the generators offline or hiring several engineers to collect the data. These models are used as a base for the operation of generators and can prevent equipment failure.

Figure 6-2.   The Use of Phasor Measurement Units Data for Model Verification

One industry expert stated that updated NERC standards now require the use of PMU-like measurements for model validation. Old physical measurement-based model validation methods did not guarantee accurate models with good predictive capability, and the PMU-based ongoing model validation techniques produce more accurate generator characterizations with better predictive capabilities. In addition, PMU-based model validation techniques can be used for renewable generation and transmission assets such as high-voltage direct current lines. And PMU data can be used for system model validation, not just generator and transmission asset models.

Other PMU benefits highlighted by a small number of experts fall within the realm of communication. On this note, precise timing makes it possible to develop algorithms that allow high-performing computers to operate under the same time. Additionally, depending on the broadband communication architecture, high-speed time-stamp measurements enabled by GPS can be streamed from a substation to the control center, allowing operators to have a reliable view of the system.

Together, most of the benefits highlighted above are associated with a reduction in the likelihood and duration of outages. As outlined below, a reduction in the likelihood and duration of outages will be valued from the customer's perspective (customers' lost productivity or willingness to pay [WTP] to avoid outages). In addition, some utility operating costs are associated with fault location and repair crew dispatch that come from using GPS. However, we calculated these benefits as part of the telematics sector and did not include them in the electricity sector to avoid double-counting benefits.

6.3.2   Quantitative Findings

We quantified four sources that benefit from using GPS in the electric utility sector:

1. A reduction in the frequency of routine[22] power outages
2. A reduction in the duration of routine power outages
3. A reduction in the probability of large-scale power outages[23]
4. Savings related to validating generator models

---

[22] Routine power outages are those related to ongoing weather events and equipment failure.
[23] Large-scale power outages, such as the 2003 Northeast Blackout, are low-probability but high-impact events.

Although experts discussed other potential benefits associated with using GPS/PMUs, they were not able to quantify the level of adoption/use or the technical or economic impact of using GPS/PMUs. For this reason, some of the potential benefits discussed in the previous qualitative section (such as more efficient generator dispatch) are not included in the quantitative findings.

Reduction in the Frequency of Routine Power Outages

Based on the published literature and expert interviews, we estimated that deploying PMUs prevented approximately 84.5 billion customer hours of routine outages from 2010 through 2017, resulting in an economic benefit of $6.62 billion ($2017).[24] This estimate is based on the following approach and sources of information: PMUs can help prevent 1.5 to 2% of routine outages (NASPI, 2015a). We used the midpoint of 1.75% in the analysis. This figure was confirmed during the expert interviews. It took approximately 5 years for PMUs to be gradually installed to cover most of the country's electric grid (from the passage of the American Recovery and Reinvestment Act (ARRA) of 2009 until the end of 2014), and by the end of 2015, they covered approximately 100% of the grid (see Table 6-4). Outage data from 2010 through 2017 in units of customer-hours were obtained from NASPI (2015a) and the DOE (2018). The total number of electricity customer and the proportion of this total that the residential, commercial and industrial sectors represent were estimated by using 2016 values and applied for all years (EIA, 2018a). We obtained the estimated lost economic value from 1 hour of power outage by customer class from LaCommare and Eto (2006):[25]

- residential customers ($2.7 per outage hour)

- commercial customers ($886 per outage hour)

- industrial customers ($3,253 per outage hour)

To determine the economic benefit of deploying PMUs, we estimated the number of avoided outage hours that could be attributed to PMUs (based on their adoption over time) and then valued the economic benefits. Table 6-4 shows the annual benefits from reducing the frequency of routine power outages for the residential, commercial, and industrial sectors. Total benefits were approximately $6.6 billion, with the majority coming from the commercial sector. Benefits varied by year, reflecting the difference in the frequency of outages from year to year and the adoption of PMUs over time.

---

[24] We multiply the total customer hours of outages for each of the 8 years we are studying (2010-2017) by 1.75%. This percentage represents the average share of customer hours of outages that could be prevented with synchrophasor technology according to NASPI (2015a).

[25] The estimated loss of economic values from 1 hour of power outage by customer class is in 2002 dollars. Values were converted to 2017 dollars using the real GDP inflation index provided by the Federal Reserve Economic Data (FRED)

Table 6-4.   Savings from Reduction in the Frequency of Routine Power Outages

Years	PMU Deployment Rate as a Percentage of the Transmission Grid (%)[26]	PMU-Avoided Outage Benefits, Sector ($ million)			Total PMU-Avoided Outage Benefits ($ million)
		Residential	Commercial	Industrial	
2010	10	4.0	182.5	30.9	217.5
2011	20	14.1	640.4	108.6	763.1
2012	50	42.1	1,914.9	324.7	2,281.7
2013	64	12.9	588.4	99.8	701.1
2014	82	14.7	669.0	113.4	797.1
2015	95	11.9	539.0	91.4	642.3
2016	100	13.7	621.0	105.3	740.0
2017	100	8.8	398.2	67.5	474.5
Total		**122.2**	**5,553.4**	**941.6**	**6,617.3**

Reduction in Power Outage Duration

In addition to reducing the frequency of power outages, experts indicated that PMUs have helped decrease the duration of outages by 1 to 2%. Based on this input and after accounting for customer hours saving in terms of frequency, we estimated that deploying PMUs prevented approximately 71,200,000 in the duration of customer hours outage from 2010 through 2017 resulting in an economic benefit of $5.6 billion ($2017) in terms of cost savings from 2010 through 2017. The approach for quantifying this impact is similar to that used to estimate the benefits from a reduced frequency of outages in that it is based on the value of reducing the total number of outage hours.

In the analysis, we used the midpoint of a 1.5% reduction in duration. The reduced duration stems from the capacity to detect and locate faults more quickly, which enables faster power restoration because of a more efficient dispatch of first responders and repair crews. To avoid double-counting, we considered only benefits related to the value of an hour's outage to electricity consumers. Other benefits such as reduced utility operating costs (labor, vehicles, and fuel) were calculated here but are captured in the telematics sector of this report.

Table 6-5 presents the savings from the reduced duration of outages resulting from using PMUs. Total savings from 2010 through 2017 are estimated to be approximately $5.5 billion.

---

[26] The approximate number of PMUs deployed during these years were obtained from the Energetics report (Energetics Inc, 2016). We leveraged the fact that PMUs provided nearly 100% coverage of the transmission system by 2015 and worked backwards to calculate the percentages.

Table 6-5.   Savings from Reduction in the Duration of Routine Power Outages

Years	PMU Deployment Rate as a Percentage of the Transmission Grid (%)	PMU Cost Saving Benefits, Sector ($ million)			Total PMU Cost Saving Benefits ($ million)
		Residential	Commercial	Industrial	
2010	10	3.4	153.7	26.0	183.1
2011	20	11.9	539.3	91.4	642.6
2012	50	35.5	1,612.6	273.4	1,921.5
2013	64	10.9	495.5	84.0	590.4
2014	82	12.4	563.4	95.5	622.9
2015	95	10.0	453.9	77.0	540.9
2016	100	11.5	522.8	88.6	622.9
2017	100	7.4	335.4	56.9	399.7
Total		**103.0**	**4,676.6**	**792.8**	**5,572.4**

A Reduction in the Occurrence of Large-Scale Outages (e.g., 2003 Northeast Blackout)

Experts stressed that the enhanced monitoring capabilities enabled by PMU data have also reduced the probability of the occurrence of major outage events such as the 2003 Northeast Blackout. Economic studies estimated that this catastrophic blackout cost approximately $4 to 10 billion ($2003)[27] (ELCON, 2004).

A Midcontinent Independent System Operator (MISO) report cited by NASPI (2015a) highlights that the probability of an event of such magnitude could be reduced from 1 in 20 years to 1 in 30 years through the use of PMUs because of accelerated event analysis, which could help prevent wide-scale cascading failure. Such a decrease in the frequency of large-scale outages translates to an annual probability reduction from 5 to 3.33%, or a 1.67% decline. Given this reduction, RTI estimates that PMUs saved nearly $455.5 million on large-scale outage costs between 2010 and 2017 (see Table 6-6). Put another way, the country has saved approximately $455.5 million as a result of a 1.67% decline in the frequency of major outages such as the 2003 Northeast Blackout. These savings are separated from those associated with preventing routine outages because of the rarity, wider impacts, and increased costs

Table 6-6.   Savings from Reduction in the Probability of Large-Scale Power Outages

Years	Annual Expected Savings on Major Outage Cost Attributable to PMUs ($ million)
2010	9.0
2011	17.8
2012	43.6
2013	56.1
2014	71.3
2015	83. 0
2016	87.3
2017	87.3
Total	**455.4**

---

[27] Values was assumed to be in 2003 (matching the year of the Blackout) as it was not explicitly stated in the original source

associated with such large-scale events. As with previous calculations, we scaled system-wide benefits by the share of the system with PMUs over time.

Generator Model Validation Savings

All experts indicated that PMUs/GPS have also reduced the cost of generator model validation testing. RTI estimates that from 2010 through 2017 PMUs have helped power plants save approximately $3.1 billion ($2017) on model validation test costs.

This estimate is based on the following inputs and assumptions:

- PMUs save an average of $400,000 per model (approximately $431,700 in 2017 dollars) validation test according to (Yang & Kosterev,[28] 2012) through reduced labor costs and reduced generator downtime.

- Every generator model in the country must be validated at least once every 5 years per NERC standards (NERC, 2017).

- The population of generators from 2013 through 2017 that require model validation tests (>20 MVA) was approximately 7,000 (EIA, 2018b) (see Table 6-7). Apparent power (MVA) units were calculated by dividing the generators' nameplate capacity (MW) by their nameplate power factor. (Note: Values for the years 2010 through 2012 were estimated by averaging the total population of generator values between 2013 and 2017 because we lacked readily available data on generator power factors for these years).

- The rate of deployment of PMUs since the passage of the ARRA serves as a proxy to estimate the number of utilities using them to validate generator models.

Table 6-7. Generator Model Validation Savings

Year	Rate of Deployment of PMUs as a Percentage of the Nation's Grid (%)	Number of Operable Generators in the United States (>20 MAV)	A Fifth of All of the Generator Models Were Validated (Model Validation Occurs Every 5 Years)	Final Estimated Number of Generators that Have Undergone Model Validations Using PMUs	Total ($ million)
2010	10	6,975[a]	1,395	144	62.3
2011	20	6,975[a]	1,395	284	122.7
2012	50	6,975[a]	1,395	696	300.8
2013	64	7,141	1,428	917	395.8
2014	82	7,124	1,425	1,163	502.0
2015	95	6,978	1,396	1,326	572.5
2016	100	6,827	1,365	1,365	589.6
2017	100	6,804	1,361	1,361	587.6
Total					**3,133.3**

[a] Because of the lack of readily available up-to-date data, RTI estimated these figures by averaging the values from 2013 through 2017.

---

[28] Values were assumed to be in 2012 to match the date of release of the original source.

Summary of Retrospective Quantitative Impacts

Table 6-8 shows the combined annual impacts from the four benefit categories we quantified. Total benefits from 2010 through 2017 sum to be around $15.7 billion; the annual benefit in 2017 is $1.5 billion.

Table 6-9 presents an upper and lower bound range around the point estimate of $15.7 billion in benefits. The range is based on the upper and lower bounds of the impact estimates. For example, the reduction in the frequency of outages was cited to range from 1.5 to 2.0%. The point estimate was calculated using the midpoint of 1.75.

Table 6-8.   Total Benefits Quantified

| Year | Savings from Reduction, Power Outages ($ million) | | | Generator Model Validation Savings ($ million) | Total ($ million) |
	Frequency of Routine	Duration of Routine	Probability of Large-Scale Outage		
2010	217.5	183.1	9.0	62.3	471.9
2011	763.1	642.6	17.8	122.7	1,546.2
2012	2281.7	1,921.5	43.6	300.8	4,547.6
2013	701.1	590.4	56.1	395.8	1,743.4
2014	797.1	622.9	71.3	502.0	1,993.3
2015	642.3	540.9	83.0	572.5	1,838.7
2016	740.0	622.9	87.3	589.6	2,039.8
2017	474.5	399.7	87.3	587.6	1,549.1
Total					**15,730.0**

Table 6-9.   Upper and Lower Bound Estimates of Retrospective Benefits

Benefit Type	Low ($ million)	Point Estimate ($ million)	High ($ million)
Frequency of routine power outages	$5,672	$6,617	$7,562
Duration of routine power outages	$3,715	$5,572	$7,430
Large-scale power outages	$351[a]	$455	$560[a]
Validation of generator models	$783[b]	$3,133	$5,483[b]
Total	**$10,521**	**$15,777**	**$21,035**

[a] Upper- and lower-bound estimates were based on MISO (2015) annual benefit estimates.

[b] Upper- and lower-bound estimates were based on low and high estimates of the economic effects of PMUs on the validation of generator models shown on NASPI methodology report (NASPI 2015)

6.4 Potential Impacts of a 30-Day GPS Outage

In the event of an unexpected failure of GPS and all other Global Navigation Satellite System (GNSS) systems, all industry experts agreed that the impact on the grid would be minimal and the country would not experience sudden or immediate system-wide outages as a result. The unlikely scenario of a widespread loss of power comes from the fact that all the applications for which utilities are currently using GPS capabilities through PMUs are not considered to be critical for the operation of the grid. Although PMUs' main use, precision timing, gives operators and utilities the ability to time-stamp events by synchronizing elements of the grid to UTC time with high precision, the industry is not yet implementing such capacity to perform control operations. Experts entertained a 5- to 10-year time frame but could not provide costs because those vary by utility. In addition, as it currently stands, most devices in the grid do not rely on time synchronization to operate.

6.4.1 Qualitative Discussion of 30-Day Outage

As described in detail in the previous sections, the primary way in which utilities are currently employing time stamps is to perform post-event and forensic analyses to understand the behavior of the grid and prevent future equipment and power failures. Beyond time stamps, utilities are also leveraging PMU data to tune up models and develop more accurate generation estimates. With these applications as a backdrop, the main consequences of losing GPS would almost solely be reflected in an increase in the difficulty of managing the system and responding to outages efficiently and in a timely manner.

While problematic, the consequences derived from a scenario in which time stamp and modeling applications are not present pose no existential risk to the electric grid. In other words, generators will not trip off, and T&D operations will not stop functioning if GPS satellite communications fail unexpectedly.

PMUs themselves have a built-in backup feature that enables them to maintain holdover for several days. Although this holdover will start gradually degrading after several days, it will give utilities enough time to adjust to the absence of a standard global time by, for example, manually calibrating the time.

During this adjustment period, the industry could fall back on devices that are not PMUs but possess PMUs' functions such as relays and digital and dynamic disturbance recorders. However, one of the drawbacks associated with some of these non-PMU recorders is that, even though they have local time, they do not have timing synchronized to the time standard, making it difficult to put together all the data associated with the time at which events occur. Utilities could also turn back to SCADA, the monitoring system distributed across the grid that enabled operators to visualize the grid before PMUs were available. While SCADA does rely on GPS to a certain extent, its fundamental operations will not be jeopardized by a GPS failure. That said, SCADA time stamps are considered to be significantly slower than those provided by PMUs. When also taking into consideration the limitation of non-PMU recorders, it becomes clear that some loss of efficiency would undoubtedly materialize during the loss of GPS satellites.

The precision timing application in which such loss of efficiency will be reflected the most is phase angle measurement. As referenced before, to compare and synchronize phase angle measurements in different parts of the grid, utilities need microsecond levels of precision that were not possible with the SCADA

system. The deployment of GPS with its inherent precision-timing capabilities, its ability to reference UTC time, and its country-wide reach was the factor that enabled utilities to perform these operations with the time requirements they needed.

In the event that the GPS signals that PMUs rely on fail, two scenarios could potentially take shape. In the first scenario, if utilities are either prepared for or aware of a GPS failure that could seemingly go on for weeks, they could turn on their failure mode to deliberately disregard or flag any data coming from PMUs. In the second scenario, if GPS unexpectedly fails, utilities would not know that the measurements being provided by PMUs are not correct. Then after becoming aware of this failure, operators would not be able to trust those measurements, thereby rendering them useless.

Although the industry has been trying to develop clocks that could serve as viable alternatives for performing these measurements, a perfect backup capable of performing these operations with the same level of precision as that provided by GPS does not yet exist. Unable to rely on PMU measurements and having GPS as their only readily available source of standard time, utilities could ultimately lose the ability to continue using phase angle measurements.

Besides the potential loss of phase angle measurement, an unexpected failure of GPS could also lead to other efficiency losses associated with situational awareness such as power generation dispatch estimates. If power suppliers stop trusting the accuracy of PMU data because of a GPS failure, companies relying on their data for wide-area visibility would need to adjust their generation dispatch estimates to be slightly more conservative. However, in spite of the loss of efficiency derived by this adjustment, more conservative estimates would also increase the level of flexibility associated with power generation because suppliers would have to increase their reserve margins. As stated by an industry expert, *"companies that depend more on analyses [of power generation data] and end up adjusting generation dispatch estimates to be a little more conservative would also be more tolerant to different events that could happen in the future,"* explaining that *"the closer you get to the optimum level of generation, the less room you have for unexpected risks."*

Finally, the remaining application area for which PMUs are being used, generator model validations, will not face an immediate impact from a GPS failure. Per NERC regulations, such validations only have to be done once every 5 years, giving utilities more than enough breathing room to adjust to their new situation. Should the time frame of a GPS failure coincide with the exact point in time in which plants must validate their models, immediate adjustment will come in the form of hiring more engineers to collect the necessary data.

Another scenario in which the loss of GPS could immediately become apparent is if one or more environmentally caused outages occur in parallel to the positioning system failure. In this situation, experts highlighted that it would become difficult to find the exact location where the faults occur to quickly send crews to make the necessary repair. The longer it takes for utilities to restore power, the longer the duration of the outage(s) will be, which, in turn could worsen the economic impact of natural disasters.

Beyond these scenarios, the remaining plausible consequences of a GPS failure will materialize within the context of a heightened state of uncertainty and an increase in the probability of outages derived from the preventive capabilities of PMUs.

6.4.2   *Quantitative Costs Associated with 30-Day Outage*

RTI estimates that a 30-day outage of GPS would result in an increase of approximately 877,000[29] customer outage hours because of an increased frequency of outages and an increase in approximately 739,000[5] customer outage hours because of an increased outage duration. As shown in Table 6-10, the result would be an economic cost of $274.8 million ($2017), with the bulk of the loss accruing to the commercial sector. Table 6-11 provides the upper- and lower-bound estimates for the 30-day failure benefits, which range from $211.6 to $338.0 million.

Table 6-10. Economic Loss Associated with a 30-Day GPS Outage

	PMU Cost Saving Benefits, Sector ($ million)			Total ($ million)
Time Window	**Residential**	**Commercial**	**Industrial**	
Increased frequency	$2.8	$121.2	$21.2	$149.2
Increased duration	$2.3	$105.4	$17.9	$125.6
Total				**$274.8**

Table 6-11. Range for 30-Day Failure

Benefit Type	Low ($ million)	Point Estimate ($ million)	High ($ million)
Frequency of routine power outages	$127.9	$149.2	$170.5
Duration of routine power outages	$83.7	$125.6	$167.5
Total	**$211.6**	**$274.8**	**$338.0**

---

[29] The increase in the frequency of customer outage hours was derived by multiplying the estimated amount of routine outages that could be prevented using PMU technology, or 1.75%, by a one month estimate of the annual average customer outage hours that have occurred in the United States between 2010 and 2017. For its part, the increase in the duration of customer outage hours was calculated using the approximate 1.5% reduction in the duration of outages that PMUs have enabled by a new 1-month customer outage hours estimate calculated taking into account frequency results to avoid double counting.

6.5   Notes on Technology Transfer

Government laboratories and funding have played an important role in the development, deployment, and adoption of PMUs. In the mid-1960s, power system operations and wide-area measurements had become an important area of research as a result of the blackout of 1965 in the U.S. Northeast and the resulting need to make power systems more secure. However, it was recognized that the technology of the mid-1960s was not capable of allowing simultaneous measurements with high data rates Phadke (2002). When GPS began to be fully deployed in the early 1980s, it was regarded as the most effective way of synchronizing power system measurements over great distances (Phadke & Thorp, 2008).

After decades of research that gave way to important technological milestones in the development of the underlying technology of PMUs, the first prototype was developed in 1988 by researchers from Virginia Tech (Phadke, 2002). Over these years, their efforts were supported by American agencies including the U.S. Department of Energy (DOE), EPRI, and NSF, all of which provided principal funding for the early development of PMUs.

Upon development, PMUs were then tested by BPA, American Electric Power, and New York Power Authority, utilities that also provided funding for specific research in applications of PMU measurements regarding system protection and problem control (Phadke, 2002). These initial installations were followed by the manufacturing of the first commercialization-ready PMUs by Macrodyne in 1991, which were based on the prototype developed by Virginia Tech (Phadke, 2002; Energetics, 2016).

In collaboration with the two Power Marketing Administrations, DOE launched the Wide Area Measurement Systems in 1995. Through this project, the first synchrophasor network was funded and deployed to provide a wide-area measurement and monitoring system to enhance real-time situation analysis (Energetics Inc, 2016). For the duration of the project, experts from western utilities, BPA, EPRI, Western Area Power Administration, and DOE National Laboratories, including the Pacific Northwest National Laboratory (PNNL) and the Oak Ridge National Laboratory, collaborated to address many of the project's technical goals such as evaluating the then cutting-edge technology applicable to wide-area measurements and developing instrumentation and requirements for relevant power system applications (Mittelstadt et al., 1996).

In parallel, the Institute of Electronic and Electronic Engineers (IEEE) published Standard 1344-1995, the first standard for synchrophasors, which required less than 1 μs error in timing. During the interviews we conducted, an expert from the academic sector highlighted the important role that NIST played in the development of synchrophasor standards. In conjunction with DOE, the IEEE Power and Energy Society, Power System Relaying Committee (PSRC Working Group H11), and BPA's synchrophasor lab, NIST developed test methods for PMUs in 2005. In 2011, IEEE SA published C37.118.1-2011 IEEE Standards for Synchrophasors Measurements for Power Systems, which included several performance limits based on testing actual and simulated PMUs at NIST and dynamic tests developed by NIST and BPA (Goldstein, 2014). In this regard, BPA in collaboration with PNNL had for more than a decade developed laboratory testing technology supporting the Western Electricity Coordinating Council certification of PMUs. In addition to this testing technology, the creation of the C37.118 also leveraged NIST's "Static

Calibration and Dynamic Characterization of PMUs" tests aimed at characterizing PMU performance (Huang et al., 2008). These collective efforts were consolidated by the NASPI Performance and Standards Task Team, supported in part by DOE's Consortium for Electric Reliability Technology Solutions (Huang et al., 2008).

Experts also highlighted the pivotal role that NASPI played in the evolution and deployment of PMUs. Created in 2007, NASPI served as one of the first efforts by the federal government to modernize the country's power grid. This initiative was a collaboration between the electric industry, academia, and government agencies, including NERC and DOE, to accelerate the development and deployment of PMUs across the grid (NERC, 2010). Some of the activities undertaken by NASPI Working Groups included

- developing tools to support the assessment of system performance;

- deploying tools enabling the monitoring of real-time power grid operations;

- creating reports of synchronized measurements and performance guidelines; and

- developing communication and storage infrastructure for data from PMUs and establishing and maintaining contact with organizations working on PMU research, development, and demonstration activities (NASPI, 2012).

Although this initiative has been funded by several different sources since its conception, ARRA of 2009 was among the organization's top and most important financial contributors (Beau et al., n.d.). This legislation spawned the Smart Grid Investment Grant (SGIG) Program, which provided federal financial assistance to 99 projects elaborated by electricity providers to upgrade their systems (smartgrid.gov, n.d. (a)). Of those 99 projects, 14 were dedicated to the advancement and spread of synchrophasor technologies across 12 different states. Together, the 14 awards totaled almost $425 million in federal funding assistance, an amount that was used as a matching fund to cover up to 50% of project costs (smartgrid.gov, n.d. (b)).

NASPI served as a forum for ARRA SGIG recipients, industry experts, and government officials from NERC and DOE to solve problems, develop new techniques and standards, and share information and lessons learned (smartgrid.gov, n.d. (c)). For instance, DOE, in partnership with the electric industry, started developing a standardized communications network design aimed at supporting synchrophasor data collection and sharing (NERC, 2010). Subsequently, a NASPI team created NASPInet, a data architecture encompassing phasor gateways and a data bus that was to be integrated into the users' enterprise IT infrastructure. This architecture was created with the purpose of improving the interoperability and performance of synchrophasor systems. Later, elements of it were implemented on most of the newest SGIG projects (NERC, 2010).

6.5.1   *Technology Transfer Moving Forward*

Government laboratories and organizations continue to be active in the research needed to further integrate PMUs into the electricity system. Many of the experts interviewed believe that the real benefits from GPS-based PMUs are yet to be realized. For example, to fully integrate PMUs and enable real-time

system control, advances need to be made in several areas. A 2017 report drafted by members of PNNL, NIST, and NASPI provided a structured set of terminology required to describe the accuracy, reliability, and timeliness of PMU data. The ultimate goal of this report was to set a common and consistent language associated with output quality to bring forth better solutions to PMU data quality issues (NASPI, 2017).

In addition, government research continues on resilience to GPS spoofing to protect this critical infrastructure and avoid catastrophic events. This research includes ongoing government efforts related to developing testbeds, advancing proofs of concepts, and developing standards and protocols related to the issue. For example, NIST's ongoing Power Quality Measurements and Fault Detection and Identification program is developing research and proof-of-concept investigations into the underlying principles of power grid protection strategies that incorporate synchronized phasor measurements. The project leverages the NIST smart grid testbed resources to develop strategies to enhance grid protection.

6.6   Future Applications

Beyond the applications GPS is supporting today, electric utilities have not yet fully realized the full potential of PMUs. Even though full grid coverage of PMUs basically occurred around 2015, experts stated that PMUs are not being used as much as they could, given the current state of knowledge regarding their capabilities. To some extent, this reality is the result of a latent sense of risk aversion present across the electric industry. When it comes to the day-to-day operations of the grid, few want to be the ones responsible for making a decision that could cause a failure.

Today, there is still a desire by utilities to perform certain key activities such as control operations manually rather than automatically. In addition, current cyber rules impede the use of PMUs for these types of operations. But, as the grid continues on its current path of modernization, the role of GPS and PMUs as it pertains to time synchronization and real-time control operations will become more important. Acknowledging this trend and given the security concerns associated with GNSS, utilities are preparing themselves by ensuring that isolators can maintain enough holdover for a period of time longer than current levels. At the current pace, experts estimate that it would take about 5 years to implement less vulnerable timing synchronization systems, just in time for the projected 10 years they also estimate it will take for timing to be regarded as critical as other components.

Experts were asked about the use and/or importance of developing a potential backup system to GPS, such as eLoran. All experts thought the electricity sector would welcome a backup system such as eLoran in that it could support the highly accurate time-stamp needs provided by GPS. However, there was less consensus on what (if anything) the sector would be willing to pay for such a service. Estimates for a large utility varied greatly from $10,000 to $100,000 per year for an eLoran service.

6.7   Concluding Remarks

Together, the electric industry and the U.S. government have invested over $8 billion to modernize the nation's electricity grid (smartgrid.gov, n.d.). In addition to the SGIG spawned by the ARRA, investment in PMUs was made possible by the ubiquitous and low cost of GPS signals, which provide precision timing and synchronization for the electricity system where electrons flow at close to the speed of light.

This study estimates that the return on this investment is approximately $15.7 billion since 2010 and, at a minimum, should generate an additional $5 billion annually moving forward.

Although GPS-based PMUs are not used in real-time operations of the electricity system, they do provide valuable information that has helped harden the grid to events, speed up fault detection, and enhance generation model verification. Industry experts interviewed as part of this study confirmed these technical and economic impacts.

Although the core concepts and technologies underlying the PMUs were primarily developed at U.S. universities, government laboratories were instrumental in the testing, validation, deployment, and integration of PMU applications in the current electricity system. And there was strong consensus among experts that in the absence of the availability of GPS PMUs would not have been deployed and the future benefits of a smart grid system would be greatly in question.

GPS-based PMUs are not currently being used for real-time operation of the electricity system. For this reason, a 30-day failure of GPS would not significantly affect grid operations and hence would have a relatively modest economic impact (estimated to be about $274.8 million). However, the future potential of greater integration of PMU capabilities into the operations of the electricity system implies that the returns on the U.S.'s investments in GPS and PMUs have potential to significantly increase in the future.

7. Financial Services Sector

The financial services sector uses GPS to time stamp financial transactions. GPS's timing capability allows exchanges and trading houses to cost-effectively time stamp every transaction request received in keeping with the precision required by financial regulations.

However, experts who specialize in the intersection between precision timing and financial services note that a number of alternatives to GPS meet or could have met the precision timing requirements specified by U.S. Securities and Exchange Commission (SEC) regulations and industry standards. Alternatives include a system of networked atomic clocks, network time protocol (NTP), or Loran.

GPS was adopted because the signal was ubiquitous, convenient, and inexpensive to acquire. The high level of timing precision (5 to 10 ns) was not the driving factor for adoption. As such, it is unlikely that there would have been any delay in notable industry advances, such as high-frequency trading (HFT) if GPS has not been available. Retrospective economic impacts associated with GPS for the financial services sector, relative to available alternatives, are estimated to be negligible.

In the event of a 30-day GPS outage, financial markets would need to adjust, but operations would be minimally affected. Most exchanges and sizable trading houses have rubidium or cesium clocks that can provide sufficient holdover to continue operations. Although the financial services sector views the falsification of GPS signals, or spoofing, as a significant concern because it can affect data reliability, sector representatives do not view an observable loss of GPS for 30 days as having a substantial economic impact.

7.1 Sector Introduction and Overview

The growth in the use of GPS in the financial services sector is linked to the precision-timing regulatory requirements. A main driver of the precision timing has been HFT.

HFT uses statistical algorithms to place and execute large amounts of stock orders within extremely short time intervals. Although the profit per transaction from HFT is often small, at high volumes the approach can yield significant revenue. As of 2012, automated transactions initiated by co-located servers accounted for 50 to 70% of the trading volumes on the U.S.'s major exchanges (Humphreys, 2012).

Throughout the growth of HFT, its use has been controversial. Despite its efficiencies, HFT increases the chances of fraud in the stock market. Larger, faster traders could have advantage over smaller, slower traders (Lombardi, 2015). The difference in size and speed usually translates into much larger trade volumes that could drive up stock prices. This situation creates an incentive to prioritize the transactions of large investors, thereby increasing the likelihood of fraudulent activities. For example, illegal activities known as "front running," in which the transactions of larger and generally faster traders are prioritized over those from small investors to drive up prices and where trading order can be manipulated, become increasingly possible if trades are time stamped by a clock with a resolution of only 1 second or greater (Lombardi et al., 2016). As a result, HFT has been a driving force behind regulations that increase trading time-stamp precision.

Fraudulent activities related to HFT have occurred. A 1996 SEC report concluded that the National Association of Securities Dealers (NASD) and NASDAQ did not consistently operate under their customers' best interests because unchecked collusion was present among market makers and trades were not correctly executed. In an attempt to remedy this situation, NASD issued several rules, numbered as 6950 through 6957 (SEC, 2006) aimed at improving market surveillance and overall operations, including time-stamp precision. Rule 6953, entitled "Synchronization of Member Business Clocks," required all computer systems and clocks on NASDAQ to be synchronized to within 3 seconds of the NIST atomic clock before daily operations begin every business day (Lombardi et al., 2016). This rule took effect in 1998, and the enforcement of identical time requirements spread to the New York Stock Exchange through the adoption of Rule 132A in 2003. Although the 3-second synchronization requirement prompted financial markets to stop using decimal clocks and any other types of clocks unable to display seconds, it was still considered to be somewhat coarse (Lombardi et al., 2016).

In 2008, after NASD had been merged with other entities to form the Financial Industry Regulatory Authority (FINRA), the Order Audit Trail System Rule 7430 required all stock market clocks in the United States to be synchronized to within 1 second of NIST time (Lombardi, 2015). This was done to continue minimizing the probability of fraud.

FINRA Regulatory Notice 14-47, implemented in February 20, 2017, further decreased the synchronization requirement for stock market transactions to 50 milliseconds. However, this is still a relatively modest regulatory requirement when compared with the nanosecond level of precision provided by GPS.

7.2   Sector Applications

7.2.1   How GPS Is Used

In the financial services sector, precision timing has two main uses: time synchronization and latency. Time synchronization makes it possible to determine with a high degree of accuracy the order in which trades and transactions are executed. Latency capabilities deal with the travel times of transactions between two venues located at two different geographic points. GPS enables the fast realization of lengthy measurements, which reduces the time it takes for two or more market participants at different locations to interact with one another.

In addition to helping avoid the front-running issues referenced earlier, synchronization and latency capabilities help exchanges and participants improve their level of coordination, allow for better and more accurate real-time analyses, and meet SEC regulatory requirements. From a regulatory point of view, it is important to have time stamps precise enough to discern causal relationships from one venue to another and any other cause-and-effect relationships between market centers. Assessing this relationship is highly dependent on the geographic distance between the centers. The travel time from one financial location to another typically ranges from 100 to 200 microseconds. Therefore, the timing needed to discern the sequence in which orders are executed must be within or below 100 microseconds. GPS easily enables

time stamps with such precision, providing a direct reference to UTC's authoritative source of day-to-day time.

In the event of the loss of GPS reception, most exchanges and trading houses have backup systems to ensure time-stamp accuracy and avoid sending incorrect data with potential time errors. These systems often include a rubidium clock capable of maintaining relatively accurate time should a temporary failure of GPS occur. When GPS is temporarily disrupted, these rubidium clocks are prepared to "run free," or undisciplined, to maintain the correct time. Using these clocks is also referred to as going into "holdover" mode. In the short term, the frequency stability between UTC and undisciplined rubidium clocks is virtually the same. However, the undisciplined rubidium clocks start drifting after about 1,000 seconds and will deteriorate to approximately 1 microsecond synchronization after several days (Lombardi et al., 2016). As described in the following section, this level of drift would likely not affect trading over a 30-day GPS outage.

7.2.2   Trading Activities Supported by GPS

Table 7-1 presents the main trading applications that require time stamps and the level of precision needed in terms of maximum divergence from UTC. For example, HFT requires the highest level of precision at 100 microseconds. Other trading activities typically require significantly less precision.

Table 7-1.   Finance Sector Precision Timing Uses and Needs

Type of Trading Activity	Maximum Divergence from UTC	Benefits: Qualitative Description	Counterfactual	Technical Impact Metric	Economic Value Metric	Potential Magnitude of Impacts
HFT	100 µs	It enables stock exchanges to handle many thousands of trades within a 1-second interval	Dedicated precision timing system (atomic clocks) for financial services sector	Bid/ask spread was down to 3 points in 2014 (from 90 points 20 years before)	Economic value of HFT (in terms of liquidity and arbitrage)	High
Voice trading	1 s	Primarily used to confirm order receipts, discuss current and future market conditions, trade performance, and allocation instructions	NIST time/broadcast	No impact on trading activities	Cost of non-GPS timing system	Low
Request for quote system	1 s	Provides the bidder with important information about the requirements of a specific task or project	NIST time/broadcast	No impact on trading activities	Cost of non-GPS timing system	Low

(continued)

Table 7-1.   Finance Sector Precision Timing Uses and Needs (continued)

Type of Trading Activity	Maximum Divergence from UTC	Benefits: Qualitative Description	Counterfactual	Technical Impact Metric	Economic Value Metric	Potential Magnitude of Impacts
Negotiated transaction	1 s	Companies can buy or sell assets and other companies	NIST time/broadcast	No impact on trading activities	Cost of non-GPS timing system	Low

Source: Gopalakrishnan (2016).

Although HFT represents the majority of transactions, it is by no means the only transaction mode used. Voice transactions are still widely used in the daily operations of financial exchanges. The role of voice communications in the market is important given that institutional investors still execute "single-stock" trades, also known as "high-touch" channel trades, via telephone. Financial products such as "swaps" are considered to be more complex, reason why their transactions are still conducted via telephone by a large number of trading professionals (Groenfeldt, 2016). For these types of transactions, reliable time stamping is important, but the required level of precision is low.

Another financial mechanism requiring time stamping is the request for quote (RFQ), a type of procurement solicitation whereby companies ask outside vendors to offer a quote to help them complete a task, such as purchasing a sizable amount of a specific product (Titton, Ratanaubol, & Teach, 2016). Given that an RFQ focuses mostly on pricing and many bidders may provide different price quotes at different times, correctly recording the specific time at which the bids are made is necessary. In a similar vein, when companies undertake negotiated transactions to purchase and sell or when auction processes between buyers and seller take place, reliable time stamping is required.

However, again, for all of these non-HFT trading activities, the level of precision required is only around 1 second.

7.3   Methodological Notes

Our approach to assessing the economic impacts builds on the financial services sector's precision timing needs, determining which needs GPS is currently meeting, and determining what alternative precision timing systems are, or could be, available. We conducted initial scoping interviews to identify preliminary hypotheses regarding the counterfactual scenarios and the potential technical impacts. The preliminary assessment was then verified/refined through more extensive interviews with industry experts.

7.3.1   *Approach for Quantifying Retrospective Benefits*

In the absence of GPS, the financial services sector would have almost certainly developed an alternative time-stamp system. For example, it is possible that exchanges and large trading houses would have used available technologies such as network time protocol (NTP) in conjunction with their existing network of atomic clocks and time distribution systems. NTP can be used to synchronize all computers to within a few milliseconds of UTC. One expert also said that the industry could have used line cording between two locations with cesium clocks on each end. Alternatively, it is plausible that an enhanced Loran system

would have been developed to provide the precision timing needs of the financial services sector (as well as other sectors). Using an enhanced Loran system would likely have been the least-cost approach for meeting precision timing needs, and this is the primary counterfactual from which potential impacts were analyzed.

An important part of our analysis was also to assess whether the market penetration of HFT would have been delayed or affected had GPS not been available and a less precise Loran system had been used instead. (Note: we also recognized that HFT was primarily driven by advances in computing power and speed.)

7.3.2   *Approach for Quantifying the Potential Impacts of a 30-Day Outage*

As mentioned earlier, in the event of an unanticipated 30-day GPS outage, trading locations would rely on their backup systems to provide accurate synchronization capabilities. These backup systems typically include high-quality oscillators, such as rubidium or cesium atomic clocks, capable of providing highly precise time (Lombardi et al., 2016).

However, HFTs are programmed to withdraw from the market as soon as any time-stamping irregularities are detected. This means that if the precision of transaction time stamps were affected in some way algorithmic traders should automatically stop executing any operations (Humpreys, 2012). Thus, it is possible that after a complete absence of GPS signal for a period longer than the backup systems can handle, financial exchanges would resolve to shut down HFT transactions, given their inability to accurately time stamp the trades of these high-speed transactions. Should this voluntary shutdown not occur, regulatory agencies have the authority to step in and order exchanges to shut down to avoid financial disarray and potential fraud associated with time-stamping inaccuracy.

During interviews with industry experts, we investigated if backup timing systems in existence today can provide the required precision to maintain trading over the 30-day window. We also investigated if the traceability of different entities' backup timing systems within the financial services sector would be an issue.

7.3.3   *Interviews with Industry Experts*

We interviewed experts throughout the financial services sector to investigate both the retrospective impact of GPS never having been available and the impact of a 30-day unexpected failure of GPS. Table 7-2 presents the target population groups and the topic areas and example questions covered during the interviews. Note that interview topics were not restricted to the bullets associated with each target group but were expanded to include all topics that matched interviewees' areas of expertise. Also listed are the types of firms and organizations targeted for the interviews. However, the entities listed in the table are not necessarily those we interviewed. The sources of the information presented in the results section have been kept confidential.

Table 7-2.   Target Population for the Financial Services Sector Interviews

Target Population Groups	Example Target Companies/Organizations[a]	Topic Areas/Questions
Exchange operators and trading firms	▪ Large and small trading firms ▪ NASDAQ ▪ IEX Group	▪ System efficiency gains from GPS's level of timing precision ▪ Pervasiveness of backups systems such as rubidium clocks ▪ Holdover and what would happen after the "several days" backup window is exhausted ▪ Impacts on HFT in terms of decreased transactions ▪ Reliance of non-HFT financial services on GPS technology
Equipment manufacturers, product providers	▪ Juniper Networks ▪ Orolia ▪ Microsemi ▪ PICO Trading	▪ Holdover and what would happen after the "several days" backup window is exhausted ▪ Pervasiveness of backups systems such as rubidium clocks
Financial regulators	▪ NASD ▪ SEC ▪ U.S Commodity Futures Trading Commission (CFTC)	▪ Financial or regulatory penalties for not complying with FINRA rules ▪ Stopping or limiting HFT during prolonged time-stamping irregularities or failure
Risk assessment experts	▪ Authors of studies ▪ Academic experts ▪ Consulting companies ▪ Department of Homeland Security	▪ System efficiency gains from GPS's level of timing precision ▪ What are the alternative precision timing systems? ▪ Current level of preparation of financial markets for a 30-day GPS failure

[a] All the companies/organizations listed in the table were contacted; however, not all participated in the interviews.

A total of 30 experts were identified and contacted, and 15 (50%) agreed to participate in the interview process. The majority of the experts interviewed were from exchange operators and trading firms.

After completing the interviews, we compiled and analyzed all responses to assess the counterfactual and potential impact of GPS timing services. As shown in Table 7-3, there was consensus that GPS provides a valuable service to the financial services sector, but in its absence alternative sources of precision timing would have been available and backup systems today have sufficient holdover to cover a 30-day outage.

Table 7-3.   Impact of GPS in the Financial Services Sector (%)

	Is GPS the Primary Source of Precision Timing?	Would Alternatives to GPS Been Available?	Would Loran Have Been an Adequate Substitute System?	Would HFT Have Evolved Differently in the Absence of GPS?	Would a 30-Day Failure of GPS Affect Trading Today?	Is Today's Backup Systems' Holdover Adequate for 30 Days?
Yes	100	100	60	0	0	100
No	0	0	40	100	88	0
Maybe	0	0	0	0	12	0

7.4   Retrospective Economic Benefits Analysis

While a variety of factors prompted the industry to gradually adopt GPS-based timing, all experts agreed that if GPS had not been available the industry would have met its time-stamp needs via other approaches with little to no additional cost. The sector would have used available technologies such as NTP over the internet or Loran-C (if nationally available), in conjunction with their existing backup system of atomic clocks, to meet their timing needs.

Experts noted that precision timing to support time-stamps requirements has been around for decades. Before the use of GPS, the sector used timing sources such as the old Geostationary Operational Environmental Satellite system, NTP, and the internet, which enabled them to reference time back to UTC. Others pointed out that the industry could also have relied on a fiber-based system instead as it was rolled out. As stated by one expert,

> *Had GPS not been there, the industry would have probably obtained timing through fiber, and then improved upon it. They would have figured out a way to better the fiber connection to lower fluctuations and achieve more precise training of the isolator.*

Others stated that the industry would have figured out a way to use the Iridium Satellite constellation to get time close to the 100-microsecond level of precision they need. One expert stated that if GPS had not been available but other satellites were, exchanges would have used atomic clocks and a two-way satellite transfer between NIST and the underlying clock system. Once a month or during periodic time intervals, these transfers would have been calibrated, which would be sufficient to compensate for drifts occurring over time. Experts highlighted that purchasing a few additional atomic clocks would not be an issue for firms because it would require only a small amount of investment relative to their total revenues.

Although experts regarded Loran-C as a potential alternative, they were more uncertain about its potential because of concerns about coverage limited primarily to coastal areas. However, others stated that Loran's development and use could have been accelerated and expanded to include cities such as Chicago that are home to the nation's biggest exchanges.[30] A final possibility offered was that NIST could have maintained more time servers or set up a WWBD transmitter in an important location like New York.

There was also widespread consensus that the evolution of HFT would not have been delayed. At its core, HFT relies on processing power and speed. Although algorithms are fast, they are not highly synchronization dependent.

Adoption of alternative precision timing approaches could have been more costly; experts indicated that these costs would have been modest and insignificant for the financial services sector. Under the counterfactual scenario of an expanded Loran system, experts believe most precision timing needs could have been met. There may have been some additional investment in atomic clocks, but these are already in place today as backup systems should GPS service be interrupted. Thus, it is unclear how many additional clocks might have been required.

---

[30] Note that our primary counterfactual is that in the absence of GPS Loran system coverage would have been expanded to fully cover the United States.

In summary, we conclude that if GPS had not been available there would have been negligible impact on the service offerings, efficiency, and operating costs of the financial services sector. As a result, we did not quantify any retrospective benefits for this sector.

7.5   Potential Impacts of a 30-Day GPS Outage

In the event of a 30-day outage, all experts agreed that the nation's financial operations would not be significantly affected, and trading on the markets could continue largely uninterrupted. The absence of any major impact is because GPS is an enhancing technology and not an enabling one.

Most backup systems used by financial market participants have sufficient holdover capacity to maintain timing for a 30-day outage window. Backup clocks would lose their connectivity but automatically would start using their internal isolators. Experts stressed that the holdover capacity is adequate. Sometime after the 30-day mark, even the best atomic clocks would start experiencing a drift of around 100 microseconds. At this point, financial market participants would find it harder to comply with current synchronization requirements of 100 microseconds for HFT transactions.

If regulatory requirements did become an issue because of holdover drift, regulators would need to decide whether to shut down a market or adapt to lack of timing precision. The majority of experts stated that regulators and market participants would likely come to an agreement that ensures the integrity of the market at a newly adjusted time-stamping requirement. It was noted that time-stamp accuracy is not a technical or operational issue but a subjective regulatory one that would likely be relaxed as opposed to a drastic and costly decision to stop trading.

Some interviewees pointed out that not all market participants have access to these clocks. Experts stated that some modest-sized HFTs may not necessarily own an atomic clock and may only have a small GPS antenna and receiver. The decision to own only these GPS items may leave such small traders more susceptible to a GPS failure. However, the temporary absence of a few smaller traders during the 30-day window would not significantly affect the overall functioning of the market.

In fact, experts stated that if some HFT firms were to drop out of the market immediately after a GPS failure, they would likely get back online within a day or so. This return can be attributed to the resourcefulness and adaptive capacity these traders are perceived to have, which experts underscored would enable them to adapt to their new circumstances upon becoming aware of the GPS outage.

While not causing an interruption of financial trading, an expert pointed out that the loss of GPS may cause some trouble to bank servers. Currently, banks manage and rely on thousands of servers that periodically generate logs that require accurate time stamps. There is an assumption that the time stamps in those log entries are correct and aligned, and to ensure that time stamps are always correct and aligned, servers are pegged to NTP. Immediately after GPS goes away, some of the clocks used by banks will start ticking at different rates. While some clocks may go faster, others may go slower. However, to maintain the integrity of time stamps relative to one another, banks would have to pick one single clock, regardless of whether the chosen clock is correct. Ultimately, big banks with thousands of servers across the world would find it difficult to coordinate them all because clocks would inevitably start to drift.

Given the large realm of backup options, the impact of a GPS failure on the overall market in terms of trading volume and market efficiency would be imperceptible. Thus, we did not quantify 30-day GPS outage impacts for this sector.

However, as regulatory bodies across the world continue to require more precision, experts said that the financial industry will become more dependent on globally synchronized timing. As the dependence on GPS increases, all experts agreed that 5 years from now answers to questions regarding a GPS outage scenario could be more worrisome and trading venues could face more risk.

7.6   Concluding Remarks

Over the last several decades, fundamental changes regarding how financial transactions are conducted have increased the need for more precise timing. With the advent of HFT, having a reliable reference to an authoritative source of time such as UTC has become a priority for exchanges and trading firms alike. Because of the ever-larger volume of transactions that occur in less than 1 second, regulatory bodies have also tightened their time-stamping requirements to ensure the integrity of the market.

To meet these requirements and achieve precise time synchronization, the industry has been relying on the precision timing services provided by GPS. However, all experts interviewed agreed that if GPS had not been available to the financial services sector, adequate alternatives are or would have been available. In addition, experts agreed that backup systems with sufficient holdover are in place so that a 30-day outage would not interrupt transactions substantially.

At this time and relative to available alternatives, we conclude that a loss of use of GPS will not yield meaningful economic impacts to the financial services sector, although a free, ubiquitous signal provides convenience.

8. Location-Based Services

GPS chips in smartphones and other consumer devices receive satellite signals and generate precision location information that software applications use to deliver services and experiences to users. Apps help users navigate, learn what or who is nearby, track location in real time, check in and interact, play games, and enjoy experiences tailored to their geographic position (Spiekermann, 2004; Ryschka et al., 2016). There is a public safety component as well. Enhanced 911 (E911) automatically provides a caller's location to 911 dispatchers, shortening response times for emergency assistance.

The location information needed for location-based services (LBS) to operate is obtained from a combination of GPS, Wi-Fi hotspot, and cell towers. However, GPS is often the most critical of these. LBS would be far less precise without GPS, which could undermine some applications' utility. For example, without GPS, navigation systems could not accurately track a driver's position and deliver live turn-by-turn directions.[31] Similarly, E911 would be limited to less precise cell tower triangulation only.

In this case study, we quantify the benefits GPS-enabled LBS generate for users (e.g., driving times reduced by turn-by-turn directions) and society (e.g., air pollution reduced by shorter driving times). We estimate that GPS-enabled location services for smartphones and consumer devices generated about $218 billion in private and public benefits between 2007, the first year for which we could reliably calculate benefits, and 2017. Under the forward-looking assessment of a 30-day outage, we estimate that losses would total $2.9 billion.

Our estimates are likely conservative estimates because data limitations meant that we were unable to monetize all social benefits. For example, because turn-by-turn directions also reduce the number of miles driven, there may be fewer automobile accidents. Emergency services may arrive earlier because of E911. Although we could not monetize benefits such as these, we discuss many qualitatively.

8.1 Sector Introduction and Overview

For the purposes of this study, we considered three types of LBS:

1. <u>Navigation services</u> refer to navigation devices and smartphone applications that provide users with turn-by-turn driving directions and real-time alerts on road conditions.

2. <u>Non-navigation smartphone applications</u> refer to applications that use location information to enhance social networking, gaming, local search, and advertising (see Table 8-1).

3. <u>Emergency services</u> refer to emergency calls from cell phones to be located more accurately through services like E911. GPS also allows survivors to be more accurately located and damage mapped during natural disasters.

---

[31] One way to assist users with identifying their starting place in such apps would be to use cell towers for positioning. This was an approach used in a beta version of Google Maps with My Location, which was temporarily available for smartphones that did not have GPS capabilities (Gohring, 2007).

Table 8-1.   Examples of Smartphone Location-Based Services

Category	Description	Popular Examples
Navigation	Turn-by-turn navigation, real-time route updates, and location services	Google Maps, Waze, MapQuest
Tracking	Users can track family, pets and objects for safety concerns; fleets of vehicles can be tracked, and arrival times estimated	Find My iPhone, Tile, Trackr
Advertising	Businesses can send ads or coupons to users upon entering a store	Starbucks, ShopAdvisor, Shopular
Ridesharing	Cars are directed towards users and navigated using their location	Uber, Lyft, Rydar
Geosocial	Allows users to share their locations with friends, find nearby friends or events	Foursquare, Facebook Check-In, Instagram
Information	Find nearby services, get facts, reviews and information about areas that users enter	Yelp, TripAdvisor, NearMe
Communication	Access to message boards only available to other users in a location, sending geo-tagged images to friends	Yik-Yak, Snapchat, Twitter
Weather	Get accurate, precise weather reports or severe weather alerts	Dark Sky, Arcus, Weather Channel app
Social networking	Finds possible matches based on their proximity to other users	Tinder, OkCupid, and many others
Gaming	Games based on interaction with real-world landmarks, augmented reality	Pokémon GO, geocaching, Zombie Run

8.1.1   Introduction of GPS-Enabled Location-Based Services (1980–2006)

After GPS was first made available for civilian use, except for personal GPS receivers, the few consumer applications of GPS technology that were available were found in luxury items.[32] Further development of LBS occurred after the E911 mandate was passed in 1996. This mandate required mobile network operators to be able to locate emergency callers on mobile phones within a certain degree of accuracy. Most network operators did not have this capability and had to make significant investments to meet the mandate. To generate additional returns, many network operators searched for commercial applications of location technology (Bellavista et al., 2008). Early LBS applications consisted of "finder services," which would upon request return lists of nearby points of interest. Unfortunately, these generated little consumer demand and were phased out soon afterward.

Cell phones and in-car portable devices became popularly available between 1999 and 2001. The first mobile phone with a GPS component, the Benefon Esc!, became available in 1999 (Sullivan, 2012). Around the same time, companies like Garmin and TomTom began offering personal in-car navigation devices that provided turn-by-turn directions.

In the early 2000s, several advances reignited LBS development. Qualcomm developed "assisted GPS," or AGPS technology, which combined GPS signals with cellular signals to provide accurate location to

---

[32] The Mazda Eunos Cosmo was the first production car with a built-in GPS navigation system. It was produced for the Japanese market (Leite, 2018).

users within a few feet (Hampton, 2016). Other key advances included those in chip processing power, miniaturization, memory, graphical interfaces, and 3G wireless broadband. These technologies laid the foundation for LBS for personal devices.

Providers began offering services for fleet management (covered in the Telematics sector), as well as child and pet trackers. Apps that initially used less accurate and reliable cell tower triangulation switched to GPS. Some users, with GPS-capable phones and spreading location technology, began writing simple applications that shared their location data with other users. Many of these early initiatives grew into successful businesses in gaming, health, and marketing.

8.1.2 *Widespread Adoption of Location-Based Services (2007–Present)*

The first iPhone was released in 2007, kicking off production of smartphones with built-in GPS components and providing a platform for location-based apps. Smartphone ownership by American adults has increased from 35% in 2011 (the first year for which data are available) to 77% in January 2017. In January 2017, 92% of 18- to 29-year-olds owned a smartphone (Pew Research Center, 2017). This trend is illustrated in Figure 8-1.

Apps like Google Maps, Yelp, and Foursquare brought LBS to the mainstream. In 2011, approximately half of smartphone owners reported having ever used GPS for directions (Zickuhr & Smith, 2011); by 2012, about three quarters of smartphone owners said they had used LBS on their phones at least once

Figure 8-1.   Percentage of U.S. Adults Who Own Devices

Source: Pew Research Center Mobile Factsheet (2018).

(Zickuhr, 2012). By 2015, 95%, 94%, and 82% of U.S. adults aged 18 to 29, 30 to 49, and 50 or older, respectively, reported having used their phones to get directions, recommendations, or other information related to their location (Anderson, 2016). Consumers' willingness to use these services has also grown: in 2013, 35% of smartphone users reported intentionally turning off the location features on their phone (Zickuhr, 2012), but by 2016, 90% of users left them on (Kaplan, 2016).

Beyond smartphones, the market for portable navigation devices was and anticipated to grow at about a compound annual growth rate (CAGR) of 15% by 2020 (TechNavio, 2016). The automotive navigation market is also valued at $11.3 billion in 2016 and anticipated to grow at a CAGR of 8% by 2025 (Inkwood Research, 2016).

LBS are now integrated into the everyday lives of millions of consumers. They can be a valuable part of one's entire day, from locating car keys in the morning, checking traffic and choosing a faster route to work, to looking up a nearby restaurant for lunch and reading its reviews, getting a geofenced reminder to complete an errand after leaving the office, tracking the route taken on a run, and finding a nearby date (Ryschka et al., 2016).

8.1.3 *Previous Research on Estimating Value of Location-Based Services*

Most data on LBS were developed by market research firms focused on sector trends, size, and growth. Few studies attempt to quantify LBS' economic benefits.

One study by Lohan et al. (2011) took a WTP approach in assessing consumers' valuation of LBS. They asked third-year students at two European universities how much, in addition to their current monthly smartphone costs, they would be willing to pay for various LBS applications. They used a 1 to 5 Likert scale, with values corresponding to a WTP of 0% extra, up to 1% extra, up to 5% extra, up to 10% extra, and up to 25% extra. Out of ten categories, they found these consumers were most willing to pay for emergency and navigation services, with more than 45% of respondents willing to pay up to 25% more for a good emergency location service. Figure 8-2 displays the mean Likert scores for the students' WTP for various LBS application categories.[33]

---

[33] The ten categories were "1) applications related to social interactions and networking (e.g., finding out where own friends are, location-based reminders, etc.); (2) applications related to automatic road tolling and road taxes (e.g., automatically paying the road tolls, based on the used highways, bill sent home); (3) applications related to increased social wellbeing (defined here as: health and fitness advices based on mobility patterns, child or pet tracking, lost item tracking, etc.); (4) applications related to decreased pollution and a more eco-friendly environment (e.g., getting location-based information about congested roads and alternative routes, getting information about average speeds recommended in various zones in order to decrease pollution, etc.); (5) applications related to navigation and route planning (e.g., multimedia guide when visiting a new town, with information updated according to own location, finding out about cultural/sports events nearby); (6) applications related to entertainment/infotainment (e.g., mobile games tailored to own location and/or movements); (7) applications related to natural disasters (e.g., getting information about the probability of an earthquake, a tornado, a Tsunami, etc. at current location); (8) applications related to emergency situations (e.g., getting faster help in the case of a road accident, being informed when a friend/ relative needs emergency help, etc.); (9) mobile advertising (e.g., if someone wants a product in a specialized store, let's say a camera, he or she could receive the offers from nearby shops that are also selling cameras, just by pointing their own camera phone at the wanted product, or just by storing information on their own phone about the searched product); and (10) geo-tagging (e.g., automatically adding geographical metadata, such as location information, to their own digital picture)" (Lohan et al., 2011, pp. 431–432).

Figure 8-2.   Location-Based Services' Significance for End Users

Significance measured as WTP extra compared to current monthly fee; average values: (1) maximum 0% extra, (2) maximum 1% extra; (3) maximum 5% extra, and (4) maximum 10% extra.

Source: Lohan et al. (2011)

Another study by the research firm AlphaBeta quantified the value created by digital maps (AlphaBeta, 2016). AlphaBeta used a willingness-to-accept (WTA) estimate, surveying consumers to find amount of a monthly cash discount on their phone bills that they would be willing to accept to permanently forgo the use of both their preferred digital map service, and all digital map services. Respondents in this survey were offered several options to choose from, including a value they chose to enter. In North America, they found the average user in 2016 would forgo digital maps for $155 per month, cumulating to $43 billion per year ($158 and $43.7 billion in 2017 dollars, respectively).

Our approach differs from these two studies in multiple ways. The Lohan et al. study is based on a survey of students at two European technical universities, while our work is based on a survey of U.S. residents from nationally balanced age groups. It was also designed to assess willingness to pay for several different features of LBS, rather than all LBS itself, and framed its questions in terms of the additional percentage of their existing phone bill the students would be willing to add at 10% maximum, rather than any whole number as we asked. The AlphaBeta study is more similar to our work, but differs in several key ways. First, while our survey generates both a willingness-to-accept and a WTP estimate (see Section 1.2.1 Estimating Private Benefits in this report for details on the difference), we build our estimate from the much smaller WTP estimate. Second, while AlphaBeta's study offered respondents several options of choices, our survey was completely open ended. This likely caused the variances we observe in our responses but also avoided anchoring respondents' choices. Lastly, our approach differs

from AlphaBeta's in that we measure value for all LBS, while AlphaBeta only measures value generated by digital maps (a subset of LBS). Overall, AlphaBeta's report is a helpful contribution to the literature that informs our approach.

8.2   Methodological Notes

The value created by LBS can be divided into two components. First, there are direct benefits that are enjoyed by the users of LBS themselves (i.e., private benefits), such as the efficiency a driver gains from turn-by-turn navigation. Second, there are indirect benefits enjoyed by the rest of society (i.e., public benefits) because navigation services help drivers reach their destination with fewer miles traveled, consuming less fuel, and emitting less pollution.

Below we discuss our approach to estimating private and public benefits. Next, we use these estimates of private and public benefits to consider two different scenarios to better understand the value of GPS to LBS in the United States:

1. <u>Retrospective economic impact assessment</u>: For this scenario, we estimate the benefits that have been generated by GPS-enabled LBS since 2007. As discussed in Section 1.2.1, this was the year the first smartphone was introduced, which began the widespread adoption of LBS.

2. <u>30-day outage economic impact assessment</u>: For this scenario, we estimate the costs of a 30-day, unplanned outage of GPS, which would disable LBS.

Our approach was also informed by qualitative interviews with experts in LBS, whose comments added contextualization to our survey results and use of publicly available data sources.

8.2.1   *Approach for Quantifying Private Benefits*

To estimate private benefits, we conducted an open-ended contingent valuation survey to estimate consumers' WTP for the use of LBS. Data were collected for this survey over a 2-week period in April and May 2018 through a web-based survey platform. A total of 1,973 respondents started the survey. Of these, 1,000 respondents met the eligibility criteria and completed the survey. Eligibility criteria included demographic quotas designed to ensure the sample was reflective of national demographics.

The questions contained in this survey can be divided into four sections. First, respondents were asked whether they use LBS on any devices (Table 8-2). Anyone responding that they do not use LBS was removed from the survey.

Second, respondents were asked a series of questions regarding their age, gender, region and income levels. Answers to these questions were used to establish quotas so that the sample was reflective of the general population of the United States. As a result, some potential respondents (919 total) were removed from the survey after answering these questions, if their demographic was already adequately represented.

Table 8-2.   Use of Location-Based Services on Various Personal Devices

Do you use location-based services on any of the following devices? Select all that apply.	Respondents (%)	N
Smartphone (e.g., iPhone or Android mobile phone)	85.3	1,675
Tablet	32	629
GPS navigation device (e.g., TomTom or Garmin)	27.5	541
Built-in navigation system in a vehicle	19.3	380
None of the above	8.6	169

Note: N denotes the number of positive responses to each question, i.e., users of that device, and not the total to have answered the question.

Third, all remaining 1,000 respondents were asked about the ways they use LBS. Most commonly, they reported using LBS to get turn-by-turn driving directions, search for nearby attractions, and acquire traffic information (see Table 8-3).

In the fourth section, we questioned respondents on the private benefits they receive from using GPS-enabled LBS. We used two approaches for designing questions to measure these private benefits. First, we used a WTP approach in which we asked respondents for the most they would be willing to pay for guaranteed access to LBS. If consumers are rational, this value should reflect all the benefits they receive from LBS, including time saved, fuel costs avoided, personal enjoyment, and convenience (because they would never pay more for the services than the value the services generate).

Second, we use a willingness-to-accept approach in which we asked respondents for the minimum amount they would accept to give up access to LBS. Again, if consumers are rational, we would expect this value to reflect all benefits they receive from having access to LBS (because they would not accept a value that is worth less to them than the value of the services).

Table 8-3.   Ways of Using Location-Based Services

In what ways do you use location-based services? Check any you use at least once a month.	Respondents (%)	N
Turn-by-turn driving and walking directions (e.g., Google Maps)	67.5	675
Searching for nearby attractions like stores or restaurants (e.g., Yelp, TripAdvisor)	65.9	659
Traffic information (e.g., Waze, Google Maps)	51.3	513
Social (e.g., check-in apps and dating apps)	39.7	397
Fitness (e.g., tracking distance walked, run or biked)	36.7	367
Ride-hailing (e.g., Uber or Lyft)	25.1	251
Gaming (e.g., Pokémon Go)	22.6	226
Geofencing (e.g., get reminders to run an errand when you leave work)	12.5	125
Other	1.9	19

Based on these two approaches, we randomly asked every respondent one of the following two questions:

- **WTP Question:** "Imagine your ability to use location-based services is going to be taken away for one month unless you pay an extra fee. What is the **most** you would pay to avoid losing this ability for one month?"

- **Willingness-to-Accept (WTA) Question:** "What is the **smallest** amount of money you would accept in exchange for giving up the ability to use location-based services for one month?"

We also asked a subset of respondents the same questions about their WTA and WTP for turn-by-turn navigation, if they indicated that navigation is one of the features of LBS they use.[34] These questions were phrased identically to those above except they only referred to the ability to use turn-by-turn navigation.

The WTP and WTA questions above are known as open-ended contingent valuation questions and are often used to measure the private benefits consumers receive from market and nonmarket goods. The major advantage of using these types of questions to measure private benefits is that they are relatively straightforward to analyze. This is because they allow us to obtain a WTP and WTA estimate for each respondent, and we can therefore straightforwardly estimate the mean WTP and WTA for the entire population of LBS users from this sample (see Food and Agriculture Organization of the United Nations [FAO], 2000).

However, open-ended contingent valuation questions also have disadvantages. As discussed in Carson (2000), these questions are difficult to answer because the respondent must exert a great deal of mental effort to formulate a response. As a result, these questions can often draw a large amount of zero responses (as a result of respondents giving up on answering the question or protesting the scenario) and a small number of very large responses (because respondents just throw out a wild guess). This issue has the potential to greatly skew our measurement of mean WTP/WTA.

To mitigate this problem, we used two strategies. First, we excluded all respondents who completed the survey in less than 1 minute because this suggests they did not attempt to answer the questions thoughtfully (20 respondents fit this criterion, leaving a sample of 980 respondents). Second, as suggested in FAO (2000), we only considered a "trimmed" sample when estimating mean WTP/WTA (i.e., a sample for which we removed the upper and lower 10% of responses to exclude potential outliers).

8.2.2   *Approach for Quantifying Public Benefits*

GPS-enabled LBS benefits society in many ways beyond its direct benefits to individual users. For the purposes of this study, we focused on the following benefits:

---

[34] In addition to asking respondents about their WTP (or WTA) to avoid a 1-month outage of LBS, we asked them about their WTP (or WTA) to avoid a 2-month outage of LBS. Our goal in asking this question was to use answers to both questions to extrapolate these estimates out to 12 months so we could better assess how much consumers would be willing to pay (or willing to accept) to avoid a 1-year outage of LBS. However, because of unexpectedly high variance in the data, the 1-month estimates were not statistically different from the 2-month estimates. Therefore, the 2-month estimates were not used in the analysis below.

- ▪ **Avoided health problems:** Because LBS help drivers find the shortest routes to their destination, they help reduce the number of miles traveled. This reduction in miles means fewer fossil fuels are burned and fewer emissions are created, which, in turn, helps avoid health problems associated with air pollution (e.g., asthma and bronchitis, heart attacks, death).

- ▪ **Avoided accidents:** Because LBS helps reduce the number of miles traveled, there are fewer opportunities for accidents to occur.

- ▪ **Improved emergency services:** As previously mentioned, GPS enables emergency calls from cell phones to be located more accurately and quickly through services such as E911, which leads to fewer deaths and improved health outcomes.

Because of data limitations, we only focused on monetizing health benefits associated with a total reduction in fuel use. We describe how we assessed each of these public benefits below.

To estimate the health benefits associated with GPS-enabled LBS, we must first estimate how much less fossil fuel was burned as a result of these services between 2007 and 2017. This estimate will enable us to then estimate how much less air pollution was generated during this period.

Unfortunately, direct estimates are not available for how much GPS-enabled LBS reduced total fuel usage. Therefore, we must estimate total fuel reduction indirectly using secondary data from a variety of different sources. Key data sources are summarized in Table 8-4 (note that not all of these data sources were available for every year between 2007 and 2017, so some were extrapolated and interpolated as necessary). Specifically, we used the following three formulas to estimate total fuel reduction (TFR). First, TFR in year *t* is estimated as follows:

$$TFR_t = Miles_t/MPG_t$$

where

- ▪ $Miles_t$: The number of miles that are no longer driven in year *t* thanks to navigation services helping users find the shortest routes to their destination. Estimated below.

- ▪ MPG_t : Average miles traveled per gallon of fuel consumed (light-duty vehicles) in year *t*. Obtained from the Federal Highway Administration (FHWA, 2018) for 2007 through 2016.

Second, $Miles_t$ is estimated using the following formula:

$$Miles_t = Hours_t \times MPH_t$$

where

- ▪ $Hours_t$: Hours of driving avoided thanks to navigation services helping users find the shortest route to their destination. Estimated below.

- ▪ MPH_t: Average speed traveled in year *t* by noncommercial drivers, measured in miles per hour. This is estimated by dividing total vehicle miles driven by consumers (in light-duty vehicles, urban and rural), obtained from FHWA, by the hours consumers spent driving, obtained from AAA (Tefft, 2018).

Third, we estimated hours as follows:

$$Hours_t = THD_t \times GPS \times Adoption_t$$

where

- THD_t: Total hours consumers spent driving in year *t*. Obtained from AAA.

- GPS: Percentage reduction in travel time due to GPS-enabled navigation services. Specifically, AlphaBeta (2016) found that turn-by-turn navigation reduced travel time by 11%.[35] To obtain this estimate, researchers first surveyed commuters on their digital map usage habits (how often they use maps and whether they use them for traffic avoidance, finding unfamiliar places or other purposes, and what kind of trips they use them for). Next, they created a traffic crawler using Google Maps' API, which simulated thousands of trips on different modes of transit (cars, buses, etc.), at various times of day in different cities. They used these data to estimate time savings as the difference between the fastest route identified with the traffic crawler and what the API and surveys suggested was average travel time. Using this method, they found that, on average, a digital maps user in the U.S. sees a 11% reduction in travel time, or 50 hours per year.[36] Note that AlphaBeta (2016) valued this time saved using local wage rates. However, we did not take this approach because we believe it would double count to some degree the value that users indicate they see in their WTP responses.

- $Adoption_t$: The proportion of consumers that have and use turn-by-turn navigation services (i.e., the adoption rate of LBS). We estimated the adoption rate of LBS by multiplying the fractions of consumers that own a smartphone by the fraction of smartphone owners that use LBS. Both estimates were obtained from Pew Research (Pew Research Center, 2017).

After estimating total fuel saved in each year from 2007 through 2017, we converted these estimates into emissions by applying emission factors for five key pollutants: fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxide (NO_x), ammonia (NH_3), and volatile organic compounds (VOCs). We monetize the health benefits associated with these emissions reductions using the Environmental Protection Agency's (EPA's) CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool. This tool calculates high and low estimates for the economic value of reductions in the number of adverse health events (e.g., fewer cases of asthma and bronchitis, fewer heart attacks, fewer deaths) caused by air pollution. More detail on how the COBRA health estimates were calculated is provided in Appendix A. Results for these calculations are discussed in Monetized Public Benefits.

---

[35] In addition to AlphaBeta (2016), a second study that quantified the reduction in travel time due to the use of navigation devices is Lieberman (2009). The findings in this study are relatively similar to the findings in AlphaBeta (2016). Specifically, they find that drivers who use navigation systems that include real-time traffic updates spend 18% less time driving on average and emit 21% less CO2 than drivers without navigation devices. However, we do not use Lieberman's (2009) estimate in this analysis for three reasons. First, this study was conducted in Germany, so its findings may be less generalizable to the United States. Second, it is less recent than the AlphaBeta study (conducted in 2009 rather than 2016). Third, it was funded by NAVTEQ, a portable navigation device retailer, which may make its claims less unbiased.

[36] The 50 hours per year figure is based on global data and not available for North America specifically.

Table 8-4.   Key Secondary Data Sources for Quantifying Health Benefits

Variable	Source	Relevant Years Available
U.S. population[a]	U.S. Census	2007–2017
Rate of smartphone ownership[b]	Pew Research (Mobile Fact Sheet)	2011–2018
Percent of smartphone owners who use LBS	Pew Research (Anderson, Zickuhr)	2011–2013, 2017
Travel time reduction attributable to LBS	Report by AlphaBeta	2016
Hours spent driving by consumers[c]	AAA	2014–2016
Total vehicle miles driven by consumers (in all light-duty vehicles, urban and rural)	FHWA	2007–2016
Average miles traveled per gallon of fuel consumed (light-duty vehicles)	FHWA	2007–2016
Accidents per 100 million miles driven	BTS	2007–2015

[a] Annual estimates as of July 1.

[b] Data were not available from 2007 to 2010. These estimates were generated by extrapolating backwards using an exponential trend based on available data from 2011 to 2018. In addition, data were not available for 2017. Pew Research estimated that smart phone adoption was 77% in November 2016 and January 2018. Therefore, we assumed an adoption rate of 77% for 2017. Some Pew Research data had multiple values per year; for these, the yearly average was used.

[c] Data were not available for years 2007-2013. To estimate for these years, we calculated average MPH for 2014, 2015 and 2016 by dividing AAA's total hours driven by the FHWA's total VMT for those years. We then assumed that MPH remained constant for 2007-2013 at the average MPH for the years 2014-2016, and divided VMT by MPH to estimate total hours spent driving. 2017 VMT data were also not available, and we assumed they remained the same as 2016 VMT. The two AAA reports, available for years 2014-2015 and 2015-2016, listed different values for 2015, and here we preferred the more recent study.

To assess avoided accidents, we estimated the reduction in the number of crashes, injuries, and fatalities created by drivers driving fewer miles as a result of turn-by-turn navigation services. Specifically, we estimated total crash reduction, TCR_t, as follows:

$$TCR_t = Accidents_t \times (Miles_t/100,000,000)$$

where

- $Accidents_t$: Rate of car accidents per 100 million miles driven. Obtained from the Bureau of Transportation Statistics.

Similarly, we estimate the total crash injury reduction, $TCIR_t$, and total crash fatality reduction, $TCFR_t$, as follows:

$$TCIR_t = Injuries_t \times (Miles_t/100,000,000)$$

$$TCFR_t = CarFatalities_t \times (Miles_t/100,000,000)$$

where

- $Injuries_t$: Rate of car injuries per 100 million miles driven. Obtained from the Bureau of Transportation Statistics.

- $CarFatalities_t$: Rate of car fatalities per 100 million miles driven. Obtained from the Bureau of Transportation Statistics.

We estimated the total reduction in accidents, injuries, and fatalities attributed to those accidents, but we did not monetize the value of this reduction because of the difficulty in separating the private and public value of avoided accidents.

To assess improvements in emergency services, we conducted a literature review for relevant peer-reviewed articles that assessed the benefits of E911, faster emergency service response times, and other improvements in emergency services' location technology. We additionally reviewed news sources and government publications containing relevant information from officials in the Federal Communications Commission (FCC) and other emergency services. This qualitative assessment addresses the high-level benefits GPS brings to first responders' ability to locate and reach callers in emergency situations.

8.2.3   *Estimating Costs of GPS-Enabled Location-Based Services*

Although GPS-enabled LBS generate private and public benefits, costs are associated with developing and providing these services. In addition, for the user, there is no additional fee for LBS functionality on a smartphone, once the device and mobile data are purchased. For the hardware producer, the largest cost would likely be the GPS chip that enables LBS functionality. Chips cost less than $5 apiece in 2007 (Privat, 2007), and the price is likely to have fallen substantially since then. Given that costs are low, relative to expected benefits, we omitted them from this analysis.

8.3   Retrospective Economic Benefits Analysis

As previously discussed, GPS-enabled LBS were not widely adopted until the release of the first smartphone in 2007. Below we discuss how we estimated the private and public benefits generated by these services. We summarize the results of this analysis in Table 8-5.

8.3.1   *Monetized Private Benefits*

As described in the methodology section, we fielded a survey to 1,000 LBS users to assess how much they would be willing to pay to avoid losing access to LBS and the minimum amount they would be willing to accept to give up access to LBS. We take the sample mean as an unbiased estimate of individual WTP or WTA. Table 8-6 displays the results from the survey for each of these sample means and 90% confidence intervals.

Table 8-5.   Monetized Private and Public Benefits Generated by Location-Based Services

Year	U.S. Population (million)	Smartphone Adoption Rate (%)	LBS Usage Rate (%)	U.S. LBS Users (million)	Private Benefits ($ million)	Public Benefits ($ million)	Total Benefits ($ million)
2007	301.23	27%	11%	8.95	$1,413	$215	$1,629
2008	304.09	29%	22%	19.40	$3,066	$446	$3,512
2009	306.77	33%	33%	33.41	$5,280	$771	$6,051
2010	309.34	37%	44%	50.36	$7,959	$1,181	$9,140
2011	311.64	35%	55%	59.99	$9,481	$1,413	$10,894
2012	313.99	44%	74%	102.23	$16,157	$2,401	$18,558
2013	316.23	54%	74%	126.37	$19,971	$2,983	$22,954
2014	318.62	57%	82%	148.92	$23.536	$3,591	$27,127
2015	321.04	68%	90%	196.48	$31,051	$4,726	$35,777
2016	323.41	73%	90%	212.48	$33,580	$5,240	$38,820
2017	325.72	77%	90%	225.72	$35,673	$5,567	$41,240
Total					**$187,169**	**$28,534**	**$215,702**

Note: U.S. LBS users is calculated by multiplying the U.S. population by the smartphone adoption rate by the LBS usage rate. All dollars are 2018 dollars, since they are based on willingness to pay estimates obtained from a survey conducted in that year.

Table 8-6.   Mean WTP and WTA for Location-Based Services and Turn-by-Turn Navigation Services

	Navigation Services Only	All Location-Based Services
Maximum **WTP** to avoid 1-month outage of services	$8.11 (n=143)	$13.17 (n=197)
Minimum **WTA** to avoid 1-month outage of services	$98.35 (n=136)	$150.97 (n=210)

Note: Sample size used for calculating each result is reported in parentheses.

There are several important points to make when considering these results. First, the mean willingness-to-accept estimate is much larger than the mean WTP estimate, a pattern common in contingent valuation studies. Hanemann (1999) provides a thorough discussion of the economic theory behind why these values can differ significantly. To make our benefits estimates as conservative as possible, we choose to only use the smaller WTP estimate to value the private benefits of GPS-enabled LBS.

Second, most of the value that users derive from LBS seems to come from turn-by-turn directions. We made this determination by comparing how much users are willing to pay (or willing to accept) for navigation services versus LBS as a whole. Specifically, we found that respondents were willing to pay an average of $8.11 to avoid losing access to turn-by-turn direction services for 1 month and $13.17 to avoid

losing access to all LBS. This suggests 62% of the value of LBS is provided by turn-by-turn directions as measured by WTP (62% = $8.11/$13.16).

Third, the confidence intervals surrounding our mean estimates are very wide (reflecting the fact that there is a still great deal of variability in the responses even after trimming the sample). For example, the 90% confidence interval for the WTP to avoid losing all LBS for 1-month ranges from −$23.97 to $50.31. When estimating ranges for private benefits (discussed below), we did not consider negative benefits to be economically meaningful (this suggests the provision of LBS actually imposes costs on users, which seems doubtful). Therefore, when calculating lower bound estimates of total economic impacts, we assume private benefits are zero.

To calculate the total personal benefits provided by GPS-enabled LBS each year, we multiplied our estimate of an individual's WTP for 1 month of LBS ($13.17 per month) by the number of months in a year (12 months), by the U.S. population that owns a smartphone and uses LBS. For example, we estimate there were 225.723 million LBS users in 2017, which implies they received $35,673 million in benefits ($35,673 million = 225.753 million * $13.17 * 12). A potential limitation to this approach is the fact that we assume that willingness to pay would be consistent each year included in our study; it's likely that users in previous years would have valued LBS lower due to there being fewer technological advances. We considered discounting WTP in previous years but were unable to settle on a justifiable factor to discount by. We believe that this is accounted for by scaling the benefits we find by the number of LBS users, which was smaller in previous years, and the lesser value to users is reflected in the fact that there were fewer users.

8.3.2   *Nonmonetized Private Benefits*

Benefits from Non-smartphone Navigation Devices

Personal navigation devices (Garmins, TomToms, etc.) and in-vehicle navigation systems provide similar value as general LBS and have since their introduction in the late 1990s and early 2000s. Our analysis of individual WTP includes the value perceived by consumers who use LBS on any device, including smartphones, tablets, in-car navigation systems, and portable navigation devices. However, in aggregating the total value experienced by all consumers, we multiplied individual willingness-to-pay estimates by an estimate of the total number of U.S. adults who use LBS on smartphones. This estimate therefore does not include value perceived by consumers who only use LBS on devices other than smartphones. About 85% of our sample reported using LBS on a smartphone, so we may be undercounting the total individual value consumers realize from LBS by leaving out those who only use LBS on devices other than smartphones. We leave these benefits out of our calculation to avoid double counting any users who use multiple devices to access LBS.

We also do not include the value provided by personal navigation devices used before 2007 because of issues with data availability. We would need not only the number of Americans who used a personal navigation device during this period, but also an estimate in the travel time reduction that personal navigation devices provided pre-2007. It seems implausible that AlphaBeta's 12% reduction in travel time

would have been achieved with pre-2007 navigation devices, because it was calculated using live-updating digital maps with real-time traffic information, and the quality of navigation was likely lower in earlier years. Leaving out this amount of value from our calculation lends to the conservative nature of our estimate.

8.3.3   *Monetized Public Benefits*

We estimate that GPS-enabled LBS helped U.S. consumers save 2.3 billion driving hours in 2012. This is the product of 65 billion driving hours, a 11% reduction in travel time, 44% of American adults owning smartphones, and 74% of smartphone owners using LBS. As an example calculation for the year 2012, given that according to the authors' calculations, average driving speed is 41.3 mph and average fuel economy is 21.6 mpg, LBS helped U.S. consumers save 95.4 billion vehicle-miles and 4.4 billion gallons of fuel in 2012.

Repeating similar calculations for each year from 2007 through 2017 and adding together the results suggest LBS helped consumers save 52 billion gallons of fuel and drive 1.1 trillion fewer vehicle-miles during this 11-year period (Table 8-7).

We convert the 52 billion gallons in fuel savings into emissions factors of five key pollutants, detailed in Table 8-8. These emission factors were then fed into the COBRA model to produce outputs.

Table 8-7.   Total Fuel Savings in Gallons, 2007–2017

Year	Total Fuel Savings (Millions of Gallons)	Total Vehicle Miles Traveled (VMT) Savings (Millions of Miles)
2007	412.75	8,792
2008	846.74	18,459
2009	1,452.02	31,509
2010	2,205.98	47,429
2011	2,618.81	56,043
2012	4,418.04	95,430
2013	5,449.26	117,704
2014	6,512.17	139,361
2015	8,505.86	187,129
2016	9,361.32	205,949
2017	9,874.27	217,234
Total	**51,657.24**	**1,125,036**

Table 8-8.   Total COBRA Inputs, 2007–2017

Category	Reduction Amount
Fuel reduction	52,261.76 thousand gallons
SO_2 reduction	297.78 thousand metric tons
NO_x reduction	675.37 thousand metric tons
NH_3 reduction	40.81 thousand metric tons
VOC reduction	3,990.83 thousand metric tons

COBRA outputs a high and low estimated scenario, and we present the simple average of these two as a midpoint estimation. In total, we estimate that the reduction in driving attributable to widespread use of LBS has saved $28.9 billion in avoided health expenses since 2007. These health expenses include mortality, hospital admissions, heart attacks, upper and lower respiratory issues, bronchitis, and lost productivity from missed work and restricted activity. This estimate is the midpoint of COBRA's low and high case estimates, $17.9 billion and $39.8 billion, respectively. The largest share of these benefits comes from avoided mortality.

8.3.4   Nonmonetized Public Benefits

GPS-enabled LBS provides many public benefits we do not quantify in our estimation because of the uncertainty and complexity, but we discuss them below.

Avoided Accidents

In the same way that reduced driving from turn-by-turn navigation reduces pollution, it will also result in fewer accidents, preventing property damage, injury, and death. The U.S. Department of Transportation's Bureau of Transportation Statistics (Table 2-17: Motor Vehicle Safety Data, 1960-2015) reports that in 2016 (the most recent year of data availability at the time of writing) there were 229 crashes, 99 injuries, and 1.19 fatalities per hundred million vehicle-miles driven on U.S. roads. Given our estimation that LBS usage reduced vehicle-miles driven by 1.1 trillion vehicle-miles between 2007 and 2017, we can attribute approximately 2.4 million avoided crashes, 975,000 avoided injuries, and 13,000 avoided car crash deaths in this 11-year period to LBS.

However, we were unable to separate this from personal value captured in WTP. It is possible consumers are aware of, and value, the fact that driving less reduces their accident likelihood statistically—a rational consumer with perfect information would be—however, not all consumers are rational; hence, it is likely that not all of this private benefit is captured. More importantly, we were unable to separate out only accidents where other drivers are involved and only valued the other driver's loss (this externality from an individual's accident is a social cost). Because we cannot monetize this public benefit, we consider our overall impact estimates to be conservative.

Emergency Services

In 1999, legislation mandated that telecommunications companies build out E911 capabilities, which would allow 911 operators to locate users calling from a mobile device, either using cell tower triangulation or GPS, in the case of GPS-enabled devices. Several studies have estimated the benefits of these capabilities. Athey and Stern (1998) found that cell-tower E911 services led to ambulances arriving on the scene of cardiac emergencies 5% faster and transferring patients from the scene 10% faster relative to counties with no 911 or Basic 911, which resulted in decreased mortality. Stratmann and Thomas (2016) found that the availability of GPS-enabled E911 decreased lethality from violent crimes by 37% relative to E911 without GPS and improved response times and decreased lethality relative to the cell-tower E911 capabilities in place before the adoption of GPS. Finally, the FCC estimated that improved location accuracy that decreases an emergency dispatcher's response time by a single minute would save approximately 10,000 lives annually (Federal Communications Commission, 2014).

These benefits are undoubtedly valuable, but we were unable to accurately quantify them at the national level with readily available data sources because we are unable to locate data on emergency vehicle response times for the entire country (some localities record these figures, but not many, and there is significant variation in the methods localities use to record response times). We also lacked data on the rollout of different phases of E911 at different geographic levels; we would need to know which locations had which location capabilities when to make accurate assessments of the impact of introducing GPS-based E911.

GPS-based E911 is also not yet consistently reliable or available in all locations. While FCC regulations require mobile phones to track a person's location within 100 to 300 meters of their actual location (Federal Communications Commission, 2000), not all public safety answering points can access this information or a phone's more accurate GPS location. Many still rely solely on directions given by the caller or cell-tower triangulation, which can place a caller miles away from their true location, sometimes even in different counties (Smink, 2018). The FCC has set a deadline of 2024 for mobile phone operators to provide several improvements to their location capabilities, including providing dispatchable locations within 50 meters, improved indoor locating abilities, and vertical location, for 80% of wireless calls in some areas (Indoor Location Accuracy Benchmarks, 2018).

8.4   Potential Impacts of a 30-Day Outage

In the event of a 30-day outage, many LBS would lose precision and some functionality. In particular, navigation services like Google Maps and Waze could not provide live turn-by-turn directions to their users without the precise location data provided by GPS. To quantify the economic impact associated with losing navigation, we assumed that the private and public benefits that they generate will be totally lost.

In the case of private benefits, this means losing $8.11 per user per month in 2017. Given that there were 226 million LBS users in 2017, this corresponds to a loss of $1.83 billion ($8.11 x 226 million).

In the case of public benefits, this means losing the benefits generated by LBS users driving fewer miles with the aid of turn-by-turn directions. In the previous section, we estimated average public benefits to be

$5.57 billion in 2017. Therefore, we estimate the average value of public benefits during an average 30-day period to be $457 million ($5.57 billion divided by 365.25 and multiplied by 30). It is important to note that actual losses may be larger or smaller depending on the actual month the outage occurs because some months are associated with more miles driven than other months.

In addition to the economic impact of losing navigation services, a 30-day GPS outage will also have consequences for non-navigation applications. However, it is difficult to predict what those consequences will be ahead of time because, depending on how quickly app developers respond to the outage, it is possible that many applications that use GPS location but do not depend on it for complete functionality could switch to a reasonable alternative, such as using cell-tower triangulation for a very general location, having users input their current ZIP code, or having users select their location from a map to obtain information about local weather, businesses, and attractions.

To account for the fact that some applications could continue to work during a temporary GPS outage, we assumed that only half of the value generated by non-navigation services will be lost. Specifically, we estimated that consumers are willing to pay an average of $5.06 per user per month for non-navigation LBS (this estimate was obtained by subtracting our estimate for the value of navigation services, $8.11, from our estimate for the value of all LBS, $13.17). Half of this value is $2.53. Given that there were 226 million LBS users in 2017, this corresponds to a loss of $571 million ($2.53 x 226 million). Combining our estimates of economic losses associated with reduced functionality for navigation and non-navigation services, we predict that a 30-day GPS outage will generate approximately $2.86 billion in losses.

In addition to these quantified losses, it is important to note that a 30-day GPS outage will result in consequences that we cannot quantify. In the emergency sector, we could expect the benefits of GPS-E911 services to disappear, which would increase the time it would take to respond to 911 calls, resulting in quantifiable reductions in survival rates of individuals involved in adverse medical events, accidents, and violent crimes.

8.5   Concluding Remarks

In summary, we find that between 2007 and 2017, LBS generated $218 billion in private and public benefits for U.S. residents alone. We estimate that LBS users would experience private and public losses during a 30-day outage totaling $2.9 billion.

We view these as conservative estimates because we are not able to monetize all public benefits generated by LBS. Specifically, we discuss the following nonmonetized public benefits of LBS:

- **Avoided accidents:** In the same way that reduced driving from turn-by-turn navigation reduces pollution, it will also result in fewer accidents, preventing property damage, injury, and death. We estimate that turn-by-turn navigation helped avoid 2.4 million crashes, 975,000 injuries, and 13,000 car crash deaths in this 11-year period to LBS.

- **Emergency services:** Beyond turn-by-turn directions, other GPS-enabled emergency services like E911 help locate people in need of emergency services more quickly, which reduces response times and saves lives. For example, the FCC estimated that improved location accuracy

that decreases an emergency dispatcher's response time by a single minute would save 10,000 lives annually (Federal Communications Commission, 2014).

Looking to the future, the LBS sector is growing rapidly, consistently improving, and integrating itself into consumer life more deeply every day. According to market forecasts, the LBS sector is expected to grow from $17 billion in 2017 to $69 billion by 2023, at a CAGR of 25.4% (Markets and Markets, 2018). It is likely that in coming years new technologies that build on GPS to add value to LBS will continue to develop, opening a wide range of commercial application possibilities. These might include greater reliance on autonomous vehicles, which would need extremely accurate location data to become a reality (Boudette, 2017). Unmanned aerial vehicles (UAVs, or drones) also rely heavily on accurate and up-to-date location data to function, and any increased integration of UAVs into private and commercial use will also rely heavily on LBS (Dennehy, 2015). Many LBS applications will increasingly rely on integration with Internet of Things (IoT) devices as well, allowing users to locate lost items like keys and phones, manage connected home devices like thermostats and security cameras remotely, and take advantage of physical objects that can share their location data in other ways (Strout, 2016).

Improved accuracy may bring about improved indoor locating abilities, which until now have been a challenge. Recent advances have made indoor location at a centimeter level of accuracy possible, enough to pinpoint users' locations and have a wide variety of applications in retail, health, disaster management, and other sectors (Zafari et al., 2019). However, to achieve such hyper-accurate indoor location, some technologies may come to rely on not just GPS but also on other location technologies. Indoor Atlas, for example, a company specializing in indoor location, combines GPS signal with geomagnetic positioning, inertial navigation, beacons, Wi-Fi positioning, barometric pressure, and other sources to provide extremely accurate indoor navigation in shopping centers, malls, offices, and other buildings where GPS signal alone struggles to give accurate and reliable location information (Positioning Technology, n.d.).

In general, it is expected that LBS-using devices will continue to improve their accuracy, response time, and battery-use efficiency, increasing the value consumers perceive from their use and their importance to the U.S. economy. LBSs have gone from being a futuristic idea to a fixture of everyday life and will clearly remain central to the lives and habits of Americans for the foreseeable future.

9. Maritime Industries

GPS is used pervasively in commercial shipping, fishing, and recreational boating for navigation and tracking. GPS is the primary means of navigation for nearly all vessels. This case study focuses on GPS' use in the maritime sector, what would have been used for navigation and port operations if GPS had not been made available, and alternatives should there be a GPS outage.[37]

For the purposes of this analysis, we have divided the maritime sector into five subsectors:

- commercial fishing
- recreational fishing and boating
- port operations
- navigation in seaways
- passenger transport including cruise lines

We find that although GPS is pervasive throughout the maritime sector, if it had not been made available, the sector would have most likely continued to use Loran-C or similar technologies with minimal impact on operations or economic output. The accuracy provided by Loran-C is sufficient, and in the absence of GPS most electronic navigation systems would have evolved using this alternative. Thus, we do not quantify retrospective benefits.

In contrast, because currently there is no backup for GPS, an unexpected outage of GPS today would have significant economic impacts. We estimate a 30-day outage of GPS to have an impact ranging from $7.8 to $14.6 billion, with a point estimate of $10.4 billion. The largest impacts are associated with interruptions in port operations and the resulting economic impact of supply chain disruptions. The range of impacts associated with the 30-day outage analysis reflects the fact that there is some uncertainty regarding the extent to which subsectors in the maritime industry (primarily ports) could respond and adapt over the 30-day GPS outage time period to mitigate impacts.

9.1   Sector Introduction and Overview

The maritime sector uses GPS for precision positioning and navigation and as an enabling technology of the Automatic Identification System (AIS), the Global Marine Distress and Safety System (GMDSS), and Vessel Monitoring Systems (VMS). GPS is the primary means of navigation for nearly all vessels except for smaller recreational boats.

GPS acts as an enabling technology for several technologies in the maritime sectors. The following technologies are either entirely dependent on GPS or use GPS for some functions and would operate in a diminished capacity in the absence of GPS. Some of these technologies are widely used and are present

---

across many of the subsectors analyzed in this report.[38] Others are specific to a single subsector and are discussed in greater detail later in the report.

9.1.1 Gyrocompasses

Gyrocompasses, or gyroscopic compasses, are nonmagnetic compasses that use a spinning gyroscope and the Earth's rotation to find true north and use GPS for calibration. Finding true north is more navigationally useful than finding magnetic north. Unlike traditional compasses, gyrocompasses are unaffected by ferromagnetic materials, such as steel. These characteristics make gyrocompasses particularly well suited for use on ships. As such, they are widely used and are the preeminent means of finding geographic direction.

Gyrocompasses are subject to "steaming" errors due to rapid course changes. These errors cause the gyrocompass north to be deflected east or west depending on the direction of travel. Modern gyrocompasses rely on GPS input to correct these errors.

9.1.2 Automatic Identification System

GPS acts as an enabling technology of AIS. AIS is a shipboard broadcast system that acts like a transponder designed to be capable of providing information about the ship to other ships and to coastal authorities automatically (U.S. Coast Guard, 2018b; International Maritime Organization [IMO], 2019a). This information includes dynamic information such as position, speed, heading, and rate of turn as well as static information such as call sign, name, vessel type, and destination (MarineTraffic, n.d.). AIS is required under the IMO's International Convention for the Safety of Life at Sea (SOLAS) for all passenger ships, tankers, and other ships over 300 gross tons. AIS is primarily used in ship reporting, navigation, and collision avoidance.

9.1.3 Electronic Chart Display Information System

ECDIS is a geographic information system that replaces paper navigation charts. It displays geographic information from electronic navigational charts[39] or digital nautical charts[40] and overlays position information from GPS and other navigational sensors. Additionally, ECDIS integrates with radar, AIS, depth sounders, and Navtex and overlays data from these systems on the electronic chart. ECDIS is a useful tool for mariners because it displays information from several systems in a single location. ECDIS is not required by IMO or U.S. Coast Guard regulations but is approved as a replacement for nautical charts and is widely used.

9.1.4 Vessel Monitoring Systems

A VMS consists of a National Marine Fisheries Service (NMFS)–approved transmitter that "… automatically determines a vessel's position and transmits that position to an NMFS-approved

---

[38] For additional detail, see gyrocompass https://www.marineinsight.com/marine-navigation/gyro-compass-on-ships-construction-working-and-usage/.

[39] For more information, visit https://nauticalcharts.noaa.gov/charts/noaa-enc.html.

[40] For more information, visit https://www.nga.mil/ProductsServices/NauticalHydrographicBathymetricProduct/Pages/DigitalNauticalChart.aspx.

communications service provider. The communications service provider receives the transmission and relays it to NMFS" (National Oceanic and Atmospheric Administration, n.d.). GPS is the primary means of providing position data for VMS. VMS is used by environmental groups and NMFS to monitor and enforce compliance with fisheries regulations. VMS is required on commercial fishing vessels operating in some U.S. fisheries. Fishing vessel operators working in these fisheries are required to declare their catches via electronic logs that are transmitted through VMS.

9.1.5   Portable Pilot Units

PPUs consist of a combination of sensors, a laptop, and software that assists pilots in safely navigating a ship into a port. These sensors are independent of the piloted ship's sensors. PPUs use several sensors including gyroscopes, inertial sensors, and GPS receivers. These sensors provide essential data to the pilot such as the roll and pitch of a vessel, speed, position, and heading. The use of pilots is compulsory in most ports, and most pilots use PPUs.

9.1.6   Global Marine Distress and Safety System

GMDSS is "an integrated communications system using satellite and terrestrial radiocommunication systems" (IMO, 2019b). GMDSS is required under the IMO's SOLAS regulations for vessels over 300 gross tonnage on international voyages and all passenger ships. In the case of an emergency, GMDSS alerts search and rescue organizations such as the U.S. Coast Guard. Additionally, it alerts nearby vessels that may be able to offer assistance. The system relies on GPS to provide the vessel's position to rescue authorities.

9.1.7   Digital Telecommunications

Digital communications systems that use time division multiplexing use the GPS signal for timing corrections. Maritime vessels use a combination of analog radios in the UHF and VHF bands and digital communications such as satellite radios.

9.2   Methodological Notes

Our approach to assessing the economic impacts began by identifying the location accuracy needs that GPS currently meets and determining what alternative precision timing systems are, or could be, available for use. We conducted a literature review and initial scoping interviews to identify preliminary hypotheses regarding the economic impacts associated with the two counterfactual scenarios: (1) if GPS had never been made available and (2) an unanticipated 30-day failure or GPS. The preliminary assessment was then verified/refined based on a more extensive number of interviews with industry experts. We then identified what the technical impacts would be and quantified these impacts using a combination of market and nonmarket valuation techniques.

Table 9-1 provides an overview of the maritime sector's applications and accuracy needs. Although the level of accuracy required for different maritime applications varies, in many instances, the level of accuracy provided by Loran-C is sufficient. The primary exception is for container tracking in ports, which requires an accuracy of one-half the width of a container (which is approximately 1.7 meters).

Table 9-1.   Maritime Industry Location Accuracy Uses and Needs

Application	Accuracy Needed	Benefits: Qualitative Description	Counterfactual to Use of GPS	Technical Impact Metric	Economic Value Metric	Potential Magnitude of Impacts
Navigation in seaways	1–2 miles	Precise tracking of ships and estimated arrival time	Loran-C or traditional navigation methods	Increase in travel time due to location uncertainty	Economic impacts of longer shipping time	Low
Navigation in ports	10 meters	Harbor pilots use to reduce uncertainty of surrounding ships	Loran-C and increased reliance on harbor pilots	Increase in travel time due to increase caution	Economic impacts of longer shipping time	Low
Site location for commercial fishing	20–40 meters	Commercial fishing to locate catch and avoid underwater obstacles	Loran-C or traditional charts and maps	Decreased ability to locate underwater obstacles or catch	Lost revenue	Medium
Recreational boating and fishing	20–40 meters	Helps less skilled boaters navigate	Loran-C or traditional charts and maps	Fewer or shorter recreational boating days	Individuals' value of recreational boating	High
Search and rescue	50–100 meters	Search teams are able to precisely locate distress calls	Radio receivers if available	Response time to providing assistance	Value of injury or loss of life	High
Port logistics	1–2 meters	Enables complex logistics management system to maximize efficiency	Land-based positioning system	Slower processing and reduced throughput of containers	Economic value of delayed delivery	Very high

9.2.1   *Approach for Quantifying Retrospective Benefits*

Before the advent of GPS, Loran-C, a land-based positioning, navigation and timing (PNT) system, was used for marine navigation purposes. Loran-C provided the same kind of timing and frequency signal as GPS, but Loran-C was less accurate and less precise (see Table 9-2).

Based on discussions RTI has conducted with positioning experts, it is very likely that Loran-C would have continued operation, and potentially been expanded, if GPS had not been made available to the commercial maritime sector. Thus, the counterfactual scenario used in the analysis is that Loran-C would have continued to be used to meet positioning needs in the maritime sector if GPS had not been available. Thus, the economic benefits from the retrospective analysis are based on the increased precision GPS provides (1.6–4 meters) compared with Loran-C (18–90 meters).

9.2.2   *Approach for Quantifying Potential Impacts of a 30-Day Outage*

Under a 30-day failure of GPS scenario, we assumed that neither Loran-C nor eLoran would be available as a backup. Neither one of these systems is operating today, nor could these systems be implemented within the 30-day time window of our analysis. We also assumed that other international global navigation satellite systems, such as GLONASS or BeiDou, would not be available for use within the 30-day time window. Many of today's existing GPS applications are not compatible with these systems. (However, this may change in the future as product markets globalize.)

Hence, the counterfactual for the 30-day failure of GPS is simply the quality/reliability of the maritime sector's current backup systems. Note that backup systems for GPS vary greatly across subsectors in the maritime sector. For example, cruise ships have a series of navigation backup systems (e.g., radar, charts) and highly skilled staff for such extreme events. Alternatively, small commercial vessels and recreational boaters are typically much less prepared for a failure of GPS. For each subsector described in this report, backup systems and capabilities were investigated as part of the interviews with industry experts.

Because of the variety of maritime subsectors included in the analysis, we employed several different economic valuation approaches. These valuation approaches can generally be grouped into the following categories:

Table 9-2.   Precision and Accuracy Performance

	Loran-C	GPS
Frequency	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10 ns
Positioning (meters)[a]	18–90 m	1.6–4 m

Sources: Curry (2014); Celano, Carroll, Biggs, & Lombardi (2003)

[a]   The positioning accuracy can vary widely depending on weather, geography, and the type of receiver and augmentations being applied. The accuracy quoted here for GPS is from the GPS Wide Area Augmentation System 2008 Performance Standard.

- ▪ Increased production costs: Additional labor, capital, materials, or energy is needed to produce the same product or service. For example, if decreased navigation accuracy causes ships to slow down in transit or port entry, the overall operating costs for a given trip will increase.

- ▪ Decreased productivity and lost revenue: For example, decreased accuracy may cause commercial fishing vessels to cancel trips or experience a decrease in catch, resulting in lost revenue.

- ▪ Willingness to pay (WTP): WTP is a stated preference approach where individuals or businesses are asked to value a service, activity, or product attribute. In this analysis, it was used to value

  - – lost recreational boating days and

  - – delay costs associated with supply chain interruptions.

Table 9-3 shows the valuation approach we employed for each maritime subsector. Note, for the cruise ship industry, we investigated both increased operating costs from losing GPS and potential lost revenue from canceling cruises or port destinations.

Based on the interviews with industry experts, we calculated technical impact metrics for each maritime subsector (when appropriate). This metric is typically a percentage change in operating costs or revenue or the change in the number of recreational boating days or the number of containers delayed at ports. Specifically for port operations, the metric is the number of containers-days delayed, which was then valued at the WTP to avoid a day's delay in delivering products.

We then scaled the economic impacts using national-level data. For example, we obtained data from the following sources:

- ▪ U.S. commercial fishing revenue from the U.S. Bureau of Economic Analysis

- ▪ annual number of recreational boating days from the 2016 Recreational Boating Participation study and the 2012 National Recreational Boating Survey

- ▪ number of containers processed at major U.S. ports from U.S. Department of Transportation Maritime Administration

For each maritime subsector, the technical impact metrics, valuation approach, and scaling process are described in detail in the following sections.

Table 9-3.   Valuation Approach

Maritime Subsector	Increased Production Costs	Decreased Productivity (lost revenue)	WTP
Commercial fishing		X	
Recreational boating and fishing			X
Port operations			X
Navigation in seaways	X		
Cruise ship industry	X	X	

Note: Throughout the report, all impacts are presented in 2017 dollars.

9.2.3   *Interviews with Sector-Specific GPS Experts*

We interviewed maritime experts with a range of expertise and perspectives. These groups along with key topic areas are summarized in Table 9-4. Maritime-sector interviewees were identified through publications, conferences, workshop speaker lists, trade association member lists, and referrals. We interviewed a total of 43 individuals as part of the stakeholder engagement. Table 9-5 provides the number of completed interviews by target population. Interviews were generally evenly distributed over the maritime subsectors of focus.

Following our interviews, we used a modified Delphi approach to verify our key impact metrics, such as the percentage reduction in fishing catch or the value of different types of fishing days. The modified Delphi approach was done via e-mail with our original interviewees. Based on the Delphi input, we adjusted the impact metrics slightly. However, no major adjustments were required because experts were generally in agreement about the impacts.

Table 9-4.   Target Populations and Key Issues Covered During Interviews

Population Groups	Target Companies/ Organizations	Topic Areas/Questions
Cruise line operators	▪ Cruise lines	▪ Applications of GPS in the industry
		▪ What GPS-enabled technologies are required on cruise ships?
		▪ What other navigational technologies are available?
		▪ Would cruise lines cancel or delay trips in the case of a GPS outage?
Equipment manufacturers, product providers	▪ GPS manufacturers	▪ How widely used are GPS units in the maritime sector?
		▪ What technologies are enabled by GPS?
Commercial fishing	▪ Fishing companies	▪ Industry structure and catch techniques
	▪ Vessel operators	▪ Applications of GPS in the industry
		▪ Discussion of Loran-C's viability
		▪ What are the alternatives to GPS?
		▪ Would catch revenue decrease in the absence of GPS?
Enforcement and regulation personnel	▪ National Oceanic and Atmospheric Administration (NOAA) NMFS	▪ Commercial fishery regulation structure
	▪ Regional fishery management councils	▪ Environmental impacts from violations
		▪ Benefits of GPS over Loran-C in enforcement
Industry trade associations		
Port authorities		
Government	▪ U.S. Coast Guard	▪ Overview of the maritime sector
		▪ Use of GPS in the search and rescue operations

Table 9-5.   Number of Interviews by Target Population

Target Population	Entities Contacted
Broad	6
Commercial fishing	8
Recreational boating	7
Port operations	15
Navigation	7
Cruise industry	7
Total	43

9.3   Retrospective Economic Benefits Analysis

Interviews across all our subsectors indicated that although GPS is an important navigational tool and plays a pivotal role in navigation today, it does not offer appreciable improvements over Loran-C for most sectors. It offers convenience and improved accuracy, but the improved accuracies are generally unimportant for most maritime applications. GPS-enabled technologies offer benefits to the maritime sector such as efficiency improvements and increased safety. However, we found that these technologies could have been developed in the absence of GPS and would have relied on a Loran-C signal for positioning input and corrections. Under this assumption, Loran-C fulfills many of the same roles as GPS in the maritime sector.

Commercial fishermen were among the last to stop using the Loran-C system. It was the preferred position and navigation tool for fishermen. It was not until the Loran-C system was decommissioned that commercial fishermen widely adopted GPS. While the absolute accuracy of Loran-C was worse than GPS, it had greater repeatable accuracy than GPS. For this reason, fishermen preferred Loran-C over GPS. Interviews indicated that GPS offered no advantages over the Loran-C system. If GPS was unavailable, fishermen would have continued using Loran-C and would have no negative impacts.

Before the advent of GPS, many recreational boaters used Loran or Loran-C. Loran provided a notable benefit to recreational boaters over more traditional technologies, because it saved time, fuel, and costs, particularly for longer trips. Recreational boaters unanimously thought that the accuracy of Loran was good enough for their needs and that if Loran had stayed operational that GPS would have provided minimal benefits.

Ports in the United States use GPS for navigation into and out of harbors and for container tracking. In the absence of GPS, ports would likely have adopted localized technologies such as pseudolites to fulfill the same needs. The IMO requires a 10-m minimum accuracy level for harbor entry, which Loran-C meets. eLoran or differential Loran can exceed these requirements.

Navigation in seaways is undertaken in a similar fashion to navigation in the cruise industry. Ship navigators would have used Loran-C and traditional navigation techniques and would not experience appreciable delays in the absence of GPS.

Interviews with cruise lines indicated that their navigators are trained in traditional navigation techniques such as astral or celestial navigation. Historically, the cruise industry used Loran-C in conjunction with these techniques. If GPS were never developed, cruise lines would have continued to use Loran-C with no negative consequences.

Based on our interviews with industry experts and our review of the literature, we conclude that there would have been little impact on the maritime sector if GPS had not been made available. Most of the sector was already using Loran-C before the introduction of GPS, and some subsectors continued its use until Loran-C was decommissioned. Thus, no retrospective measurable economic impact estimates were identified as part of our analysis.

It should be noted that a report by the UK Lighthouse Authority estimated the annual gross value-added impact of GNSS on the maritime industry in the UK to be £429 ($568[41]) million per year, including £350 ($463) million associated with the time and fuel savings that GNSS-supported navigation enable, £70 (93) million attributable to increased productivity of the fishing industry, and £9 ($12) million associated with the increased effectiveness of search and rescue operations (Sadlier, Flytkjær, Sabri, & Herr, 2017). However, this study did not consider a counterfactual in which alternatives to GNSS systems such as Loran had been further developed in the absence of GNSS and could have been used to support today's more advanced electronic navigation systems, with slightly less accuracy.

9.4   Potential Impacts of a 30-Day Outage

In contrast to the retrospective impact analysis, there was widespread consensus that a 30-day outage would have significant economic impacts for the maritime sector. However, impacts varied greatly across the subsectors included in the analysis. For example, operations at large ports would initially come to a standstill with the loss of GPS. Cruise ship navigators would need to "scramble" with the loss of GPS, but operations would not be significantly disrupted because of backup systems and mitigation protocols. Each of the five maritime subsectors included in the analysis is discussed individually in Sections 6 through 10.

The quantitative analysis was careful to avoid double counting economic impacts across subsectors. The primary potential source of double counting related to delay costs. Most all sectors said that using GPS increases confidence and reduces uncertainty in navigation. GPS enables location accuracy, which is not possible using other methods. Without the accuracy provided by GPS, most navigators would become slightly more conservative, slowing down when entering and exiting ports and giving wider berths to underwater obstacles or other ships. In addition, transit times for ocean crossings would increase slightly because navigators might choose less optimal routes.

---

[41] A conversion of 1 pound sterling = $1.30 was used for 2016 and then inflated to 2017 dollars. The 2016 exchange rate was accessed from https://www.irs.gov/individuals/international-taxpayers/yearly-average-currency-exchange-rates and the GDP deflator from https://fred.stlouisfed.org.

Increased transit time and increased caution close to shore will result in unexpected delays that have economic impacts associated with late delivery of commodities. However, our analysis indicated that the greatest bottleneck for the import and export of commodities would be the interruption of port logistics. Very quickly cargo ships would be queuing up for days and even week as ports are not able to process their containers. From this perspective, the 1 to 2 days of navigation delay due to the loss of GPS becomes insignificant because it does not matter if a ship is a day late arriving at a port if it will need to queue for a week before being unloaded.

As a result, we did not quantify economic impacts for navigation in seaways resulting from a loss of GPS (see Section 9 for additional discussion) so that we could avoid double counting. Any delay costs associated with navigation are already captured in the port economic impact estimates (Section 8). This is not to say, however, that the loss of GPS does not adversely affect navigation in seaways. Rather, the economic impacts of delays are captured in our port impact estimates.

Many stakeholders also felt that, at least initially, there would be an increased number of accidents and casualties as a result of an unexpected outage of GPS, particularly in the recreational sector where boaters have less training in alternative forms of navigation. U.S. Coast Guard search and rescue would also be impaired, exacerbating any potential impacts. Stakeholders did not venture to guess at the size of these impacts; thus, we did not place a monetary value on them, but we note them here as potentially more acute near-term impacts of an outage.

In addition to stakeholder interviews, RTI also reviewed historical examples of GPS jamming incidents that could speak to the impact of a 30-day GPS outage. For example, in 2016 North Korea engaged in GPS jamming campaigns against South Korea that lasted six days. During this campaign, 1,007 airplanes, 715 ships, and 1,786 cell phone base stations reported being jammed. The jamming impact was felt in the city of Incheon and in Gyeonggi and Gangwon provinces (Yonhap News Agency, 2016a, 2016b). We were unable to identify any study that attempted to quantify the economic consequences of this incident. However, in any case, it not clear whether the experiences of this incident would be generalizable to our study for two reasons. First, our study focuses on the consequences of a global GPS outage, while this GPS jamming event was geographically localized. Second, it is not clear whether this GPS jamming event actually resulted in a localized outage. According to the South Korea's Information and Communication Technology ministry, North Korea's disruptions of GPS signals had been constantly lessening and increasing during the 6 days of the jamming incident (Yonhap News Agency, 2016a). If there was not a complete outage, this could have mitigated the impact of the incident on port operations.

As shown in Table 9-6, economic impacts associated with a 30-day loss of GPS range from $7.8 billion to $14.6 billion, with a point estimate of $10.4 billion. Impacts varied greatly across the maritime subsectors with port operations and resulting economic impacts flowing through the economy accounting for 90% of total impacts.

Table 9-6.   Summary of Economic Impact of 30-Day GPS Outage (million)

Maritime Subsector	Point Estimate ($ million)	Bound ($ million)	
		Lower	Upper
Commercial Fishing	$351	$222	$630
Recreational Boating	$3,262	$2,433	$4,090
Port Operations	$6,733	$5,134	$9,774
Navigation in Seaways	$65	$60	$70
Cruiselines	Negligible		
Total	**$10,411**	**$7,841**	**$14,564**

The range in impact estimates reflects the uncertainty of the technical impact metrics used in the valuation approach, as well as the uncertainty in how well/quickly affected sectors can mitigate impacts of the loss of GPS. For example, the extent to which cargo ships can (or cannot) be rerouted to ports with excess capacity will greatly influence the extended delay time after the 30-day outage ends. However, it is unclear how flexible the land-based transportation system would be to potential rerouting. Hence, the port operations impact estimates have a relatively large range.

9.4.1   Commercial Fishing

Commercial fishing is the activity of catching fish and other seafood for commercial profit. Commercial fishing companies range in size from large corporations to small, family-owned businesses. Commercial fishermen use fishing vessels of variable size and employ a number of catch techniques that vary depending on what species they are intending to catch, as illustrated by Table 9-7.

Table 9-7.   Example Catch Techniques and Species

Catch Technique	Gear Used	Example Species
Bottom trawl	Net towed along ocean floor	Groundfish
Pelagic trawl	Net towed through mid-water	Mackerel and herring
Gillnets	Net suspended in water column	Salmon, tuna, and mullet
Pots or traps	Traps placed on the bottom of the ocean	Lobster and crab
Purse seine	Net deployed from boat and held vertical in the water	Herring, mackerel, sardines, and tuna
Longline	Line with hundreds to thousands of baited hooks	Mackerel, marlin, tuna, and swordfish
Dredge	Heavy steel frame dragged along the bottom of the ocean	Shellfish (oysters, scallops, and muscles)

Note: This table is not intended to be comprehensive.

Commercial fishing usually occurs beyond line of sight to land, and fishermen are often subjected to adverse weather and hazardous work conditions. According to the National Institute for Occupational Safety and Health of the Centers for Disease Control and Prevention (CDC, 2018), "Commercial fishing is one of the most hazardous occupations in the United States with a fatality rate 29 times higher than the national average." These risks involve "… vessel disasters, falls overboard, and machinery on deck" (CDC, 2018). The distance from shore and the likelihood of poor visibility from adverse weather make GPS a vital tool for commercial fishermen.

For the purposes of this study, we are only considering commercial fishing activities that occur within the U.S. Exclusive Economic Zone (EEZ). The U.S. EEZ extends from 3 to up to 200 nautical miles offshore. Commercial fishing in the United States is regulated under the jurisdiction of the NMFS, which is also referred to as the NOAA Fisheries Services. NMFS maintains the nation's commercial fisheries. These fisheries are divided by region, species, and catch method. Example fisheries include "Northeast/Mid-Atlantic American lobster trap/pot" and "WA/OR/CA groundfish trawl." As of 2018, there are 156 commercial fisheries under management by NMFS (National Archives, 2018).

GPS is widely used in the commercial fishing sector with virtually all fishing vessels using GPS in some way. As with the rest of the maritime sector, the primary use of GPS within commercial fishing is for navigational purposes. Commercial fishing vessels are outfitted with a GPS antenna and a unit that provides position and navigation capabilities to fishermen. Fishing vessels are also equipped with gyrocompasses, which rely on GPS for corrections. The position provided by the GPS signal and the heading provided by the gyrocompass are overlaid on the ECDIS. The ECDIS displays this information over an electronic navigational chart or digital nautical chart. Additionally, the ECDIS displays data from the ship's radar and AIS unit when applicable. The ECDIS provides fishing vessel operators a central location to view a large amount of data simultaneously.

Commercial fishermen engaged in bottom trawling are particularly reliant on GPS. They use the precision and accuracy of GPS to know where they are at any given point. By knowing their current position, they can reliably know if the bottom is sandy or rocky and can be aware of any potential "hangs" such as a reef or wreck on the bottom of the ocean. With this knowledge, bottom trawlers can safely navigate hangs to catch fish. Often, trawlers will plot a course they want to trawl and will follow this course precisely using autopilot.

Commercial fishermen who use fixed gear, such as gill nets, lobster pots, or crab pots, are also highly reliant on GPS. These fishermen mark the coordinates of where they place their equipment and rely on these coordinates to find the equipment to retrieve their catch.

Fishermen using other catch techniques, such as long line and mid-water trawling, also rely on GPS. They use GPS to find preferred fishing locations where they have previously had success. Contrary to popular belief, fishermen are not able to catch fish wherever they are. They need to find specific locations where fish tend to congregate.

The NMFS uses GPS as an enabling technology of the VMS. VMS is a regulatory device intended to prevent illegal fishing that reports a ship's location, heading, and speed at regular intervals. These data are provided by a GPS device. These geographic metadata are used to track fishing vessels and to enforce commercial fishery boundaries.

Context Prior to the Adoption of GPS

Before the decommission of Loran base stations, the use of Loran-C was widespread among commercial fishermen. While the absolute accuracy of Loran-C was not as high as GPS, it featured high repeatable accuracy. This repeatability was more important to fishermen than absolute accuracy. It allowed them to reach their preferred fishing locations reliably. Our interviews revealed that commercial fishermen were slow to adopt GPS because of the availability of and familiarity with Loran-C and the increased costs of GPS equipment. GPS did not offer any advantages over Loran-C to justify the increased equipment costs for fishermen. For these reasons, fishermen were among the last users of Loran-C. The use of and preference for Loran-C were so prevalent that many common fishing locations are still referred to using their Loran coordinates rather than reported as latitude and longitude. Once the Loran base stations were decommissioned, fishermen rapidly adopted GPS to fill the void in their positioning and navigation requirements. Today, virtually all fishermen have GPS on their vessels.

Fishermen often use and rely on technologies that are enabled by GPS such as gyrocompasses, electronic charts, and AIS. They are also required to have an onboard VMS in some commercial fisheries. These technologies have made fishing safer and more efficient and improved the regulatory capability of commercial fisheries. The experts we interviewed suggested that these technologies would likely have developed in the absence of GPS and would have relied on the Loran-C infrastructure for their positioning inputs. Thus, we are not attributing the benefits of these technologies to GPS for this analysis.

Enforcement of commercial fishing boundaries was slightly laxer when Loran-C was the primary positioning and navigation solution because of the decreased accuracy of the system. Fishermen were issued a warning rather than citations if they were under a quarter of a mile within the border of a fishery in which they were not permitted. Interviews with commercial fishing personnel indicated that the environmental impacts from decreased enforcement were negligible.

Potential Impacts Associated with a 30-Day Outage

An unanticipated 30-day outage of GPS would have widespread consequences in the commercial fishing sector. Once the Loran-C system was decommissioned, GPS was the primary means of positioning and navigation for commercial fishermen. Today, GPS is the only widespread alternative positioning or navigation solution. Without GPS, fishermen would be forced to rely on traditional techniques and technologies such as magnetic compasses, paper charts, dead reckoning, celestial navigation, and astral navigation. Commercial fishermen are unlikely to become lost during a GPS outage, but their navigational ability would be severely hindered. They would be able to find their way to shore and back to port; however, they would be unable to locate precise locations, such as preferred fishing locations.

Interviews with commercial fishermen indicated that many fishermen would simply avoid fishing during a 30-day outage of GPS, citing safety concerns for their crew, vessels, and equipment and an inability to reliably catch fish. Others would attempt to fish but would have reduced success because of the inability to locate suitable fishing grounds. They would catch some fish, but their catch sizes would be greatly diminished. A larger fishing company indicated that they would not attempt to fish at all during an outage.

Bottom trawlers would be particularly affected by a 30-day outage. Without knowing their precise location, they would be unable to determine if there are underwater hazards (hangs) where they are attempting to fish. Groundfish are often found in the vicinity of these hangs, and the hangs themselves can destroy equipment such as nets. The locations of some hangs are published in paper and digital charts. However, in general, bottom trawlers who attempted to fish during a GPS outage would risk damaging their gear and would have greatly diminished success in finding fish.

Fixed gear operators, such as lobstermen, would also experience hardship during an outage. They would be unable to find gear that they placed before the outage. Interviews indicated that these fishermen would attempt to locate their gear, but without a positioning tool such as GPS, they would be forced to travel around and search for the gear manually. Any gear placed during an outage would similarly be at risk of being lost.

Other fishermen would have a difficult time as well. Dredge fishermen, like bottom trawlers, need to know what the bottom of the ocean is like where they are attempting to fish. Some species of shellfish can only be found in narrow sandy patches alongside rocky outcroppings. Without knowing their precise location, dredge fishermen would be unable to find these locations and would be unable to fish successfully. Other fishermen, such as long liners and purse seiners, may have better luck if they are able to successfully locate fish.

Regulation of commercial fisheries would be hindered during a GPS outage. Fishermen would be unable to determine if they are within the boundaries of the commercial fishery they are permitted to fish in and would be unable to determine if they are within the boundaries of a closed commercial fishery. Similarly, law enforcement would be unable to reliably determine where the boundaries of commercial fisheries are. Regulation and enforcement personnel we interviewed indicated that enforcement would be necessarily lax during a GPS outage, but they did not anticipate any environmental damage during the 30-day window.

As part of our interview process, we asked commercial fishermen to quantify the impacts of a 30-day GPS outage in terms of lost revenue from decreased catch sizes. They collectively indicated that a 30-day outage of GPS would result in a 75% to 90% loss in revenue.[42] This loss in revenue is representative of the lost revenue from fishermen who continue to fish and those who stop operating during a GPS outage.

---

[42] This is an industry-wide estimate and does not attempt to disaggregate lost revenue for specific types of fishermen.

The commercial fishing industry experiences seasonal variations in catch revenue. Using monthly catch revenue data from NOAA fisheries from 1990 through 2016 (NOAA, 2019), we see that revenue for commercial fishermen is lowest in winter and early spring and highest during the summer and early autumn (June through September). Figure 9-1 shows the percentage share of catch revenue by month from 1990 through 2016. Because of this seasonal variability, the timing of a 30-day outage of GPS would determine the severity of the impact.

To determine the potential impacts of a 30-day outage of GPS, we analyzed monthly catch revenue data from NOAA fisheries for 2016 (NOAA, 2019). At the time of writing, this is the most recent data available. We converted these monthly revenues into 30-day revenues using this formula:

Adjusted 30-day revenue = monthly revenue x (30/days in month)

Approximately 84% of the catch revenue from 2016 did not have a month specified. We assumed that this catch revenue followed the same distribution as the catch revenue that was reported. We determined the share of annual revenue for each month and then multiplied the annual catch revenue by these shares to estimate the catch revenue for each month.

Table 9-8 shows the adjusted monthly revenue and the percentage share of revenue for 2016.

Figure 9-1.   Average Percentage of Annual Catch Revenue by Month, 1990–2016

Table 9-8.   Catch Revenue by Month, 2016

Month	Catch Revenue	% Share of Annual Revenue
January	$290,728,074	5.4%
February	$372,429,551	6.9%
March	$317,862,087	5.9%
April	$325,807,754	6.1%
May	$455,558,590	8.5%
June	$512,635,082	9.5%
July	$375,419,265	7.0%
August	$687,261,535	12.8%
September	$600,879,855	11.2%
October	$583,008,120	10.8%
November	$466,785,431	8.7%
December	$385,540,629	7.2%
Total	$5,373,915,977	100.0%

Note: Values are in nominal 2016 U.S. dollars.

To create a lower bound impact estimate, we used catch revenue from January, the month with the lowest revenue, and imposed a 75% loss in revenue. We then created an upper-bound impact using catch revenue from August, the month with the highest revenue, and imposed a 90% loss in revenue. To determine the median impact, we imposed a 75% to 90% loss in revenue to the revenues for each month in 2016. The monthly distribution of the potential impacts is skewed to the lower end. Using a gross domestic product deflator from the Federal Reserve Bank of St. Louis (FRED, 2019), we converted all 2016 nominal values to 2017 real values. These values are presented in Table 9-9.

Our analysis indicates that because of an inability to fish or reduced efficiencies, commercial fishermen would experience lost revenues ranging from $222.2 million to $630.3 million. The median of the lost revenues is $351.2 million.[43]

Table 9-9.   Quantitative Impacts of a 30-Day GPS Outage

Lost revenue (lower bound)	$222.2 million
Lost revenue (median)	$351.2 million
Lost revenue (upper bound)	$630.3 million

Note: Values are in real 2017 U.S. dollars.

9.4.2   *Recreational Boating and Fishing*

Recreational boating and fishing is a large industry and a popular activity in the United States. In 2017, there were 12 million registered boats in the United States, or approximately 1 registered boater for every 10 houses (National Marine Manufacturers Association [NMMA], 2017). An estimated 142 million individuals (adults and children) were active boaters in 2016, spending an average of 14.3 days on the water, for a total of more than 2 billion total boating days (Quarles, 2017). According to survey data,

---

[43] Note, the median is not the average of the upper and lower bounds because of the skew in the monthly catch.

recreational boaters participate in a variety of activities while boating, including spending time with friends and family, enjoying nature, relaxing, fishing, and engaging in water sports (Quarles, 2017).

We found no recent published data on the number of recreational boaters who use GPS, but active recreational boaters thought the number was quite substantial. Many said that recreational boaters rely heavily on GPS for navigation, particularly when they are in the open sea or farther from known landmarks. The degree to which recreational boaters rely on GPS also depends on whether or what kind of recreational boating they are involved in. In general, according to avid recreational boaters, recreational anglers rely more on GPS to find their favorite fishing spots, and recreational boaters with motorized vessels rely more GPS because they are more likely to venture farther from known landmarks.

Context Prior to the Adoption of GPS

Before the advent of GPS, many recreational boaters used a combination of Loran-C radios, compasses, and paper charts. Loran provided a benefit to recreational boaters over more traditional technologies, because it saved time, fuel, and costs, particularly for longer trips. Based on our interviews, recreational boaters unanimously thought that the accuracy of Loran was sufficient for their needs and that if Loran had stayed operational GPS would have provided minimal benefits to this sector. Thus, we did not quantify the benefits from the retrospective analysis for recreational boating and fishing.

Potential Impacts Associated with a 30-Day Outage

According to industry experts and avid recreational boaters and fisherman, an unexpected GPS outage would have significant impacts on the recreational boating sector. Unlike for commercial vessels, no regulations require that recreational boaters have formal navigation training or equipment. Many recreational boaters rely heavily on GPS, and in the event of an unexpected GPS outage, many boaters would have difficulty finding their way back to known landmarks or could get lost trying to do so.

For those boaters who had not yet planned their trips, they would either cancel their trip, postpone the trip, or continue with the trip but stay closer to known landmarks. The choice depends on several factors, including what kind of recreational boating and fishing they do, the distance of the trip, the length of the GPS outage, the experience level of the boater, and weather conditions.

One of the most important factors influencing the impact of the outage was the type of recreational boating being conducted. Like commercial fisherman, recreational fishermen rely heavily on GPS to locate fishing spots. These are often very spatially specific areas near landmarks such as sunken ships or coral reefs that would be more difficult to find without GPS. Saltwater fishermen are much more likely to rely on GPS to find fishing hot spots than freshwater fishermen in lakes and rivers. Recreational boaters in motorized vessels who do not fish also rely on GPS but more for navigation purposes and to avoid getting lost rather than finding very specifically defined geographic locations. Recreational boaters who do not fish and rely on nonmotorized vessels such a sailboats, rafts, kayaks, and canoes are the least likely to rely on GPS.

The first outcome during a 30-day outage of GPS would be that the recreational boaters who are far out at sea would have difficulty finding their way to their destination. Boaters would have to revert to a compass

and stopwatch and have to guess at the drift of the current to find their way. Even the most experienced recreational boaters who are trained navigators and have been boating most of their lives (40+ years) said that they would be nervous if GPS went out when they are far from their destination and that they would not undertake long multiday boating excursions in the ocean if their GPS were not working.

For those boaters who are not already at sea, the choice of whether to go boating on the eve of a 30-day outage depends on the distance they expect to travel and length of the GPS outage. Several recreational boaters said that they or their fellow boaters would either not go out on the water if GPS went down or heavily curtail their trip, but the longer the delay the more likely they would find a way to return to boating by exploring alternative technologies and/or making plans to stay closer to shore. Bad weather, such as fog, would also influence their decision on whether to go on an excursion because GPS becomes more important when visibility is low.

Our approach to valuing the impacts of a 30-day outage focused primarily on recreational boaters' choice to curtail or cancel time spent on the water as a result of the outage. Because recreational boating does not generate products or values that can be traded in markets, we used a nonmarket valuation approach to value the lost benefits due to reduced recreational boating trips. This method involved capturing people's WTP to value the enjoyment they derive from the activity. We valued the impact of a 30-day outage in two main steps: First, we calculated the total value that recreational boaters derive for an average month of trips. Then, we calculated the reduction in trips if there were a 30-day failure of GPS. This methodology incorporated national-level data sources and thus does not been to be scaled up to the national level.

$$V_b = (B_a * D_b * T_b * WTP_b)/12 \tag{9.1}$$

$$V_{Ib} = V_b * I_{gpsb} \tag{9.2}$$

where

- V_b = Value according to type of boating
- V_{Ib} = Value of GPS outage on type of boating
- B_a = Active boaters in a year
- D_b = Average days boating per active boater in a year
- T_b = Share of type of recreational boating (e.g., freshwater fishing, saltwater fishing, nonmotorized boating, motorized boating)
- WTP = WTP/day according to type of recreational boating
- I_{gps} = Percentage impact according to type of boating

We used several data sources to derive the nonmarket value of the sector, including published literature and stakeholder interview feedback (see Table 9-10). We used published literature to derive the average value of the recreational boating sector for 30 days; then we applied feedback from the recreational boating stakeholder interviews to estimate the impact of an unexpected GPS failure in terms of number of days (and, hence, enjoyment value) lost as a result of the outage.

Table 9-10. Data Points and Sources

Data	Source
WTP for recreational boating	Recreational Use Values Database (2016)
Total boating days and percentage time spent fishing vs. recreational boating	2016 Recreational Boating Participation Study (Quarles, 2017)
Percentage of motorized vs. nonmotorized boating hours	National Recreational Boating Survey (2012) (U.S. Coast Guard, 2012, p. 62)
Freshwater vs. saltwater fishing[a]	American Sportfishing Association (2018)
Impact of 30-day GPS outages	Stakeholder interviews

[a] Average values from 2017. For combined freshwater and saltwater, assumed activities were half freshwater and half saltwater.

The 2016 Recreational Use Values Database for North America, hosted by Oregon State University, aggregates more than 3,000 estimates of recreational use values from more than 400 studies from 1958 through 2015. The database incorporates use values for 21 recreational activities including saltwater fishing, freshwater fishing, motorized boating, and nonmotorized boating.[44] Table 9-11 shows the four categories of recreational use values related to recreational boating, the mean dollar value of net consumer surplus (e.g., the economic value to recreational boaters) for each category, and the number of estimates averaged in the analysis. We restricted the data to only estimates from the United States and only from the last 20 years (e.g., 1999 to the present day for the value year [indicator V118]) to try to capture the value for when GPS was available. We also excluded any estimates that were based on a self-reported "bad" model (only one study). Many of the studies contain more than one estimate, which represents the fact that some studies had multiple estimates depending on the methods used, year of the data, or contextual factors such as specific geographies. We took an average value because we had no basis for selecting one estimate over another.

Table 9-11.   Recreational Boating Values[a]

Recreational Boating Category	Mean Daily Value (2017$)	Number of WTP Estimates
Saltwater fishing	$124.74	20
Freshwater fishing	$84.91	283
Motorized boating	$95.96	9
Nonmotorized boating	$102.77	16

[a] The database combines estimates for fishing that occurs from boats with fishing that occurs from land. Although this may cause some bias, there is not enough information to speculate whether this would lead to a positive or negative bias.

---

[44] The database identifies these as "primary" activities, which helps explain why fishing and boating are separate categories even though fishing often takes place on a boat.

Results: We estimate the total 30-day value of the recreational boating sector to be $16.2 billion (Table 9-12). We estimate the total impact of a 30-day GPS outage to the recreational boating sector to be between $2.5 and $4.2 billion (Table 9-13). The greatest impact would be on motorized boating ($1.8 billion to $2.9 billion), followed by recreational saltwater fishing ($418 million to $696 million), then nonmotorized boating ($136 million to $317 million), and, lastly, recreational freshwater fishing ($154 million to $308 million).

Table 9-12. Value of Recreational Boating

Type of Boating	Total Boating Days in a Year (million)[a]	WTP per Day	Recreational Value in 30 Days ($ million)
Recreational saltwater fishing	136.0	$124.74	$1,393
Recreational freshwater fishing	441.1	$84.91	$3,077
Motorized boating	912.1	$95.96	$7,190
Nonmotorized boating	535.7	$102.77	$4,522
Total	2024.9		$16,182

Note: Totals may not sum up because of rounding.

[a] Assumed 141.6M active boaters per year and 14.3 days of active boating to arrive at total boating days in a year. Assumed that 28.5% of these total boating days are spent fishing (57% of actives boaters said they fish while boating at some point during the year but did not specify the number of days, so we assumed they fish half of those days), and of those, 76% are freshwater fishing and 24% are saltwater fishing. For the 71% of nonfishing boating days, assumed 63% are motorized boating and 37% are nonmotorized boating. All data sources are provided in Table 7-1. Assumed powerboats and personal watercraft are motorized.

Table 9-13. Impact of a GPS Outage

Type of Boating	Recreational Value in 30 Days ($ million)	Percentage Impact of 30-Day Outage	Total Recreational Impact ($ million)
Recreational saltwater fishing	$1,393	30–50%	$418–$696
Recreational freshwater fishing	$3,077	5–10%	$154–$308
Motorized boating	$7,190	25–40%	$1,797–$2,876
Nonmotorized boating	$4,522	3–7%	$136–$317
Total	$16,182		$2,505–$4,197

Note: Totals may not sum up because of rounding.

Although we did not value potential boating casualty numbers as a result of a GPS outage, several stakeholders said that if GPS were unavailable for 1 month, they would expect to see a measurable increase in the number of accidents and casualties. Table 9-14 shows the average number of accidents, deaths, injuries, and casualties per month. These data can be considered the

Table 9-14. Baseline Boating Casualty Numbers (2017)

	2012 Annual Numbers	30-Day Average
Accidents	4,291	352
Deaths	658	54
Injuries	2,629	216

Source: 2017 Recreational Boating Statistics (U.S. Coast Guard, 2018a).

baseline number of boating casualties that might be expected in the time frame of a 30-day period (with GPS), but stakeholders felt that these numbers might increase in the event of an unexpected GPS outage. Experts felt that in addition to the possibility of getting lost, recreational boaters would have a much higher risk for grounding during approaches to shore without GPS. Getting lost would be exacerbated by the fact that it would be much more difficult for the U.S. Coast Guard and its helicopters to find boaters without GPS. Additionally, because we did not attempt to monetize any stress or trauma related to boaters who are temporarily lost at sea or any accidents or casualties associated with an unexpected GPS outage, actual impacts to recreational boaters may be greater that what is estimated above.

Other impacts could occur as a result of an GPS outage that may be smaller in economic value but are still notable because of their direct impact on certain industries. Stakeholders thought there would be an economic impact and strain on "response towing" companies and their ability to respond to and tow stranded boats (see text box).

Maritime First Responders in the Event of a GPS Outage

The Conference of Professional Operators for Response Towing (C-PORT), founded in 1986, is an association representing the marine assistance industry, or those who tow in boats when they break down and often help with locating boats in search and rescue. They represent approximately 250 companies nationwide and primarily comprise small boating companies that specialize in towing stranded vessels. Maritime response towers would be one of the subsectors most directly affected in the event of a GPS outage.

According to C-PORT, even "24 hours without GPS in the maritime world would be a catastrophe." Recreational boaters already on the water would have difficulty or be unable to seek assistance in the event of an emergency such as an engine failure. These boats would potentially be stuck on the water and would need to be rescued. C-PORT members are responsible for towing boats that have broken down, while the U.S. Coast Guard is responsible for rescue operations of people. Many of the Coast Guard rescues involve helicopter rescue operations. In the event of a boating emergency, these types of rescue operations would be more likely to occur and responding effectively would be more difficult.

There would also be economic impacts associated with inefficiencies in towing operations. In the event of a GPS outage, the available backups are much less effective at identifying a boat's location. Some boats do have a VHF radio, which can be located by rescue boats with Automatic Direction Finders, but this is a less efficient way to find lost boats than GPS. Cell phones may also work if they are close enough to shore to access a signal and if boaters are able to accurately describe where they are to a first responder.

C-PORT estimates that the United States has approximately 125,000 cases of boats that needed to be towed in 2018. A majority of these boats use GPS to call for help, and market rates for boat towing are $350 to $450 per hour. Service agreements generally stipulate that responders be on the scene within an hour. In the event of a GPS outage, these towing operations would become less efficient and take longer to locate boats on the water. Assuming conservatively that the towing organization would spend an additional hour to find the boat, multiplying the market rates of the towing operation by the average number of cases per month results in $4.28M in additional costs ($400 x 1 hour per case x (125,000/365.25*30)) for this subsector.

Limitations

There is no doubt that a 30-day GPS outage would have a large impact on the recreational boating sector; however, there are several limitations to pinpointing the exact size of the impact that should be considered. We assumed that any boating days lost during the outage would not be recovered during a later time period. It is possible that people might just postpone their trips rather than cancel them. We also did not take into account any reduced spending on boat maintenance, fuel, fishing supplies, or other boating-associated costs or their overall impact on the economy. Boaters might stock up on fuel as a result of the outage initially; they would then use less fuel as the outage continued for a longer time period. These factors would have mixed impacts on recreational boaters. In addition to recreational boating,

service and retail industries that rely on the recreational boating and fishing industries, such as maintenance and equipment providers, restaurants, and retails shops near popular boating and fishing destinations, would also be affected by a 30-day GPS outage but are not included in these estimates.

Few stakeholders were able to provide percentage estimates for the impact of a GPS outage on recreational boating, and estimates varied significantly depending on the type of recreational boating being conducted. The percentage impacts for each recreational boating type provided in this analysis are RTI's estimation of impacts based on interpretation of the interviews and validated by several experts, but they could be improved on through further surveys of the recreational boating sector.

9.4.3 Port Operations

Ports are commonly recognized as places where cargo is transferred between ships and the shore. GPS is particularly critical in the operations of ports that process containerized cargo. Cargo is containerized when it is placed in standard shipping containers that can be handled interchangeably on vessels, in terminals, and via inland transport modes. Approximately 90% of dry, nonbulk manufactured goods in international trade are currently shipped in containers (USDOT, 2017).

According to the U.S. Department of Transportation, 63 U.S. ports processed containerized cargo in 2017. Summary statistics for the 15 largest container ports are provided in Table 9-15. Note that containers used in maritime trade can come in various sizes (standard lengths include 20 feet, 40 feet, and 45 feet). Therefore, the amount of container traffic processed by these ports is standardized to 20-foot equivalent units (TEU), which is equal to one 20-foot container (USDOT, 2017).

Table 9-15. Summary Statistics for U.S. Container Ports

U.S. Customs Ports	2017 Import (TEUs)[a]	Container Yard Capacity Utilization Rate (%)[b]	Standard Operating Days per Year [c]	Value of Average Container ($/TEU)[d]
Los Angeles, CA	4,590,451	75	312	$33,691
Long Beach, CA	3,792,165	75	312	$34,423
New York, NY	3,402,440	75	260	$30,140
Savannah, GA	1,863,000	36	260	$35,439
Norfolk, VA	1,233,598	83	286	$36,661
Houston, TX	1,071,689	57	260	$29,537
Charleston, SC	946,790	25	312	$40,056
Oakland, CA	879,839	53	260	$30,539
Tacoma, WA	777,147	37	260	$47,626
Seattle, WA	595,404	64	260	$31,182
Baltimore, MD[e]	468,100	23	260	$34,715
Miami, FL[e]	418,402	53	260	$37,985
Port Everglades, FL[e]	357,425	42	260	$30,391

(continued)

Table 9-15. Summary Statistics for U.S. Container Ports (continued)

U.S. Customs Ports	2017 Import (TEUs)[a]	Container Yard Capacity Utilization Rate (%)[b]	Standard Operating Days per Year[c]	Value of Average Container ($/TEU)
Jacksonville, FL[e]	322,721	24	260	$17,416
Philadelphia, PA[e]	277,470	N/A[f]	260	$29,790

[a] U.S. Department of Transportation Maritime Administration (2017).

[b] Institute for Water Resources (2012). Note that capacity utilization figures reported in this document are for 2010. They were used for this analysis because they were the most recent estimates available.

[c] RTI obtained information on the standard number of operating days per week through personal communications with port personnel for each of the following ports: Los Angeles, Long Beach, New York, Norfolk, Houston, Oakland, and Seattle. We obtained information on operating hours for the remaining ports from their websites. Next, we multiplied the number of operating days per week by the number of weeks in a year (i.e., 52 weeks).

[e] Note; these smaller ports were not included in the final impact analysis.

[f] Container yard capacity utilization estimates were not available for the port of Philadelphia.

How ports process containerized cargo can be divided into a series of three steps or activities:

1. **Vessel activities:** Vessels containing containerized cargo arrive at the port to be unloaded. After the vessel is docked, it is unloaded by a dockside crane. Arriving vessels are typically unloaded every day of the week.

2. **Container yard activities:** The unloaded containers are then sorted, stacked, and organized in a container yard.

3. **Gate activities:** Next, containers are loaded onto trucks or trains so that they can be transported to their next destination. We found that at most large ports gates are only open 5 days per week (i.e., Monday through Friday).

The extent to which GPS is used in port operations can differ greatly across individual ports. Based on industry interviews, RTI found that smaller ports that process fewer than 500,000 TEUs per year do not currently rely on GPS for much of their port operations because they process so few containers that their vessel, container yard, and gate activities are carried out through largely manual means.

In contrast, larger ports that process 500,000 TEUs or more per year employ equipment that relies on GPS for positioning and often automates the processing of containerized cargo. Specifically, at these larger ports, GPS is used in each of the three port activities described above.

1. **GPS in vessel activities:** GPS is used by container vessels to automatically estimate the time they will arrive at a destination port. This estimated time to arrival is then sent to the destination port, which uses this information to schedule labor and other resources so that the vessel can be unloaded in a timely fashion.

2. **GPS in container yard activities:** GPS is used to move the cargo containers around the container yard. Specifically, GPS is critical for logging the location of a stacked container so that it can be easily located and retrieved in the future. In container yards that are highly automated, GPS is even more critical because robotic equipment uses it to automatically establish its own position as well as the position of the containers it must retrieve.

3. **GPS in gate activities:** The cargo can then be moved out of the port using trucks that use GPS-enabled logistics systems.

As a result, only the top 10 largest ports in the United States that exceed the 500,000 TEUs threshold were included in the impact analysis.

Context Prior to the Adoption of GPS

Having precise location data has become critical for efficient operations at larger ports because it allows operators to track when vessels will arrive at the port and to track containers that are stacked within the port itself. Currently, GPS provides that location data. However, if GPS had not been available, it is likely that localized, terrestrial positioning systems would have been developed and deployed to meet the positioning needs of this subsector.

For example, "pseudo-satellite" (or pseudolite) technology has already been developed that can serve as an alternative to GPS. This technology uses terrestrial transmitters that broadcast signals that are compatible with existing GPS equipment (Raquet, 2013). An example of pseudolite technology that is already being implemented at a few ports internationally is Locata, a network of ground transmitters that blanket a chosen area with strong radio-positioning systems. For example, several terminals that are owned by the Eurogate shipping company in the port of Wilhelmshaven in Germany are implementing a Locata-based system that will automate many port operations, including container positioning (The Maritime Executive, 2018).

It is highly likely that pseudolite technologies like Locata would have been deployed in ports around the world where GPS was not available. Pseudolite technologies offer comparable efficiency improvements compared with GPS. As a result, we did not quantify the retrospective economic benefits of GPS because they would likely have existed in the absence of GPS via alternative technologies.

Potential Impacts Associated with a 30-Day Outage

Based on our interviews with industry experts, RTI learned that a 30-day GPS outage would be disruptive to larger port operations because, as described above, the location information used for creating accurate timetables of vessel arrivals and managing containing yard activities would no longer be available. As a result, ports would have to use manual means to manage the transfer of containers. For example, instead of using GPS coordinates to track containers that are stacked in the container yard, port operators would have to use manual methods similar to those used at smaller ports.[45]

The primary consequence of using manual methods to process arriving containers is that this would significantly slow down port operations. One expert commented that ports would be temporarily shut down because much of the automated equipment currently used at ports would not operate. Another expert indicated that during the outage efficiency of larger ports might drop by 50%.

It is likely that ports themselves would incur costs because they would have to implement new methods for processing containers in the absence of GPS. However, these costs are difficult to quantify because the hours involved would likely differ across ports. We also believe that the magnitude of these costs would

---

[45] Above we described pseudolite technologies that could potentially be used as a secondary system in the event of a GPS outage. However, RTI's interviews with industry experts revealed that almost no ports in the United States currently use these technologies and they cannot be installed and operationalized with a 30-day period.

pale in comparison to the costs incurred by commercial enterprises whose shipments would be delayed by reduced port efficiency because many U.S. firms keep very low inventories as part of their just-in-time inventory management strategies.[46] As a consequence, if companies in these industries cannot receive crucial components in their production process, they will not be able to rely on inventories to support their production for very long.[47] This became a real problem for many automobile manufacturers in 2002 when a dispute between the International Longshoreman and Warehouse Union and the Pacific Maritime Association led to the shutdown of 29 ports along the U.S. West Coast for 10 days. According to various news reports published during the period, several automobile manufacturing facilities were forced to halt production because of parts shortages. For example, only 4 days into the 2002 West Coast port shutdown, New United Motor Manufacturing Inc. (NUMMI, a joint venture between Toyota and General Motors) stopped production at its facility in Fremont, California, because of a lack of a single crucial part (Wolk, 2002). The NUMMI facility builds the Pontiac Vibe, Toyota Corolla, and Tacoma pickups.

RTI estimates that a 30-day outage would create up to $7 billion in losses by delaying cargo passing through ports processing 500,000 TEUs or more per year. Estimates for losses by port are provided in Table 9-16.

Table 9-16. Summary of Economic Losses by Port

Affected U.S. Ports	30-Day GPS Outage Cumulative Economic Losses ($)	Post-GPS Outage Cumulative Economic Losses ($)	Total Cumulative Economic Losses ($)
Los Angeles, CA	791,250,670	1,475,672,610	2,266,923,280
Long Beach, CA	667,845,032	1,245,522,639	1,913,367,671
New York, NY	472,925,933	345,401,450	818,327,384
Savannah, GA	304,478,094	46,338,282	350,816,376
Norfolk, VA	221,006,453	255,018,310	476,024,763
Houston, TX	145,980,331	52,849,493	198,829,824
Charleston, SC	194,029,040	28,076,006	222,105,046
Oakland, CA	123,911,513	38,474,795	162,386,308
Tacoma, WA	170,690,138	27,227,867	197,918,005
Seattle, WA	85,621,016	40,488,130	126,109,146
Total	**3,177,738,219**	**3,555,069,583**	**6,732,807,802**

---

[46] For example, in 2002, Dell Computer turned its inventory over 60 times per year (Gross, 2002).

[47] A GPS outage would affect foreign producers in a similar fashion by delaying U.S. exports that would serve as inputs in their production process. However, the purpose of this study is to estimate the economic contributions of GPS to the United States. Therefore, the delays created in transporting U.S. exports are not considered in our estimates.

To establish the reasonableness of this economic loss estimate, we reviewed other estimates in the literature of the economic consequences of port closures. For example, a 2014 analysis commissioned by the National Association of Manufacturers and the National Retail Federation estimated that if all West Coast ports close for 20 days this would result in $48 billion in lost economic activity in 2013 dollars or $50.9 billion in 2017 dollars (Inforum, 2014).[48] Another study we identified that also estimated the economic consequences of a port closure is Park (2008). This study found that economic losses created from import distances due to the Port of Los Angeles and Port of Long Beach closing for 1 month as the result of a dirty bomb would total $27 billion.

These estimates are significantly larger than our own estimates. We believe this is what we would expect for two reasons. First, Inforum (2014) and Park (2008) consider ports being entirely closed for 20 to 30 days, while we only consider a scenario where large ports operate at lower efficiency for 30 days. Second, our studies use very different methodologies. Specifically, our study focuses on quantifying economic losses from increased wait times. In contrast, the others use macroeconomic models that consider linkages across the entire economy and do not explicitly quantify losses from wait times in the same way we do.

To estimate economic losses created by delays during the 30-day outage, we first estimated the economic losses for each of the 10 ports that processes at least 500,000 TEUs or more per year (see Table 9-15). We focused our analysis on these ports because they are more likely to employ equipment that relies on GPS positioning as discussed above. Next, we summed these losses together to obtain a national impact estimate. Overall, we estimated that delays created by the 30-day GPS outage will create $3 billion in national economic losses. Note that this approach assumes that during the GPS outage vessels arriving to large U.S. posts do not reroute to smaller ports that are not affected by the outage. We believe that this assumption is justified because during such a short time period it would be difficult for supply chains to be adjusted in such a way that would allow significant rerouting.

Second, to estimate national economic losses created by delays endured after the 30-day outage is over, we needed to determine how much excess capacity is available to deplete all the backlog and return the larger ports to their normal operations. If we continue to assume that there is no rerouting of vessels, then this effectively means that it would be up to each port to clear its backlogs on its own. So the only relevant excess capacity is the excess capacity at each individual port. Therefore, we can estimate the economic losses that would be incurred at each port separately and then sum those losses together (see Table 9-16). Specifically, we estimate that subsequent delays after the 30-day GPS outage would create $4 billion in economic losses.

It is important to note that there is some uncertainty underlying this $7 billion point estimate of the economic losses created by a GPS outage. For example, one area of uncertainty relates to how much port throughput will be affected by the outage itself. As we discuss below, stakeholder interviews revealed that the immediate consequences of an outage would be dramatic, basically closing most large terminals. However, as time goes on, throughput would gradually increase as ports identify and implement

---

[48] To make this economic loss estimate more comparable to our own, we converted 2013 dollars to 2017 real dollars using the gross domestic product deflator.

mitigation strategies, with possibly as much as 50% of the throughput resuming. However, it is not clear how quickly port throughput will increase to this level. For the purposes of the main analysis, we assumed it takes 15 days. Yet, it is possible it could be shorter or take longer for port throughput to return to 50%. To see how changing this assumption would alter our point estimate of economic losses, we re-estimated the costs assuming port throughput reaches 50% of normal levels in 7 days and 30 days after the GPS outage begins. Under these assumptions, the economic losses would be 5.1 billion and $9.8 billion, respectively.

9.4.4   *Navigation in Seaways*

GPS has been thoroughly integrated into marine navigation systems, and mariners and data analysts use it regularly in their work. It is built into electronic chart viewers and AIS, and marine industry companies use the data it generates to support evidence-based decision-making. There are no official data sources on how widespread GPS adoption has become; however, most mariners interviewed for this study confirmed that GPS technology is nearly ubiquitous on maritime vessels, particularly large vessels that navigate over long distances.

Despite its pervasive use, professional mariners, including marine pilots and sea captains, are trained at navigation and can manage to get to their destinations without GPS and consider GPS to be a technology that is not necessary but "nice to have." When close to shore, professional mariners can also use visual aids and radar, and when out at sea, they can use compasses and speed, and many are even trained in celestial navigation. There could still be some efficiency and safety impacts related to navigation in the event of an unexpected outage of GPS, largely because many mariners have become highly reliant on GPS in recent years and traditional navigation skills may not be as well honed as they could be. Impacts would be particularly strong in the recreational boating sector; however, many of the impacts for commercial ships would be mitigated by the ability for trained mariners to resort to traditional technologies, techniques, and skills.

Context Prior to the Adoption of GPS

Before the advent of GPS, mariners relied much more heavily on traditional technologies but also many carried paper maps and most also adopted Loran or Loran-C when those technologies became available. Because Loran systems were land based, they did not have the same range, coverage, and reliability as GPS does today. At the time that GPS was adopted, Loran systems were improving, and eLoran, in particular, was improving in accuracy and reliability. According to experts, when GPS was developed, advances in Loran R&D and development slowed significantly; thus, it did not advance much beyond its initial capabilities. One expert remembers using an early eLoran receiver that had better accuracy than Loran-C. Many experts thought that in the absence of GPS, Loran could have been developed and could have played similar roles that GPS plays today. The development of these technologies might have required additional R&D and infrastructure development (namely expansion of the Loran towers) but could have been achieved.

Furthermore, we assumed that electronic chart viewers, AIS, and other technologies that integrate GPS could have been developed with similar advancements in Loran (though likely would have taken longer). Given that Loran systems could have been developed further in the absence of GPS, we conclude that GPS would not necessarily have provided significant, quantifiable benefits historically over alternative technologies and that the historical benefits of GPS for navigation would have been minimal.

Potential Impacts Associated with a 30-Day Outage

In the event of an unexpected 30-day GPS outage, there would be several initial operational impacts. Today, many navigation systems such as GPS, AIS, radar, and electronic chart viewers are integrated and connected to warning systems, and if GPS went down, there would be some initial chaos. Alarm bells on many ships would be activated, and electronic chart viewers and AIS would lose their location functionality. Initially, this could create concern and may overwhelm crews trying to manually override GPS on these interconnected systems. However, most experts thought that mariners would be able to take necessary precautions, such as anchoring the ship until they could figure out how to transition to navigating without GPS. For the most part, after the initial adjustment, experts felt that the slowdown for large vessels would be much less significant, because professional mariners know how to navigate without GPS and would take necessary precautions. Pilots are especially knowledgeable of their waters, and all large vessels have pilots on board.

Where impacts would be most significant is for certain approaches or narrow channels that are more difficult to navigate. There also might be slowdowns or delays especially on days with poor weather (e.g., foggy or snowy nights). Sea captains and pilots would have to slow down and be more cautious with their approach. This would take more time and cause delays; however, these delays would likely be less than the delays and backups that would occur at ports as a result of efficiency losses. We did not quantify any of these hypothetical delays because we do not want to double-count any greater delays that may be occurring at ports. If ships are delayed and they arrive at a port and cannot be admitted/processed, then there would be no advantage to them arriving earlier.

There would also be some impacts on businesses and nonprofit organizations that rely on AIS data to track vessel movements. AIS data track boat locations and movements in real time, and many businesses use this data for maritime decision-making. Historical data would presumably still be available, but Oceaneering is a publicly traded company that offers the PortVision 360 service, which relies heavily on AIS data to track real-time ship locations and maintains a database of historical vessel movements. Clients use this data to improve vessel safety and dock management and to monitor air quality and vessel speeds (PortVision, 2016). The Maritime Information Services of North America (n.d.) is "a coalition of non-profit maritime information service organizations that use AIS and other data to support safe, secure, efficient and environmentally sound maritime operations." The Army Corps of Engineers also uses AIS data to track vessel movements.

Certain subsectors within the maritime industry would be more affected than others in the event of a GPS outage. For example, one expert in the marine towing industry discussed how towboats and tugboats use GPS-assisted systems to carefully maneuver narrow or restricted channels such as certain spots in the

Mississippi River. Pilots of these boats would have to revert to older ways of navigating, which might reduce their efficiency by 20 to 25%. At first, a GPS outage might also cause a regulatory issue because towing vessels are now required to have an electronic chart viewer and AIS. If these systems are not working, then all towing traffic would have to stop until regulatory authorities figure out what to do. According to one expert, it might take the U.S. Coast Guard a few days to post a marine safety bulletin to change the rules. The tugboat and towing industry as a whole accounts for $2.6 billion in revenue per year (Kalyani, 2018). If we assume all tugboats and towboats would have to shut down for 3 days, and then there would be a 20 to 25% efficiency loss over the remaining 27 days, this would be equivalent to a $60M to $70M impact.[49]

In this section, we highlight and value some potential impacts of an unexpected 30-day outage of GPS; however, we recognize that unexpected or unforeseen impacts could arise as a result of the pervasiveness of GPS and GNSS systems in maritime navigation technologies. A report published by Johnson, Shea, and Holloway (2008) provides a cautionary analysis of both the benefits of, potential overreliance on, and overconfidence in GPS technology. It includes a summary of the famous case of the Royal Majesty passenger ship and the less well-known Sanga Na Langa ship and the role that GPS played in these accidents. The Royal Majesty grounded near Nantucket Island in 1995, largely due to issues with the GPS system on board the ship. Luckily none of the more than 1,500 passengers aboard the ship were injured, but it did cause $7 million[50] worth of damages (National Transportation Safety Board, 1997).

9.4.5   Cruise Ship Industry

Prior to GPS being widely available, cruise ships used astral navigation and traditional bearings with position plotting done on paper charts for ocean crossings. While within a few hundred miles of short cruise ships typically used to the Loran-C system. As the cruise industry has transitioned over time it has moved away from long ocean crossing trips to shorter legs cruising from port to port. As such the ability to safely and efficiently navigate in and out of ports has become increasingly important and a suit of techniques and skills have been refined. Historic alternatives for short range navigation systems included Transit satnav, OMEGA system, and DEKA in North Western Europe. Combinations of Loran-C and differential stations, OMEGA and/or DEKA produced better accuracies than any single system on its own.

The motivating factor for adopting GPS when it became available was better accuracy and simplicity. Cruise ships have continued to increase in size, and GPS allowed better navigation in ports and tight waterways (neither of which are getting larger). As GPS was adopted, there was an improved ability to navigate because continuous positioning was available. The current use of the Trackpilot systems (form of autopilot integrated into an Inertial Navigation System) is an example of a GPS-based system that is critical to the cruise industry today.

---

[49] This is not to be confused with response towing impacts, which are discussed in the recreational boating section above.
[50] The report does not specify what year this number comes from, but if we assume it is in 1995 dollars, this would be equivalent to $10.5M in 2017 dollars (inflated using the Federal Reserve Economic Data GDP Price Deflator, http://fred.stlouisfed.org).

Context Prior to the Adoption of GPS

Although the cruise ship industry is very supportive and appreciative of the availability of GPS, no one we interviewed thought there would be significant differences in the evolution or operation of the industry if GPS had not been available. Loran-C, albeit less accurate, had been adopted by the sector and would likely have continued to be used. The availability of GPS reduces the burden on navigators, but overall operations and safety would not meaningfully change.

As discussed in the general qualitative findings, most navigation systems such as Trackpilot or ECDIS could be supported by Loran-C but would not be accurate or possibly have all the functionality. Experts indicated that the way the signal on Loran-C works depends on the time of day and location with respect to the chain and the baseline. As such, accuracy would be variable, and ships likely would not use Loran-C as a sole unit of navigation. But navigation can be improved by triangulating other methods and forms of measurement. If GPS had not existed, additional costs might have been associated with private-sector technology development targeted at improving accuracy (e.g., ports might have installed terrestrial differential systems), but this could not be quantified as part of this study and was viewed by experts as a minimal cost in the long run.

As a result, we believe there are no significant retrospective impacts of comparing the use of GPS and Loran-C.

Potential Impacts Associated with a 30-Day Outage

The use of GPS in the cruise industry in many ways is similar to commercial navigation. Industry experts thought that a 30-day outage of GPS would alter navigation activities and methods but would not significantly affect cruise ships' overall operations. Ships have sufficient backup systems and well-trained staff that could accommodate for the loss of GPS. The primary impact would be an increased burden on navigators.

The cruise ship industry was asked about a range of potential impacts resulting from a loss of GPS but responded that there would be

- negligible impacts on transit time,

- some increase in port entry and exit times but no scheduling issues,

- trips would not be canceled, and

- safety would not be compromised.

Most cruises would experience minimal impact. For trans-Atlantic or -Pacific legs, there could be an impact from having to rely solely on celestial navigation if the weather is poor. SSAS and AIS would be affected.

> One cruise ship company provided the following example. Last year a ship had two GPS outages in the Baltic for 4 days. The navigators were able to compensate using radio communications and traditional navigation techniques. No significant impact was experienced other than greater burden on navigators. The ship safely maintained its schedule.

Although a satellite would maintain connection during a GPS outage, the loss of signal to compensate would lead to the inability to realign the system over time. In contrast, cruises that consist of legs that go from port to port relatively close to land would be less affected.

These sentiments were also confirmed by discussions with experts outside the cruise ship industry (pilots, U.S. Coast Guard). However, they did express some concerns with smaller international port destinations that are not marked as well as U.S. ports. But again, the impact would likely be increased caution, as opposed to safety or cancelation issues.

It was noted that GPS is not just used for location accuracy; it is also used to transmit information and tracking. Some of these functions would experience an immediate impact if the GPS signal is lost. Long-range information and tracking relay ships' positions to authorities and ports. But this would not affect the overall operation of the ship. Communication would simply have to be done manually and potentially less frequently.

Based on the interviews with industry experts, we believe there would be no significant operations or economic impacts for the cruise industry from a 30-day outage of GPS.

9.5   Concluding Remarks

GPS is used extensively throughout the maritime sector for precision positioning and navigation and enables many supporting systems such as AIS, GMDSS, and VMS. This report values the benefits of GPS to the maritime sector based on a series of interviews with industry experts, a review of existing literature, and government data on economic activity in related sectors.

Although GPS is currently pervasive throughout the maritime sector, we find that if GPS had not been available to the maritime sector over the past few decades the sector would have continued to use Loran-C or similar technologies with minimal impact on operations or economic output. For most maritime applications, the accuracy provided by Loran-C is sufficient, and the incremental benefits of GPS's increased accuracy are only marginal.

The retrospective finding of minimal benefits from the maritime sector's historical use of GPS is sensitive to the counterfactual assumption that most of the electronic navigation systems used today would have evolved using Loran-C if GPS had not been available (although Loran-C would have been slightly less accurate). This was the opinion of the majority of industry experts we interviewed and hence was used as the counterfactual baseline for the analysis.

In contrast, because there is no backup for GPS currently, an unexpected outage of GPS today would have significant economic impacts. We estimate a 30-day outage of GPS to have an impact ranging from $5.1 to $14.7 billion, with a point estimate of $10.4 billion for the maritime sector. The large impacts are associated with interruptions in port operations and the resulting economic impact of supply chain disruptions.

The range of benefits associated with the 30-day outage analysis reflects the fact that there is some uncertainty regarding the extent to which subsectors in the maritime industry could respond and adapt over the 30-day GPS outage time period to mitigate impacts. Because the sector has experienced only sporadic loss of GPS to date, for some sectors (such as port operations) we estimated a fairly broad range of impact estimates. However, for other maritime sectors (such as commercial fishing) there was more consensus on the significance of the impact.

Note that in all instances this study strived to use conservative assumptions and not all maritime applications were included in the detailed analysis and hence the impact estimates. For this reason, we consider the impact estimates presented to be a conservative estimate of the impact of a GPS failure.

10. Surface Mining

The mining sector relies on precision positioning signals provided by GPS to explore and identify promising ore bodies and support mine-site construction, extraction, and hauling processes. GPS also has been a key technology for making mines more productive and safer by reducing collisions and reducing the number of workers who are exposed to dangerous situations.

Analysis indicates that if GPS were not available for civilian use, the U.S. mining sector would have relied on a suite of technology alternatives that may have afforded some but not all of GPS's advantages. We estimate that for mines that have fully adopted GPS-enabled technologies, the gross productivity gains are 12.5% per year (measured as cost reductions holding output constant). Net productivity gains from GPS compared with a counterfactual without satellite-based positioning are 9.4% per year. We estimate cumulative net productivity benefits of $12.3 billion for the U.S. mining sector since 1990.

In the event of a 30-day outage of GPS, it is likely that there would be substantial short-term disruption to mines relying on GPS. Mines tend not to have backup systems for GPS-enabled technologies and would need to fall back on work practices that were in place before precision positioning. Most mines, and especially larger ones, would likely contract with additional workers to meet their immediate needs in areas such as real-time surveying. Fleet management would also be harder to optimize without GPS which would result in more idle time of haulage trucks and machines.[51] We estimate that production during the 30-day disruption could decline in the short term by 24%. The direct economic loss from a 30-day outage would be approximately $950 million.

10.1 Sector Introduction and Overview

GPS positioning is used widely in resource extraction. We focus on open pit surface mines, which rely heavily on GPS-enabled technologies and applications across the mine life cycle, from initially mapping ore deposits to designing and building mines to operations. Because GPS signals are generally limited to line of sight and cannot be received reliably underground, underground mines have accrued limited benefits.[52] Therefore, we exclude underground mining, and when we refer to "mining," we mean the surface mining portion of the mining sector unless otherwise noted.

U.S. mines produced an estimated $75 billion of raw materials in 2017 (U.S. Geological Survey, 2018). Although production statistics are not disaggregated for surface mines, as of 2015, 12,637 active surface mining operations across the United States employed 194,000 workers (Centers for Disease Control and Prevention [CDC] National Institute for Occupational Safety and Health [NIOSH], 2015), which is about 82% of total mine workers. Figure 10-1 shows the distribution of mining operations and employment across the United States. Each dot on the map represents the location of an active mining operation.[53]
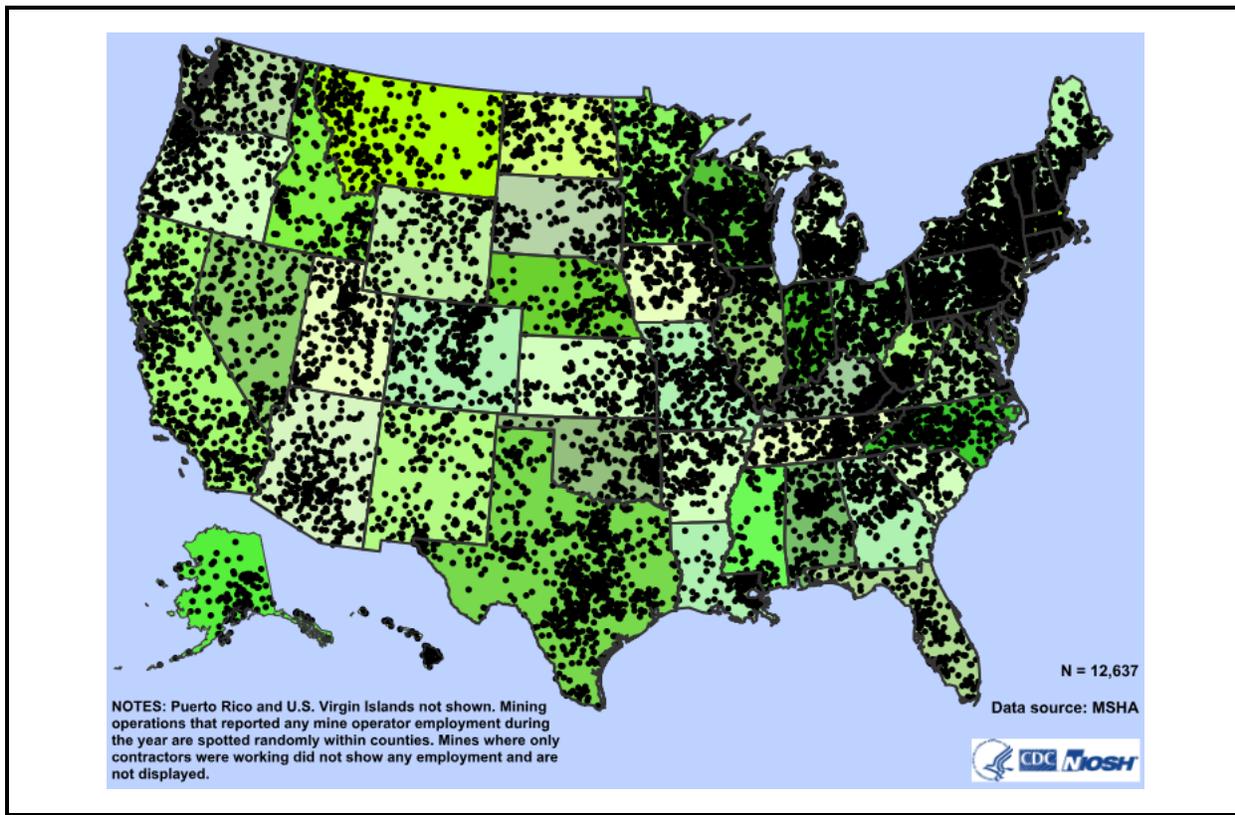
---

[51] Some surveying activities could be delayed.

[52] Underground mines rely on other positioning technologies such as RFID and Wi-Fi trilateration (Li & Saydam, 2015) and SLAM.

[53] Active mines are those that report operator employment during the year. Mines at which only contractors were working did not show any employment and are not displayed.

Figure 10-1. Active Surface Mining Operations and Mine Operator Employees, 2015

NOTES: Puerto Rico and U.S. Virgin Islands not shown. Mining operations that reported any mine operator employment during the year are spotted randomly within counties. Mines where only contractors were working did not show any employment and are not displayed.

N = 12,637

Data source: MSHA

Source: CDC NIOSH (2015).

Companies in the mining sector rely on GPS extensively for a wide range of applications including

- exploration and surveying,
- construction,
- extraction,
- optimization of fleets within the mine site, and
- outbound logistics.

Mines use GPS to increase the precision of operations and reduce labor costs. Increasing precision and reducing labor costs increase overall productivity, which means that GPS allows companies to hit similar levels of production with fewer input costs.

According to experts in the use of GPS for mining, the greatest uptake has been in industry segments that have greater profit margins. For example, large precious metal mines in the western United States such as the Bingham Canyon copper mine run by Rio Tinto[54] would be a likely place to find GPS ingrained in all aspects of operations. However, we learned that companies in the aggregates industry (e.g., construction materials) have been less likely to invest in GPS, which is the result of their smaller size and narrower

---

[54] http://www.austmine.com.au/News/rio-tinto39s-kennecott-mine-a-hub-for-innovation-1

profit margins. Additionally, mines that are owned by major parent companies that can amortize capital investment costs over larger levels of production and reach greater economies of scale have tended to invest more in GPS-enabled technologies and human capital.

10.2 Methodological Notes

Our approach to assessing the economic impacts of GPS in the mining sector was to identify precision positioning needs in the sector, determine which needs GPS currently meets, and determine the alternative precision positioning systems that might have emerged in the absence of GPS. We also considered available backup systems.

We conducted initial background research to identify preliminary hypotheses regarding the counterfactual scenarios and the potential technical impacts. The preliminary assessment was then refined and developed into a quantitative analysis based on secondary data collection, additional research, and structured interviews with relevant experts.

10.2.1   *Precision Positioning Needs in the Mining Sector*

Mining operations rely on real-time kinematic (RTK) GPS for high-precision applications. RTK GPS relies on measurements of the phase of a GPS signal's carrier wave in addition to the actual code embedded in the signal. RTK GPS also relies on a terrestrial base station for real-time corrections in measurement errors.

RTK GPS is typically accurate to 1 centimeter and serves several broad purposes: site surveying, asset management, machine guidance, collision avoidance, and automation. Site surveying is used to facilitate infrastructure design and maintenance in mines, both before and during active operation. Benefits of employing RTK GPS in site surveying operations include reduced surveying labor costs and more precise construction design, which improves mine yields, reduces waste, and lessens environmental impacts. The use of GPS in surveying operations leads to a reduction in the amount of personnel involved in surveying operations, which results in secondary safety effects.

Real-time positioning data provided by GPS sensors allow optimization software to better allocate and dispatch equipment around the mine. The primary benefits of tracking the precise location of assets are increased productivity and reduced equipment needs. GPS is also used to direct digging operations more precisely, which improves efficiency and reduces the amount of waste products from these operations.

Mines employ other sensor technologies to augment GPS's capabilities. Radar, as well as localized positioning systems, is used to guide trucks in parts of the mine where depth or lack of line of sight to the sky degrades the GPS signal. Autonomous trucks also employ onboard radar and laser sensors to avoid collisions and alert the truck (or a human driver, in the case of a human-operated vehicle) of obstacles and people nearby. Enhanced close-range sensor equipment is especially important in mines because of the prevalence of blind spots based on mine geographies and operator fatigue (Evans, 2009). The risk of collision and the potential cost of an accident are amplified by the large size of mine machinery and low visibility due to dust, snow, or other unfavorable conditions (Lorimer, 2010). CDC NIOSH (2015) reports that 53% of fatal and 17% of nonfatal surface mining injuries come from machinery or hauling. A

summary of current precision positioning needs is included in Table 10-1 and is discussed in greater depth in Section 9.3.1. In the future, an emerging application area is mine automation. Currently, however, no U.S. mines have deployed fully autonomous fleets, so this technology area is not considered in the estimation of benefits.

10.2.2   *Approach for Quantifying Retrospective Benefits*

The most likely counterfactual to the absence of GPS availability is that localized positioning systems would have been developed and deployed. Although mining operations might benefit from a Loran-based system, they primarily use RTK GPS, which has much higher levels of precision and reliability than Loran-based systems.[55] If Loran were highly localized and augmented, it could be a feasible alternative. However, other technologies would likely have emerged as the dominant PNT technology. If Loran had gained traction, it would be limited to mines with more shallow dig areas and to applications like basic fleet management and material tracking.

Table 10-1. Mining Precision Positioning Timing Uses and Needs

Application	Precision Needed	Uses and Benefits
Site surveying	RTK GPS (1 cm)	• Facilitates infrastructure design and maintenance in mines, both before and during active operation • Reduces surveying labor costs and provides more precise construction design, which improves mine yields, reduces waste, and lessens environmental impacts • Reduces the amount of personnel involved in surveying operations, resulting in secondary safety effects • Ensures that mine operations do not extend beyond the permitted area into private property, environmentally or culturally protected areas, etc.
Extraction activities and machine guidance	RTK GPS (1 cm)	• Helps direct digging operations where they need to go with more precision • Improves efficiency and reduces the amount of waste products from these operations
Real-time optimization of mine operations	RTK GPS (1 cm) to standard unaugmented GPS (3–5 m)	• Enables more efficient allocation and dispatch of equipment around the mine • Benefits include less idle time, increased productivity/throughput, and/or reduced equipment needs
Tracking and measuring ore	Various	• Material tracking is enhanced because of GPS-connected machinery; workers can estimate sizes of stockpiles using "walk-around" techniques with a handheld GPS device • Mine operators have greater visibility into material movements and quality to inform routing
Safety benefits	Various, along with augmentation of other onboard sensors	• Reduces the risk of collision and the potential human and economic costs of accidents

---

[55] For example, Loran is known to have signal reception challenges in deep mining pits.

As a result of the depth limitations of GPS in mining operations, GPS alternatives have already been developed. These alternatives include localized solutions such as ground-based satellites called pseudolites (literally "pseudo-satellites"), radio systems, radio-frequency identification (RFID), laser technology, electronic distance measuring, and radar. For example, Locata is a network of ground transmitters that blanket a chosen area with strong radio-positioning systems. Although it is designed to extend GPS, it can also operate independently of GPS when GPS is not robust or is completely unavailable.[56] Another technology used for positioning of robots that could be useful for mine site operations is called Simultaneous localization and mapping (SLAM). SLAM has been used for indoor warehousing logistics and autonomous navigation as well as underground mining, so surface mining is a potential use case, especially in the absence of GPS. The geographical range of SLAM is typically limited to line-of-sight but is dependent on the array of sensing technologies in use.

Despite the existence of non-GPS technologies for sensing and positioning, these other technologies could not replicate the functionality of GPS. Interviews with experts suggest that about 75% of the benefits if GPS would not be realized, although there were differences in opinion among experts because of the context-specific nature of each alternative.

The following primary technical impacts are associated with the decrease in precision positioning:

- less efficient mine site design as it relates to the position of mine infrastructure and roads relative to the best ore deposits;

- decreased yields due to less precise surveying/detection of ore and less precise drilling and excavating, which means more waste material that has to be sorted processed;

- less efficient usage, dispatch, and real-time optimization of trucks and machinery within the mine; and

- more surveyors required per job, which increases labor costs and potentially increases safety risks as more surveyors are in the field.

Our economic model of the retrospective impact of GPS on the mining sector was developed from secondary data on industry production and industry structure along with parameters for adoption, impacts, and applicability of impacts that we estimated from the expert interviews and validated where possible.

Production Output and Industry Structure

We gathered information on production output and the industry structure of the mining sector from several sources:

- **U.S. Bureau of Economic Analysis (BEA), gross domestic product (GDP) by Industry Series, 1990–2017:** Gross output by industry for the four mining sectors of interest: coal mining; iron, gold, silver, and other metal ore mining; copper, nickel, lead, and zinc mining; and other nonmetallic mineral mining and quarrying was available for 1997–2016. Gross output for the entire mining sector was available for 1990–2017. We estimated gross output by industry from

---

[56] http://www.locata.com/technology/locata-tech-explained/

1990–1996 using average historical shares that each industry comprised of the entire mining sector.

▪ **National Mining Association (NMA), U.S. Coal Production Trends, 1980–2017:** U.S. coal production for underground and surface mines.

Because BEA data on gross output was unavailable for 1990–1996, we estimated the output the four mining sectors of interest using the average share of total output accounted for by each subsector from 1997–2017 times the output data for the entire mining sector.

Adoption

As part of this analysis, we assembled an overall timeline of adoption based on expert interviews (see Section 9.3). Adoption rate results were validated using the trends in the literature. We excluded aggregates (e.g., sand, stone, and gravel) upon guidance from industry experts who stated adoption of GPS-enabled technologies and applications has been limited in this sector because aggregates tend to have lower profit margins than ores like precious metals. (We confirmed this with a major aggregates mining company.) Adoption has also been limited in the smaller operator tier of the mining sector because small companies generally do not have the economies of scale that can make large capital investments more cost-effective.

Overall Applicability

As discussed above, certain technical and market structure considerations affect the portion of the mining sector that has benefited from GPS. First, we restricted benefit estimates to surface mining operations because of the limitations of GPS that make it technically infeasible for use in underground mines (Li & Saydam, 2015). Second, we focused only on the segments of the mining sector that are likely to be heavy users of GPS. Thus, we completely excluded aggregates mining, which to date has limited adoption of GPS-enabled technologies. Third, we applied benefits only to the top 80% of the market's production, which is a rule-of-thumb for the share of mining production accounted for by larger mining companies that have integrated GPS more fully into their mine life cycle. In other words, we applied this share as a discount factor to the results to attempt to account for the portion of mines, typically small "mom-and-pop" mines, that tend not to rely on GPS. We did not include mining support companies[57] in our analysis because we did not explicitly target them as a stakeholder group or design data collection to focus on benefits to support industries. The impact assessment was primarily focused on large, end-use sectors.

10.2.3   *Approach for Quantifying the Potential Impacts of a 30-Day Outage*

In the event of an unanticipated 30-day outage of GPS (and other GNSS), the loss of signals would have significant impacts. The most likely counterfactual depends on the particular application.

This outage scenario would result in more manual work and less efficient mining operations because of an inability to optimize mining operations throughout the day. Mine operators would have limited ability to deviate from the daily mining plan, even if conditions changed or new information came in because it would be much harder to adjust in real time without accurate positioning data. Survey methods would

---

[57] Mining support companies perform work on a contract or fee basis that is often performed in-house by mining operators.

revert back to traditional optical surveying methods, but there may be a labor shortage because additional surveyors would need to be hired quickly. In addition, equipment necessary for these methods may not be in place. However, some surveying activities could be delayed.

These operational implications of a 30-day, unplanned outage of GPS translate into two primary economic impacts:

- a decrease in production during the 30-day outage

- an increase in labor costs during the 30-day outage

These impacts would be particularly acute for mines with a greater reliance on GPS because backup technology infrastructure is uncommon. However, long-term impacts are unlikely because the mining sector could quickly recover once GPS signals reached full functionality again.

The approach to quantify economic impacts in the 30-day outage scenario was twofold. First, we asked industry experts about the presence of backup systems and what mines would do during an unanticipated 30-day outage. We also asked for the percentage change impact on in overall mine productivity. Second, using an average measure of lost productivity, we applied this impact to monthly production during an average 30-day period based on annual data for 2017. We only applied the lost productivity to an applicable portion of the mining sector that accounts for the adoption patterns of GPS and ore type.

10.2.4   *Interviews with Sector-Specific GPS Experts*

We identified experts in the application of GPS to mining operations through a variety of sources, including academic journal articles, trade associations, speakers lists for major conferences, internet searches, and referrals. Interviews lasted 30 to 60 minutes and were facilitated with a structured interview guide. We documented interviews with written notes and organized responses into a matrix of interview answers to facilitate thematic and quantitative analysis of interview responses.

Interview questions were framed around

- ways GPS is used in mining, including levels of precision needed for different applications,

- initial adoption of GPS for mining and the pace of adoption over time,

- the benefits of GPS on productivity, labor costs, safety, and other more qualitative items,

- alternative technologies before GPS and what would have emerged in the absence of satellite-based positioning systems,

- ways the sector would cope with an unanticipated 30-day outage, and

- the technology transfer aspects between government and the private sector.

Experts represented multiple stakeholder types, including but not limited to

- mining companies and industry consultants,

- GPS equipment providers,

▪ industry associations, academics, and

▪ government experts.

The industry experts' disciplines included mining engineering, geology, surveying, and geospatial science, among fields. We identified and contacted 44 experts across 39 distinct organizations, and 21 (48%) agreed to participate in the interview process. The largest group interviewed comprised mining companies and industry consultants. These individuals tended to be the most knowledgeable about the operational implications of each scenario. Equipment providers tended to be the most bullish about the benefits of GPS relative to alternatives.
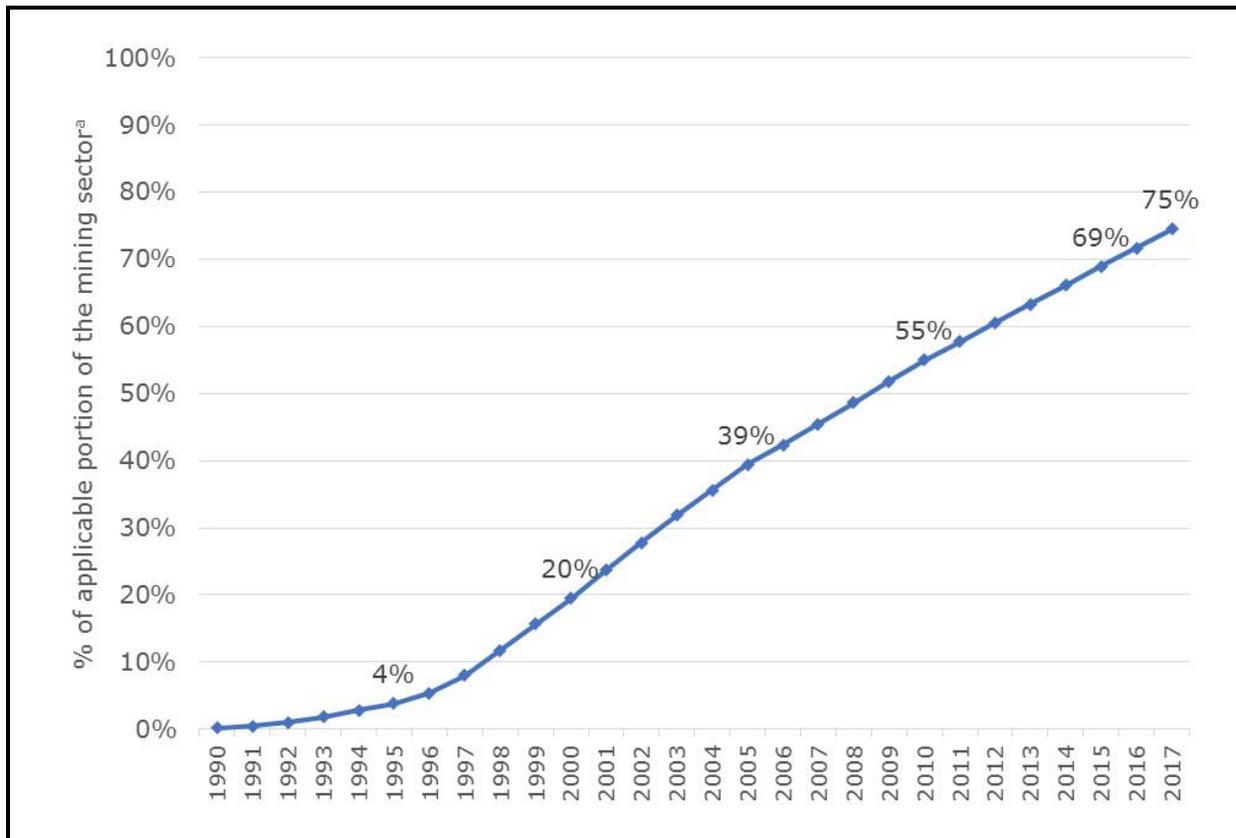
After completing all interviews, we compiled and computed all responses to identify the adoption timeline for GPS in the mining sector, as shown in Figure 10-2.[58] GPS was first used in the mining industry around 1990, but adoption did not begin in earnest until about 1995. The earliest applications of GPS in the mining sector were in surveying and then expanded into precision drilling and digging. The average benefits per mine increased over time as GPS-enabled technologies improved and industry professionals figured out how to broaden the use of GPS to additional applications such as fleet management.

One expert remarked that compared with other sectors, the mining sector has been somewhat slower to adopt GPS technology. A key moment in the adoption of GPS in the mining sector occurred when RTK GPS, invented in the early 1990s, became a reliable, mainstream technology in the late 1990s (Gakstatter, 2009). RTK GPS could be used for real-time surveying, high-precision navigation, and other real-time applications requiring accuracy from millimeters to decimeters (Langley, 1998). Other developments that drove adoption of GPS in the mining sector were the reduction in the cost of GPS receivers and the interoperability of receivers between multiple GNSS constellations.

Based on expert interviews, GPS and GNSS have been widely adopted. We conservatively estimate that within applicable portions of the mining sector GPS reached about 75% adoption as of 2017. This adoption percentage reflects the fact that a tier of the mining sector comprises smaller mines or commodity mines subject to low profit margins that cannot justify complete adoption of GPS-enabled technologies or systems. However, all mines are using GPS in some form or fashion, even if only for basic navigation purposes.

---

[58] For each interviewee, we constructed an adoption timeline based on anchor points they provided and how they described the pace of adoption over time. We then averaged the responses for each interviewee to construct a mining sector adoption curve.

Figure 10-2. Cumulative Adoption of GPS in the Mining Sector between 1990–2017

Source: RTI analysis of expert interviews.

[a] Adoption rate within applicable portions of the mining sector described above.

10.3 Retrospective Economic Benefits Analysis

Mining industry experts agreed that GPS has become a critical technology for the industry. Had GPS not been available, it is likely that localized positioning technologies would have become the dominant positioning technology for mining operations. Indeed, some localized positioning technologies like pseudolites were developed in response to some of GPS's limitations.

Results are segmented into qualitative and quantitative findings in the subsections below. Quantitative results should be interpreted as rough order-of-magnitude estimates because of measurement error. For example, experts indicated disentangling the effect of GPS precision positioning from some of the other complementary technologies that have been paired with GPS like fleet management and optimization software platforms is difficult because complementary technologies take in a variety of other data. Other complementary technologies include sensing systems onboard hauling trucks that are often paired with GPS as part of collision avoidance systems. There is also uncertainty related to the precision positioning technologies that would have emerged in the absence of commercially available GPS.

10.3.1   *Qualitative Findings*

The applications of GPS listed in Table 10-1 have increased productivity in the mining sector over time, resulting in fewer input costs, holding production constant. Individual mines may seek to increase production for given level of cost, decrease costs for given level of production, or somewhere in between. At the industry level, in a competitive market, aggregate production could be seen as fixed or driven factors unrelated to GPS, so we believe it is appropriate to frame the analysis in terms of holding production constant.

Site Surveying

Surveying in mining, as in other sectors, has been greatly simplified by the widespread adoption of GPS. Surveying teams can do more work with fewer people in a shorter time frame. Industry experts agreed that virtually all mines use GPS in some form or fashion for basic surveying. Industry standard site surveying typically requires high-precision RTK GPS at the 1-centimeter level. Mine surveying spans the life cycle of the mine (exploration, design, construction, maintenance, and active operation) and real-time surveying is used for a variety of purposes during the active operation. GPS provides more precise construction design and build relative to the location of ore deposits. The precision of design (as well as the associated operations) helps reduce the extraction of non-ore waste materials and ultimately improves yields.

The benefits of GPS for the surveying industry are described in Section 12. Any benefits from using GPS that accrued to surveying service providers were captured in the surveying section. Because many large mines have their own full-time surveyors, any benefits that accrued to the mining sector from directly employed surveyors are captured in this section.[59]

Extraction Activities and Machine Guidance

According to one expert, drilling, blasting, and loading operations were some of the applications that drove adoption once GPS had been adopted for basic mine site surveying. These extraction activities require high-precision surveying to know exactly where to go, and GPS simplified the surveying process compared with traditional methods. Experts agreed that this application of GPS has been widely adopted.

Fully autonomous extraction operations, however, have not yet been adopted in the United States on a meaningful scale. That said, machine guidance systems are much more common and are a natural step toward automation. Machine guidance systems use positioning technologies such as GPS and geospatial models to provide real-time spatial guidance to equipment operators (U.S. Department of Transportation, 2012) or directly to machines. The precision of extraction activities (as well as the associated design and planning mentioned above) helps reduce the extraction of non-ore waste materials either through better targeting of ore deposits or improved processing by better tracking the quality of extracted ore that needs to be directed to such processes. Both of these mechanisms can ultimately improve yields. Machine guidance is partially enabled by GPS along with many other technologies working together.

---

[59] We ensured no double-counting by using IMPLAN to estimate the small number of surveying firms hired by the mining industry and subtracted those benefits from the surveying industry to avoid any double-counting with the mining industry.

Real-Time Optimization of Mine Operations

Not only does GPS help tell equipment operators where to go, it also enables systems that tell equipment when to go. Mine software platforms typically referred to as fleet management systems are enabled in part by GPS. These systems allocate equipment efficiently around the mine site compared with traditional approaches that rely more on human-led dispatch. They monitor draw and dump locations and travel times and optimize refueling practices. GPS provides a critical data input to these software tools, allowing operators to dispatch assets to their highest and best use and limit idle time.[60]

Depending on the complexity of the system, precision requirements can range from RTK GPS to standard augmented GPS. One major disadvantage of RTK GPS is that a either a reference base station is required locally or users can pay for access to networks of widely spaced base stations (Novatel, n.d.); either approach makes RTK GPS costlier to implement.

The software platforms also provide greater flexibility to mine operators because reality varies from the daily mine plan, enabling assets to be better optimized given real-world constraints like unplanned maintenance issues, bottlenecks, and other variances. Benefits from real-time optimization of mine assets ultimately result in less idle time of equipment and equipment operators, increased productivity, and greater throughput of the mine for a given level of assets. Conversely, real-time optimization allows a single person to manage more equipment if the mine has sufficient capacity.

Tracking and Measuring Ore

GPS enables a variety of material tracking and measurement applications. For example, tracking GPS-tagged materials and associated them with measurements of ore quality as they are moved around the mine site to measuring stockpiles of materials using "walk-around" techniques with a handheld GPS device. Knowing what has been extracted in terms of its quality and volume is important for routing materials for processing.

Safety Benefits

Given that mining haul trucks dwarf their human counterparts, mines have to manage serious safety risks on a daily basis. Also, open pit mines often have steep drop-offs. Haul trucks and other machines often have limited lines of sight to start with, and they have to operate in weather and dust conditions, which can further limit visibility. Finally, as a result of their sheer weight and momentum, they can have long stopping times. Avoiding accidents is crucial both from a human well-being standpoint and a financial standpoint. GPS is one of the onboard sensors in collision avoidance systems that help mitigate safety risks.

Environmental Benefits

GPS can even lessen environmental impacts by protecting sensitive environmental areas through cadastral mapping, providing "geofenced" areas that are off limits to GPS-enabled equipment. GPS paired with other sensors like radar, lasers, and other seismic sensors can measure ground movement at the millimeter

---

[60] On-road, off mine hauling benefits of GPS are included in the aggregate telematics results in Section 13.

level, which allows prediction of seismic activity such as landslides that can pose safety and environmental risks. Bingham Canyon in Utah was evacuated seven hours before a catastrophic landslide because of early warnings about displacement and instability of land from sensor systems, and no one was injured (Pankow et al., 2014). Sensor systems at Bigham Canyon are calibrated in part based on GPS positioning (Gischig, 2011). Preventative measures can also be taken to mitigate environmental risks when seismic sensor networks detect movement.

Somewhat more indirectly, more accurate design and extraction activities enabled by more GPS-based surveying techniques may reduce environmental impacts by reducing unnecessary extraction of non-ores. Experts disagreed about the direct connection between GPS and environmental benefits. Many acknowledged the knock-on or indirect environmental benefits, but most experts were not able to draw a direct connection that could be quantified.

10.3.2   Quantitative Findings

After discussing the various applications of GPS and the pattern of adoption over time, we asked experts whether GPS had an impact on overall mine productivity, labor requirements, injuries, and the environment. We reviewed their opinions for each category of benefits, and if there was a perceived benefit (or cost), asked for an estimate of the percentage change for the typical mining operation. Table 10-2 provides summary statistics on the stated percentage changes on overall mine productivity and labor requirements.

Of the 10 respondents who provided a quantitative estimate of the change in productivity, their answers varied greatly, ranging from 7.5% to 75.0%. However, answers were clustered between 10% and 20%, and because one outlier was skewing the average substantially, we decided to use a median value of 12.5% for our economic model. The change in labor requirements is not directly used in the economic model, but we report it here for descriptive purposes. The mean response was a 13.5% reduction in labor requirements with a median response of 10% reduction. Experts did believe that GPS had the ability to reduce injuries and create environmental benefits, but they could not reach consensus about the level of benefit or a way to quantify it. Most agreed that safety and environmental benefits were more indirect.

Table 10-2. Expert Estimates of Mining Sector Productivity Gains from GPS

Statistic	Change in Overall Mine Productivity	Change in Labor Requirements
Mean of expert estimates (standard error)	21.1% (6.3%)	−13.5% (4.6%)
Median	12.5%	−10.0%
Minimum of expert estimate	7.5%	−35%
Maximum of expert estimate	75.0%	0%

We then asked respondents what technology(ies) would have emerged in a scenario without GPS and, based on the positioning requirements of the various application areas in mining, to estimate a percentage of the benefits that would be lost due to lower accuracy or other disadvantages. This admittedly was a much harder question for experts to grapple with. Only a few experts provided a quantitative answer, but they were clustered between 50% of the benefits being wiped out and 100%. Additionally, others commented that adoption would be lower because the technologies are less precise than GPS and have higher upfront fixed costs to set up the required local infrastructure. Given the distribution of responses and our understanding of the likely counterfactual being more localized, less precise, with higher cost options, we assumed that the benefits of GPS would be reduced 75%, but we held adoption of the counterfactual technology the same under the actual and counterfactual because of a lack of detailed information about the counterfactual adoption curve. This may bias our benefit estimates of GPS downward, making them more conservative.

Next, we assembled a time series of outputs for the relevant mining sectors from 1990 through 2017 from which we monetized productivity benefits. Figure 10-3 shows the distribution of mining output for 2017 with the sectors we included in shades of blue. At the time we accessed data, 2017 estimates were not yet fully available at the detailed industry level, and we imputed 2017 output by industry using total mining sector output in 2017 times the average historical shares that each industry represents. These shares have been somewhat stable over time.[61]

We used data from NMA to estimate the portion of the coal mining industry comprising surface mines and excluded underground coal mining because GPS signals cannot function underground. We also excluded stone mining and quarrying, which was a rough proxy for aggregates where adoption has been minimal. The other sectors (shown in shades of blue in Figure 9-3) are primarily surface mining and have benefited from GPS.
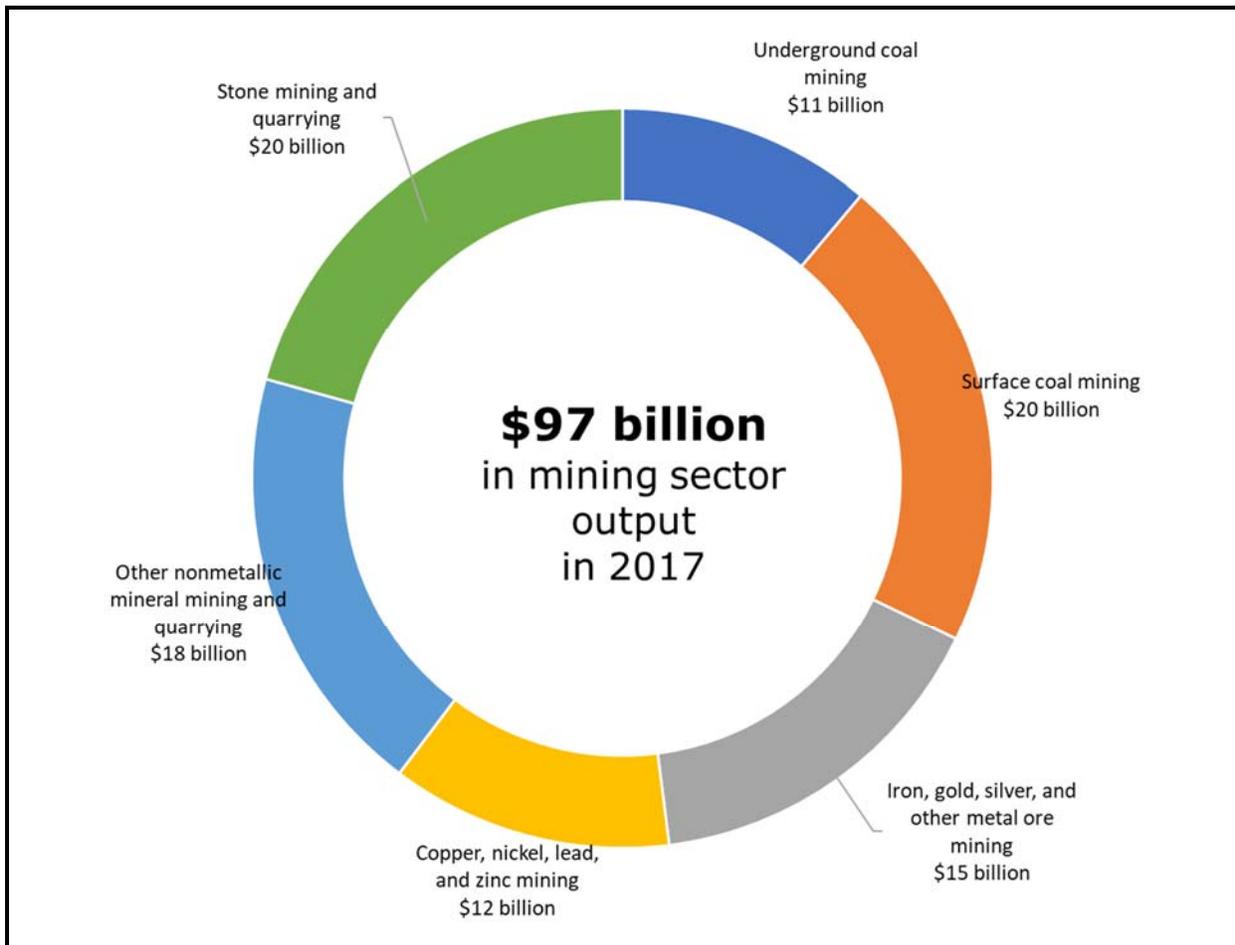
The adoption curve from Figure 9-2 was applied to the gross output of the relevant industries (depicted in shades of blue) in Figure 9-3, multiplied by a discount factor of 0.8. We applied the median productivity improvement percentage of 12.5% in the most recent year but scaled that back linearly to 1% in 1990 to represent improvement in the GPS-enabled technologies and applications over time. We also slightly scaled back the productivity percentage by using a simple translation to reflect the fact that gross output data already includes the productivity gains from GPS.[62]

---

[61] Coal production as a share of total production has changed most drastically, it's share declining by more than 10 percentage points from 1997 to 2016.
[62] The formula we used was $1 - 1/(1 + \text{productivity percentage change}_t)$.

Figure 10-3. Mining Sector Output by Mining Industry, 2017

Source: RTI Analysis of Bureau of Economic Analysis and National Mining Association data.

Note: Impact of GPS is limited to the applicable mining industries in shades of blue. Mining industries in shades of red are excluded from the analysis.

We also conservatively assumed that a counterfactual positioning technology would have been adopted at a similar pace as GPS. We assumed that this counterfactual technology would have been able to achieve 75% of the gross productivity benefit of GPS. These steps can be summarized by the following formulas for any given year:

$$Gross\ Productivity\ Benefit\ GPS_t = (Gross\ Output_t\ x\ 80\%)\ x\ Adoption_t\ x\ Impact_t$$

$$Productivity\ Benefit\ Counterfactual_t = (Gross\ Output_t\ x\ 80\%)\ x\ Adoption_t\ x\ [Impact_t\ x\ 75\%]$$

Given that we are interested in the net productivity benefit, we took the difference between these two formulas to estimate the net benefit from GPS compared with the counterfactual scenario. To normalize the historical productivity gains from GPS, we adjusted annual productivity benefits to 2017 dollars using the implicit price deflator.

As depicted in Figure 10-4, annual productivity gains from GPS increase over time as adoption increases and also as GPS-enabled technologies become more capable and applications broaden. Annual net benefits surpass $1 billion in real 2012 dollars. Net productivity benefits in 2017 were $1.1 billion, accounting for 1.4% of total mining sector output.

We estimate from 1990 through 2017 the mining sector experienced $12.3 billion in net benefits from GPS-enabled technologies and applications. Time series results are provided in Table 10-3.

Figure 10-4. Annual Economic Benefits of GPS in the U.S. Mining Sector

Table 10-3. Annual Time Series of Input Data and Productivity Benefits

Year	Output of the Applicable Mining Industries (nominal $ billion)	Adoption Rate of GPS within the Applicable Mining Industries	Productivity benefits of GPS (nominal $ billion)	Potential counterfactual productivity benefit (nominal $ billion)	Net Productivity Benefit of GPS (nominal $ billion)	Net Productivity Benefit of GPS (real $2017 billion)
1990	$53.1	0.2%	$0.0	$0.0	$0.0	$0.0
1991	$53.6	0.5%	$0.0	$0.0	$0.0	$0.0
1992	$52.4	1.0%	$0.0	$0.0	$0.0	$0.0
1993	$48.8	1.9%	$0.0	$0.0	$0.0	$0.0
1994	$53.3	2.8%	$0.0	$0.0	$0.0	$0.0
1995	$53.8	3.8%	$0.0	$0.0	$0.0	$0.0
1996	$53.9	5.4%	$0.1	$0.0	$0.0	$0.0
1997	$45.5	8.0%	$0.1	$0.1	$0.0	$0.0
1998	$45.2	11.8%	$0.1	$0.1	$0.0	$0.1
1999	$44.4	15.6%	$0.2	$0.2	$0.1	$0.1
2000	$46.1	19.5%	$0.3	$0.2	$0.1	$0.1
2001	$46.1	23.6%	$0.4	$0.3	$0.1	$0.1
2002	$46.5	27.8%	$0.5	$0.3	$0.1	$0.2
2003	$48.9	31.9%	$0.6	$0.4	$0.1	$0.2
2004	$57.8	35.6%	$0.8	$0.6	$0.2	$0.3
2005	$72.6	39.4%	$1.2	$0.9	$0.3	$0.4
2006	$87.2	42.4%	$1.7	$1.2	$0.4	$0.5
2007	$90.4	45.5%	$2.0	$1.5	$0.5	$0.6
2008	$100.6	48.7%	$2.5	$1.9	$0.6	$0.7
2009	$89.9	51.8%	$2.5	$1.9	$0.6	$0.7
2010	$96.9	55.0%	$3.1	$2.3	$0.8	$0.9
2011	$111.7	57.8%	$4.0	$3.0	$1.0	$1.1
2012	$106.4	60.6%	$4.1	$3.1	$1.0	$1.1
2013	$97.4	63.4%	$4.0	$3.0	$1.0	$1.1
2014	$100.7	66.2%	$4.4	$3.3	$1.1	$1.2
2015	$89.7	68.9%	$4.1	$3.1	$1.0	$1.1
2016	$81.1	71.7%	$3.8	$2.8	$0.9	$1.0
2017	$85.9	74.5%	$4.4	$3.3	$1.1	$1.1
Total	**$1,959.9**	**N/A**	**$44.9**	**$33.7**	**$11.2**	**$12.3**

10.4 Potential Impacts of a 30-Day Outage

In the event of an unexpected outage of GPS and other GNSS systems, industry experts agreed that surveying activities could largely be delayed at minimal cost to mines because many surveying activities are fungible, having to do with prospecting, mine site planning, cadastral surveying, surveying for drilling, and surveying when decommissioning a mine. That said, some surveying activities are done in near real-time, providing data streams directly to mine site operators.

A 30-day outage would be most detrimental for real-time fleet management on the mine site. GPS provides a critical data stream to a mine optimization software suite that responds to a variety of variables and variance from the daily plan. Without this software, industry experts expect that mine equipment and trucks will have more idle time, which will directly affect production.

10.4.1   *Qualitative Discussion*

As noted earlier, few backup systems are in place for positioning needs. Some mines have pseudolites or other localized positioning systems, but these are not common.

The precision positioning application in which such loss of efficiency will be reflected the most is real-time fleet management, namely the optimized dispatch and movement of machinery and trucking assets. The lack of efficiency will likely manifest itself mainly in increased downtime of machinery and trucks, which will reduce mine throughput during the 30-day outage. The biggest disruption would be for any autonomous mining vehicles or remote-controlled vehicles. However, so far, the use of these types of vehicles is quite limited in the United States outside of a few mega mines.

Mine operators that rely on GPS-enabled technologies may encounter efficiency issues and attempt to mitigate the loss in precision by putting more personnel in the field and reallocating labor. This response seems like a more viable alternative than attempting to react with a short-term backup system. However, there would likely be increased competition for additional workers, causing shortages and wages for contract mine workers to rise, further increasing labor costs.

With additional labor deployed within the mine to ensure efficient operation, safety issues could be a second-order effect of a 30-day outage. One expert commented that retirees may need to be hired on a short-term basis to mitigate the outage, but "*there is potential for more injuries when working with [an] older work force who may be retired.*" She estimated a 5% to 10% increase in injuries.

However, many surveying activities can be delayed without significant impacts from a 30-day outage. As one expert stated, "*So much of GPS is used for design work, if that slows down for month, it is not a big deal.*"

10.4.2   *Quantitative Costs Associated with 30-Day Outage*

We estimate that a 30-day outage of GPS would result in a 24% loss in production for the applicable set of mines. To scale this to the national level, we applied the same logic as we used in the retrospective impact but relied only on 2017 data for the relevant mining industries (excluding underground coal mining and the proxy industry for aggregates) and applied the adoption rate for 2017.

Using 2017 annual output and the applicability factors listed above, we find that 30-day production losses from an unanticipated 30-day outage could be $950 million over a 30-day period.

This estimate reflects the amount of lost production of 1.1% of the total annual output of $96.7 billion for all U.S. mining industries (Figure 9-3).[63] We did not account for potential increases in labor costs because

---

[63] 1.4% of the annual output of the non-aggregate mining sectors.

most industry experts thought the change in labor requirements would be minimal on net. Mines could offset some portion of the lost production in future months through overtime and other mitigating strategies.

10.5 Concluding Remarks

Clearly, GPS, along with complementary technologies it enables such as enhanced machinery and software platforms for mine site optimization, has improved the productivity and safety of the U.S. mining sector and led to investment in and adoption of GPS-enabled technologies. by that sector

Our research suggests that many mines reliant on GPS for various applications do not have viable backup systems in place should GPS and GNSS signals fail. In these cases, vulnerable mines would have to revert to old, suboptimal surveying and mine fleet management methods that could cause significant disruptions or at least slowdowns to production in the short term due to adjustment times and costs. There may also be human capital issues with newer workers not having the knowledge and skills required to carry out traditional surveying techniques, for example. One expert mentioned those traditional surveying methods have been dropped from education and training.

Moving forward, as the costs of GPS technologies continue to fall, GPS may gain greater penetration in smaller surface mines in the United States for proven application areas such as precision surveying, extraction, machine guidance, real-time optimization, and tracking ore as it moves throughout the mine.

Less proven is autonomous mining—hauling trucks and mobile machines that do not require a human operator or that augment human operators with autonomous technology—that relies on GPS and a wide range of other technologies. Australia has already seen some of its largest mines deploy autonomous trucking fleets and has demonstrated that they can be cost-effective. Autonomous mining may be adopted for some of the largest mines in the United States that can justify the high fixed costs because of economies of scale. However, it is harder to foresee wider adoption of autonomous trucking in the United States.

To mitigate disruption risks, a viable backup system might be wise. Loran could help surface mines in some application areas in the case of a disruption to GPS and GNSS, but without augmentation of some kind, the precision levels from Loran-based systems do not meet the standard centimeter level achieved by RTK GPS. Other localized backup systems may be more effective in terms of the positioning precision and the ability of the signal to overcome topography issues that are common with open pit mines.

11. GPS in the Oil and Gas Industries

GPS is used extensively in exploration and production (E&P) operations in the oil and gas sector. It has improved productivity, reduced labor requirements, and enhanced safety. It has also permitted oil and gas companies to drill wells in deeper water further from shore. In the absence of GPS, terrestrial operations would likely have employed a combination of radio-based navigation systems, cellular navigation systems, pseudolites, and traditional surveying and mapping techniques. Offshore operations closer to shore likely would have relied on similar technologies. However, GPS alternatives do not offer the range or precision required for deepwater operations.

We estimate that GPS has improved gross productivity by 32% for companies that use GPS technology in offshore oil and gas exploration and drilling. Relative to Loran, the incremental productivity gain for GPS is 17%.[64] Using data from expert interviews and secondary sources, we estimate that GPS has generated cumulative cost savings of $45.9 billion from 1990−2017 for offshore oil and gas operations. These cost savings have accrued for both nearshore and deepwater oil and gas operations.

In the event of an unexpected outage of GPS, offshore exploration, development, and construction operations would likely be disrupted. A GPS outage would negatively impact dynamic positioning systems for vessels, resupply efforts, and drilling operations. Production in shallow water would continue with minimal disruption, but production in deepwater would experience significant disruption. The production of existing fixed rigs would not be affected by a GPS outage. Floating rigs, on the other hand, rely on GPS for dynamic positioning during production. Therefore, production of these rigs would be affected by an outage. An outage could also negatively affect the ability to replenish the crews and supplies of both fixed and floating offshore rigs. New drilling operations that rely on GPS could also be affected. We estimate that offshore production would decrease by 41%, and future construction and development operations would be delayed during the outage. This loss would amount to a short-term output loss of about $1.5 billion.

11.1 Sector Introduction and Overview

The oil and gas sector is an important component of the U.S. economy with $326 billion in total output in 2017 (BEA, 2018). Its operations can be divided into three segments: upstream operations, midstream operations, and downstream operations (PSAC, 2019). Upstream operations, also known as the E&P sector, involve determining the location of oil and gas through exploration and extraction by drilling wells. Midstream operations consist of processing, storage, marketing, and transportation of crude oil and natural gas. Downstream operations include the refinement of oil and the production of petrochemical products and the distribution of natural gas, fuel, and petrochemical products to retail outlets.
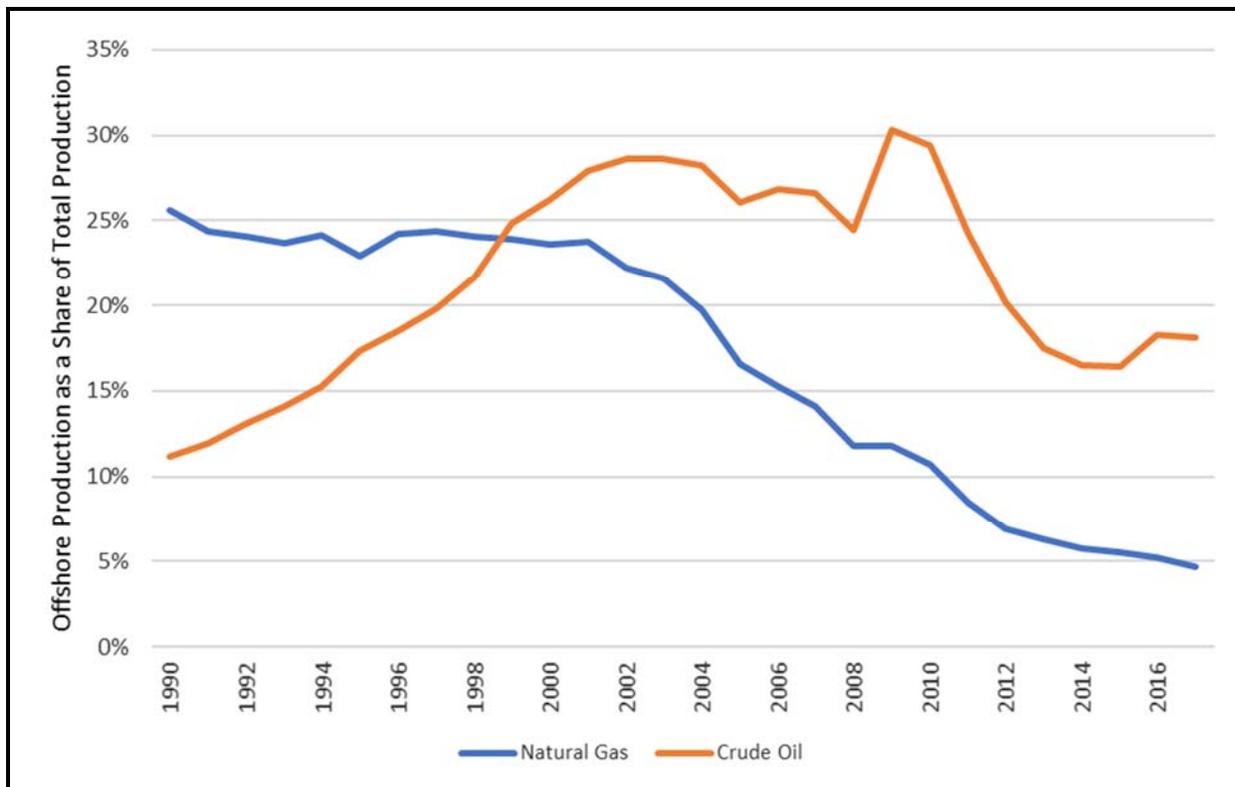
---

[64] This is defined as the productivity gains made possible by GPS minus the productivity gains that would have been possible with alternative technologies had GPS not been made available for civilian use. As in the other cases, we refer to this alternative scenario as the "counterfactual."

Of these segments, upstream operations are the most reliant upon GPS, especially offshore operations, which is the focus of this case study.[65] As of 2017, offshore operations account for about 18% of crude oil and 5% of natural gas production (EIA, 2018). The share of oil production occurring offshore declined sharply from 2010 to 2014 and has remained fairly stable over from 2014 to 2017 (see Figure 11-1). The share of natural gas production occurring offshore has been declining since 2002. Long run-projections from the EIA indicate that the offshore share of production for natural gas and oil are expected to decline to 3% and 12%, respectively, by 2050.

11.2 Methodological Notes

Our approach to estimating the impact of GPS in offshore operations was to identify precision positioning needs, determine which needs are met by GPS, and then determine what alterative precision positioning systems are currently in use or might have emerged in the absence of GPS that could have met the sector's needs. The increment between the actual and counterfactual represents the relative value of GPS. An initial literature review generated preliminary hypotheses regarding the most likely counterfactual scenarios and potential technical impacts.

Figure 11-1. Offshore Oil & Gas Production as a Share of Total Production, 1990–2017

Source: U.S. Energy Informational Administration (2018)

---

[65] Benefits of GPS for midstream and downstream operations are captured by other case studies, such as maritime navigation and telematics, and are excluded from this chapter. Use of GPS for onshore operations is captured in the surveying analysis.

We interviewed GPS experts in the oil and gas sector to gather estimates of the productivity impacts of GPS and the likely technology alternatives that would have emerged in its absence. We also explored the potential impacts of and mitigation strategies associated with a 30-day, unplanned outage of GPS. After our first round of structured interviews, we used a Delphi approach with these same experts to build consensus impact estimates. We then generated an economic model to quantify the retrospective impact of GPS and the potential impacts of a 30-day outage.

11.2.1 *Interviews with Experts in the Use of GPS for the Oil and Gas Sector*

Our expert interview guide explored topics such as

- applications of GPS, including precision levels required;
- the timeline of when GPS was first used in the offshore oil and gas sector and the rate of industry-wide adoption over time;
- economic impacts of GPS on productivity and labor requirements;
- alternative counterfactual technologies, including differences in impacts;
- backup technologies and a hypothetical 30-day, unplanned failure of GPS; and
- technology transfer issues.

We identified knowledgeable industry experts to interview by searching publications, reviewing key speaker lists at oil and gas conferences, contacting oil and gas companies, and contacting oil and gas industry associations. We also relied on referrals from other experts. These experts included from GPS equipment providers, GPS users, independent consultants, and various other sectors of the oil and gas industries.

We identified and contacted 62 experts, and 19 (31%) agreed to participate in the interview process. After analyzing the results of the structured interviews, we needed to build consensus in a few key model inputs and conducted a modified Delphi round in which we shared a subset of findings with interview participants. This round elicited targeted feedback in four key areas:

- the adoption timeline of GPS in the oil and gas sector
- productivity gains in the oil and gas sector from the use of GPS
- the productivity impacts of a 30-day, unplanned outage of all GNSS systems on the oil and gas sector
- the likelihood that a radio-based PNT system such as Loran would have been developed in the absence of GPS and the effectiveness of such a system

11.2.2 *Precision Positioning Needs*

Interviewees provided the level of accuracy required for use cases in various offshore applications areas (Table 11-1). For all, differential GPS (DGPS) was the positioning technology most commonly required. DGPS is precise at the decimeter level. We confirmed this interview finding with literature stating that the fundamental use of GPS offshore is DGPS (Corbett & Rayson, 1999). This means that the majority of

Table 11-1. Applications for GPS in Offshore Oil & Gas Operations

Application Area	Most Common Level of Precision Required for Use Cases in Each Application Area [a]	Second Most Common Levels of Precision Required for Use Cases in Each Application Area [b]	Uses and Benefits
Exploration and surveying	DGPS (1–2 dm)	WAAS (1.6–4 m)	▪ Allows operators to conduct seismic and hydrographic surveys during exploration activities ▪ Allows for more precise mapping of geological formations ▪ Facilitates infrastructure design and maintenance in terrestrial operations ▪ Reduces surveying labor costs ▪ Permits more accurate surveying results, particularly offshore
Rig moves and drilling	DGPS (1–2 dm)	RTK (1–2 cm)	▪ Permits rigs to accurately position over potential drill sites ▪ Improves accuracy of drilling operations
Dynamically positioning vessels	DGPS (1–2 dm)	RTK (1–2 cm)	▪ Enables vessels to maintain position and heading in deepwater where taut wire and other methods are unavailable
Marine construction	DGPS (1–2 dm)	RTK (1–2 cm) and WAAS (1.6–4 m)	▪ Helps direct construction operations with more precision ▪ Coupled with underwater acoustics, enables accurate underwater construction
Maritime navigation and situational awareness	DGPS (1–2 dm)	WAAS (1.6–4 m)	▪ Provides position and navigation data to vessel operators ▪ Allows fleet operators to monitor assets and improves workflow efficiency
Safety	DGPS (1–2 dm)	RTK (1–2 cm)	▪ Enables the Automatic Identification System (AIS)[66] ▪ Enables personnel tracking both onshore and offshore ▪ Provides secondary safety benefits through DP and safer drilling
Environmental monitoring and remediation	RTK GPS (1 cm)	RTK (1–2 cm) and WAAS (1.6–4 m)	▪ Enables better monitoring and tracking of oil spills ▪ Enables coordinated clean-up efforts

Source: Corbett and Rayson (1999) and RTI analysis of expert interview data.

[a] Precision level provided in this column had the highest response rate in the expert interviews.

[b] Precision level provided in this column had the second highest response rate in the expert interviews.

---

[66] AIS automatically provide information about the ship to other ships and to coastal authorities to aid in vessel monitoring and collision avoidance (IMO, 2019; para. 1).

users across offshore oil and gas application areas require precision levels of several decimeters (Landau et al., 2009), which has improved from meters level precision of DGPS circa 1999 (Corbett & Rayson, 1999). While DGPS is the standard, there is a trend in the oil and gas industry to move towards more precise methods, which is reflected in the fact that RTK GPS, which achieves centimeter level precision, was cited as the second most common level of precision for use cases in dynamic positioning[67], marine construction, safety, and environmental monitoring and remediation. However, RTK is more expensive to deploy. Wide Area Augmentation System (WAAS), which achieves meter level precision, was cited the most common second option for use cases in exploration, marine construction, and maritime navigation. Basic GPS, which only achieves precision within approximately 15 meters, was only cited as the most common second option for maritime navigation.

11.2.3   *Approach to Quantifying Retrospective Benefits*

In the absence of GPS,[68] the most likely alternative technology for offshore oil and gas positioning needs would have been a radio-based navigation system such as Loran-C or perhaps other more advanced versions that might have emerged, but according to the experts interviewed, radio-based technologies would have likely had less precision than GPS.

Loran is a long-range PNT system that transmits in the 90 to 110 kHz band. It has a range of approximately 1,500 miles and is not subject to line-of-sight limitations. Loran has reported accuracies of +/− 8 m. Such a system would be of limited use for most applications in the oil and gas industries because it lacks the precision required, as is evident from Table 11-1. It would, however, be useful for maritime navigation, fleet management, and timing for cellular communication with offshore rigs.

Some radio-based navigation systems are more accurate than Loran but suffer from much shorter ranges. These systems would require transmitting stations on static rigs to extend the range. For the purposes of our analysis, we assumed that eLoran would have developed as the dominant PNT system in the absence of GPS.

Before the development and commercialization of GPS, a number of radio-based PNT systems existed. All of these systems have been decommissioned and have been completely replaced by GPS. There are no backups systems in place for GPS other than other GNSS constellations.

We interviewed experts to refine counterfactuals and estimate economic impact on productivity, which we use to estimate cost savings. We accounted for the increase in the use of GPS over time and the percentage decrease in costs associated with its usage. We then extrapolated estimates of cost savings to the national level using secondary information about offshore oil and gas production.

---

[67] Dynamic positioning is defined as "a vessel capability provided via an integration of a variety of individual systems and functions. A computer control system automatically maintains a vessel's position and heading by using her own propellers and thrusters. Position reference sensors, combined with wind sensors, motion sensors and gyro compasses, provide information to the computer pertaining to the vessel's position and the magnitude and direction of environmental forces affecting its position" (The Nautical Institute, 2019; para. 1)

[68] We excluded commercial satellites from our analysis because they are similar to the existing GPS system.

Productivity Impacts

In addition to adoption, respondents provided quantitative estimates for the productivity impacts of GPS—the ability to achieve the same production levels with fewer input costs. About half of interviewed experts were able to provide quantitative estimates. When respondents provided a range, we used the midpoint of the range. The average productivity improvement for offshore E&P operations attributable to GPS was 32% but with a fairly wide range of responses; plus or minus one standard deviation yields a range from 13% to 51%. We applied these productivity impacts as a cost-savings, assuming that to achieve a given level of output, production costs would be decreased when using GPS compared to a counterfactual.

Because of the range of responses and degree of uncertainty we had with the results, we presented this information back to 17 interview participants who had offshore experience in a Delphi round to build consensus. We received an 82% (14 responses out of 17 interview participants) response rate in the Delphi round. Sixty-four percent of Delphi participants stated this this impact was reasonable, while 36% stated it was low. None said that it was too high. These responses gave us greater confidence that a 32% productivity gain was accurate or even conservative in that it was less the true value.[69]

We applied the 32% each year (accounting for adoption and the appropriate cost-basis). We decided not to scale back the productivity impact of GPS in earlier years because we had limited quantitative evidence about how the technology improved over time.

Adoption

One of the most important steps for the quantitative results was establishing an adoption timeline for GPS. GPS use began in the late 1980s through the early 1990s. For our model, we chose 1990 as our base year because answers from the interview phase were clustered around 1990 as the initial adoption year. Of the experts we interviewed, 88% indicated that the oil and gas sector is currently at 100% adoption of GPS in the relevant applications. Some experts' perception was that the oil and gas sector had fully adopted GPS across relevant applications as early as 2010.
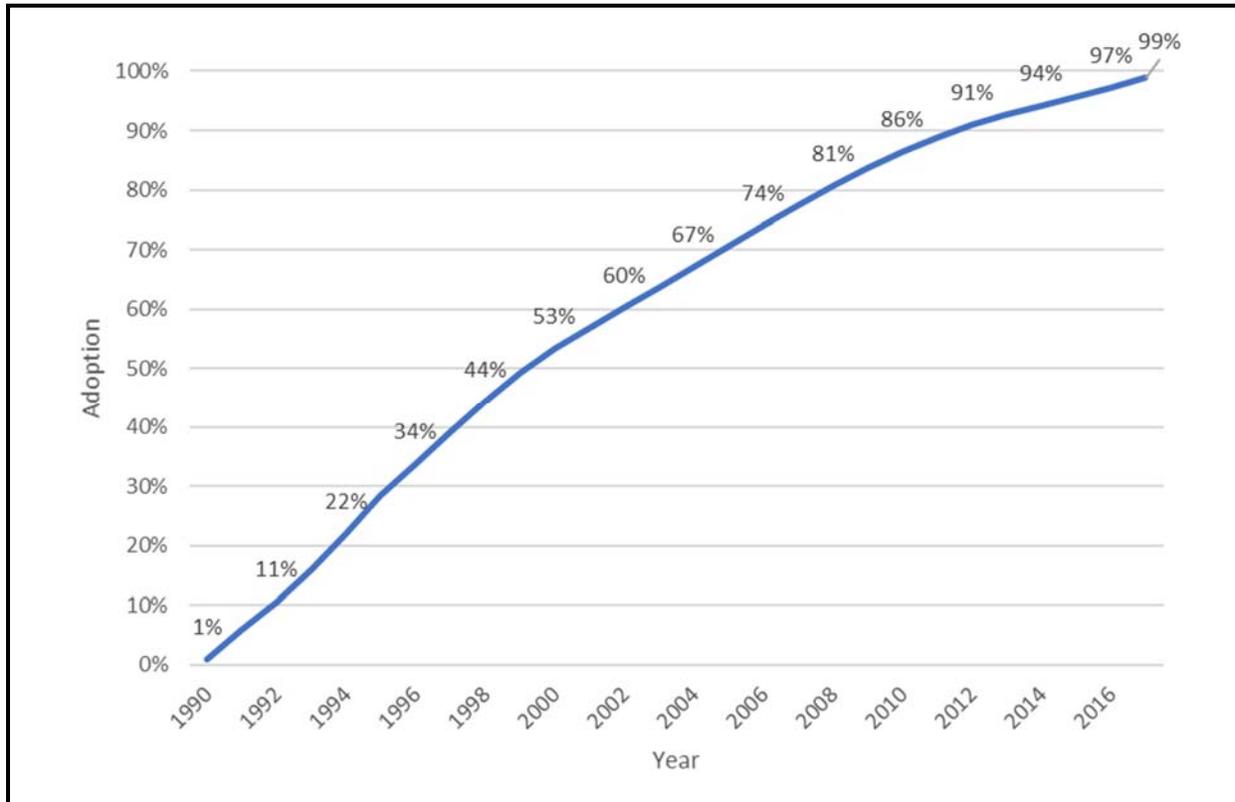
Adoption increased most rapidly in the 1990s and subsequently decelerated in later decades. The availability of DGPS in the 1990s likely played a role in the pace of adoption. By 2000, adoption surpassed 50% of the sector.

Although selective availability (SA) was turned off in 2000, we did not find that this had a significant impact on the adoption of GPS in the oil and gas sector. By the time SA was turned off, industry had already figured out workarounds to achieve required levels of precision. Specifically, by the mid-1990s, the accuracy of DGPS was sufficient for most oil and gas operations. Therefore, SA being turned off, while important, was not game changing.

Based on these observations about adoption, we have estimated an adoption curve in Figure 11-2.

---

[69] Although we received some answers regarding the change in labor requirements due to GPS, we excluded that from the analysis because it is embedded in the productivity impacts.

Figure 11-2. Adoption of GPS Technology in the Offshore Oil and Gas Sector

Source: RTI analysis of expert interview data.

Offshore Oil and Gas Costs

To scale productivity impacts to the national level, we constructed a time series of cost data for the U.S. offshore oil and gas sector from 1990 through 2017. Cost data were available from the EIA for 1990 through 2008 in the annual report titled *Performance Profiles of Major Energy Producers*. Cost data was not included in the 2009 issue. This report was discontinued by EIA following the 2009 issue. Because we do not have cost data for 2009 through 2017, we estimated costs for these years by calculating the percentage share of offshore costs relative to gross output for 1990 through 2008. We calculated that offshore costs were roughly 5.8% of the gross output for the industry. For 2009 through 2017, we multiplied the industry gross output by 5.8% to estimate offshore expenses. Gross output data was sourced from the Bureau of Economic Analysis using the industries 211000 "oil and gas extraction" (NAICS 211000) and "drilling oil and gas wells" (NAICS 213111).

Gross output data was not available for 1990-1996 for the "drilling oil and gas wells" industry which affected our ability to estimate offshore costs during those years. To estimate gross output data for this industry for these, we calculated the ratio between "drilling oil and gas wells" and a parent industry "other support activities for mining" (NAICS 213111A) from 1997 through 2017—on average 35.1%. From

1990 through 1996 we used this ratio to determine the missing output data for "drilling oil and gas wells."[70]

Cost data were limited to the categories of input costs that could reasonably be affected by GPS based on the application areas in Table 11-1. The costs basis for the analysis was the sum of exploration costs, development costs, and production costs (EIA, various). We excluded land acquisition[71] and equipment[72] where possible because they are less likely to be affected by GPS.

11.2.4   *Approach for Quantifying the Potential Impacts of a 30-Day Outage*

A 30-day outage would have widespread, negative effects in upstream offshore oil and gas operations. The sector is heavily reliant on GPS and has no robust backup systems in place. Existing wells would likely continue producing. However, exploration, construction, and drilling activities would be delayed. The ability to replenish existing platforms, drilling rigs, and drill ships with crews and supplies (for example, equipment and consumable goods) could also be impaired because there are safety concerns regarding resupply operations when dynamic positioning capabilities are not available

As with the retrospective analysis, the quantitative 30-day outage approach focused on offshore oil and gas activities. However, an unanticipated outage of GPS would have a much more severe impact on the sector. The percentage decrease on productivity over the 30-day period was estimated from the expert interviews and applied to offshore production costs for a 30-day period.

11.3 Retrospective Economic Benefits Analysis

11.3.1   *Qualitative Findings*

The applications of GPS listed in Table 11-1 have improved productivity in the oil and gas sector over time, resulting in fewer input costs to achieve production levels. Interviewees described specific applications of GPS:

- **Exploration and surveying:** The first step in extracting oil and natural gas is the exploration phase. Exploration operations include activities such as site surveys, hydrographic surveys, seismic surveys, and mapping of geological formations. These activities are undertaken to determine the location and potential size of offshore oil and natural gas fields.

  Interviewees indicated that GPS greatly improves an oil and gas company's ability to determine the size of oil and gas reservoirs, identify dangerous pockets of gas, and choose the ideal location for wells. This leads to more accurate mapping of reservoirs, more efficient placement of well sites, and improved safety through the avoidance of gas pockets.

- **Rig moves and drilling:** Once oil and gas deposits have been identified through exploration activities and the project is predicted to be profitable, drilling and then extraction can begin. Offshore drilling requires a jack-up oil rig, semisubmersible, or drill ship to be positioned over the well site prior to drilling. Wells are then created by drilling a hole into the seabed. GPS is critical for precisely positioning drilling infrastructure, and alternative positioning technologies

---

[70] Gross output was estimated using the average share of gross output from NAICS 213111 (Other support activities for mining) relative to NAICS 21311A for 1997–2017.
[71] Under exploration, we excluded "unproved acreage," and under development costs we excluded "proved acreage."
[72] Under development, we excluded "lease equipment" and "support equipment."

are limited the farther one moves from the coast. Precise positioning of wells improves yields, reduces the chance of opening gas pockets, and minimizes the creation of dry wells, which do not produce oil or gas.

▪ **Dynamically positioning vessels:** A key application in offshore operations that relies on GPS is dynamic positioning. Dynamic positioning systems use positioning data from GPS to determine the heading and position of a vessel. Propellers and thrusters are used to maintain this heading and positioning. This allows the vessels to remain relatively static, which improves safety by permitting vessels to work in close quarters to one another and to operate safely around rigs. Dynamic positioning systems are a vital component of drill ships and floating rigs because it permits them to maintain a fixed location over a well site. Without dynamic positioning systems, offshore drilling activities in deepwater would not be possible.

▪ **Marine construction:** GPS is a key tool in marine construction. It assists in accurate planning and placement of oil and gas pipelines and other subsea infrastructure.

▪ **Maritime navigation and situational awareness:** GPS is the primary aid to navigation for vessel operators. Additionally, GPS is vital to oil and gas companies' ability to manage their fleets. Real-time GPS coordinates allow for increased visibility of rigs, support vessels, construction ships, transportation ships, truck fleets, and ground crews. This permits improvements in workflow efficiency, the tracking of assets, and the safety of crew members.

▪ **Safety applications:** A secondary benefit of GPS is enhanced safety due to reduced likelihood of incidents involving equipment or personnel. For example, more accurate drilling leads to better avoidance of dangerous gas pockets, and the use of dynamic positioning helps prevent collisions between vessels. Additionally, some oil and gas companies have outfitted their crew members with personal GPS units with functioning distress signals in case of emergencies. GPS is also an enabling technology of the Automatic Identification System (AIS). The AIS provides the position, heading, speed, and course of the vessel to other ships and coastal authorities. It aids in vessel tracking and collision avoidance.

While our quantitative analysis focuses on estimates of cost savings from GPS over time, there are other qualitative benefits as well. Oil and gas companies have likely invested cost savings from GPS elsewhere over time, having second-order effects. Re-investment of cost savings was not considered in this analysis.

The use of GPS also enables offshore oil and gas operations to be more cost-effective, especially in deepwater operations where alternative positioning systems are currently limited and would likely still have been limited in the absence of GPS.

GPS also has additional benefits that we were not able to quantify but that experts described in interviews:

▪ Enhanced safety in the sector by providing greater situational awareness of where machines and workers are located at all times.

▪ Minor second-order impact on reducing waste from operations.

▪ More efficient drilling and reduced chances of accidents from dynamic positioning and fleet management lead to reduced likelihood of accidents and oil spills.

▪ Mitigating environmental crises once they occur. For example, GPS allows oil companies to track oil spills for more effective clean-up efforts.

11.3.2   *Quantitative Findings*

Using the estimated adoption rate of GPS over time, productivity impact estimates, and offshore oil and gas cost data from the EIA, we constructed an economic model to estimate the retrospective impacts of GPS on upstream offshore oil and gas sector. Cost data was converted from nominal values to 2017 real USD using a GDP Implicit Price Deflator from the Federal Reserve Bank of St. Louis.

For each year, we multiplied the total offshore oil and gas costs in Table 11-2 by the adoption rate for that year times the estimated productivity impact. We then calculated the counterfactual cost savings of the counterfactual technology, eLoran. The counterfactual cost savings were estimated using the same method above. Adoption levels for eLoran were assumed to be the same as GPS, which we believe is a conservative assumption given its limitations relative to GPS. Productivity impacts were reduced according to input during the interviews and Delphi rounds. Based on expert responses, we estimated eLoran to be about half as productive as GPS (specifically, 52% less productive). We then subtracted the counterfactual cost reduction from the GPS cost reduction to determine the cost savings of GPS relative to the counterfactual scenario where GPS was never developed.

We found that from 1990 through 2017, GPS reduced costs in the upstream offshore oil and gas sector by a cumulative total of $46.5 billion (2017 USD). Input data and results are presented annually in Table 11-2. Net cost savings and cumulative net cost savings are also depicted visually in Figures 11-3 and 11-4.

Table 11-2. Time Series of Offshore Oil and Gas Model Inputs

Year	Total Offshore Oil and Gas Costs that Can be Reduced by the Application of GPS (nominal $ billion)	Adoption Rate	Productivity Impact of GPS (nominal $ billion)	Potential Counterfactual Cost Savings of Loran and eLoran (nominal $ billion)	Net Cost Savings of GPS (nominal $ billion)	Net Cost Savings of GPS (real 2017 $ billion)
1990	$$6.2	1%	$0.02	$0.01	$0.01	$0.02
1991	$6.2	6%	$0.1	$0.1	$0.1	$0.1
1992	$4.5	11%	$0.2	$0.1	$0.1	$0.1
1993	$5.0	16%	$0.3	$0.1	$0.1	$0.2
1994	$5.4	22%	$0.4	$0.2	$0.2	$0.3
1995	$4.8	28%	$0.4	$0.2	$0.2	$0.3
1996	$6.3	34%	$0.7	$0.3	$0.3	$0.5
1997	$7.3	39%	$0.9	$0.4	$0.5	$0.7
1998	$7.7	44%	$1.1	$0.5	$0.6	$0.8
1999	$7.2	49%	$1.1	$0.5	$0.6	$0.8
2000	$7.7	53%	$1.3	$0.6	$0.7	$0.9
2001	$9.2	57%	$1.7	$0.8	$0.9	$1.2

(continued)

Table 11-2. Time Series of Offshore Oil and Gas Model Inputs (continued)

Year	Total Offshore Oil and Gas Costs that Can be Reduced by the Application of GPS (nominal $ billion)	Adoption Rate	Productivity Impact of GPS (nominal $ billion)	Potential Counterfactual Cost Savings of Loran and eLoran (nominal $ billion)	Net Cost Savings of GPS (nominal $ billion)	Net Cost Savings of GPS (real 2017 $ billion)
2002	$8.4	60%	$1.6	$0.8	$0.8	$1.1
2003	$7.6	64%	$1.5	$0.7	$0.8	$1.0
2004	$8.0	67%	$1.7	$0.8	$0.9	$1.1
2005	$10.2	71%	$2.3	$1.1	$1.2	$1.5
2006	$13.2	74%	$3.1	$1.5	$1.6	$1.9
2007	$14.2	77%	$3.5	$1.7	$1.8	$2.1
2008	$13.7	81%	$3.5	$1.7	$1.8	$2.1
2009	$14.1	84%	$3.8	$1.8	$2.0	$2.2
2010	$18.2	86%	$5.0	$2.4	$2.6	$2.9
2011	$21.6	89%	$6.1	$3.0	$3.2	$3.5
2012	$22.0	91%	$6.4	$3.1	$3.3	$3.6
2013	$25.2	93%	$7.5	$3.6	$3.9	$4.1
2014	$28.4	94%	$8.6	$4.1	$4.4	$4.6
2015	$17.1	96%	$5.3	$2.5	$2.7	$2.8
2016	$13.2	97%	$4.1	$2.0	$2.1	$2.2
2017	$19.1	99%	$6.0	$2.9	$3.1	$3.1
Total	$331.6		$78.3	$37.9	$40.5	$45.9

Source: RTI analysis.

The annual net cost savings of GPS for the upstream offshore oil and gas sector have increased over time as adoption has increased. The large dip in annual net cost savings from 2014 through 2017 is a result of the drop-off in oil production in the lower 48 states.

11.4 Potential Impacts of a 30-Day Outage

The impacts from a 30-day outage of GPS would be most challenging for offshore operations. Experts described such an outage with terms such as "catastrophic," "crippling," and "disastrous." Without GPS, virtually all exploration and survey activities would stop in the short term. These activities rely heavily on GPS (and other GNSS systems) and operators do not have backups systems in place.

Positioning rigs and drilling new wells with dynamic positioning applications would not be possible during a GPS outage because of an inability to accurately position the rig or drilling vessel over the well and maintain this position during drilling.

Experts agreed that production from fixed jack-up rigs would likely continue. These rigs are stationary, attached to the ocean floor, and connected to an established well. As such, they do not rely directly on GPS to continue operating.

Semisubmersible rigs and drill ships would be forced to cease production. Dynamic positioning systems do not work without an active GPS signal, and these vessels would not be able to maintain their position. They would be forced to disconnect from their wells and cease production during the outage.

Resupply efforts would be hindered during an outage because of a loss of dynamic positioning and navigation from GPS. This presents problems with replenishing crews and supplies to offshore rigs. Jack-up rigs, which are close to shore, would likely be less affected by these issues.

Virtually all construction and pipelaying operations would stop in the short term. This would not affect production during the outage but could have production implications in the future because of delayed development.

Experts also stated that the loss of the timing component of GPS could also lead to communication issues with offshore rigs (see the Section 4 for a detailed discussion of how the telecommunications network relies on GPS for precision timing and synchronizing communications and potential impacts of a disruption).

We asked interview respondents to provide quantitative estimates on productivity impacts during a 30-day outage scenario. On average, interview experts stated that productivity would decrease by 31%. We provided the average productivity impact to Delphi round participants, and 78% stated it was low and 22% stated it was accurate. Because there was such a strong indication that the impact was low, we revised the 30-day outage impact to 41%[73] based on Delphi responses. We believe this is reasonable given that there are no widespread backup positioning systems in place across application areas. Most of the backup system investment anecdotally appears to be in subsea acoustic positioning systems which are a viable short-term alternative for dynamic positioning applications. Acoustic positioning systems use beacons which are fixed on the ocean floor to provide a localized backup to GPS. The beacons rely on GPS for calibration during initial set up and require periodic corrections as the beacons move due to shifts on the ocean floor. Due to the reliance on GPS for initial calibration, it would be difficult to deploy acoustic positioning systems and beacons that are not already in place. Acoustic positioning systems already in place would function during the 30-day outage absent needs for recalibration.

To model the productivity impacts of a 30-day outage, we gathered gross output data for the oil and gas sector by aggregating two industries: (1) oil and gas extraction and (2) drilling oil and gas wells (BEA, 2018).[74] In 2017, annual output for these two industries combined was $326.0 billion or $25.5 billion per 30-day period.[75] We estimate that 14% of production occurs offshore and virtually all of the sector has adopted GPS. To determine the loss in productivity from a 30-day failure, we applied the 41%

---

[73] Responses from the Delphi round were incorporated into the averages by replacing respondents' original responses where they varied. The revised average 30-day outage impact was 41% after incorporating Delphi round responses.
[74] Specifically, NAICS 211000 represents "Oil and Gas Extraction," and NAICS 213111 represents "Drilling Oil and Gas Wells."
[75] We also adjusted for the fact that our adoption curve shows 99% adoption in 2017.

productivity impact to the adoption- adjusted 30-day output value for offshore oil and gas. We estimate that a 30-day outage of GPS would lead to a reduction in output equal to $1.5 billion.

It is important here to stress several limitations of this analysis. First, some portion of this short-term production loss could be made up later in the year if oil companies hire additional workers, require existing workers to work overtime, and/or figure out ways to have a higher utilization of machinery and equipment. However, this would involve higher costs for industry. Also, given that construction activities could be delayed, there may be lagging supply disruptions that we are unable to capture in the 30-day period. These supply disruptions would at least partially offset some of the rebound effect in later months. Finally, this analysis does not quantify the potential spillover effects that a short-term supply shock to oil and gas might have on other sectors of the U.S. economy. For example, if a supply shock raised oil prices, because oil and petroleum-based products are a key input for many industries, this could in turn increase prices elsewhere in the economy.

11.5 Concluding Remarks

GPS has been an important platform technology for the oil and gas sector, and it is now deeply ingrained in the upstream operations of the sector. Oil and gas companies has invested in technologies complementary to GPS such as relative positioning methods like acoustics. However, it is uncertain how widespread these investments are. Furthermore, from the expert interviews we conducted, there is no evidence the sector is investing in absolute positioning backup technologies for deepwater activities.

Currently, no existing PNT technologies can directly replace GPS at this stage in terms of its precision and global reach. Radio-based PNT systems such as eLoran are incapable of providing the accuracies needed for offshore oil and gas operations. However, they could provide stopgap backup measures to reduce the impacts should GPS and GNSS signals fail.

Radio-based PNT systems could be further enhanced to provide required position levels but would require fixed infrastructure not just onshore but offshore as well. Furthermore, their global reach will always be more limited than GPS short of large investments in fixed infrastructure.

12. Professional Surveying

The surveying industry was one of the earliest adopters of GPS, and it continues to use precision location information to improve the productivity and lower the costs of surveying tasks. Surveyors are experts at precisely measuring spatial characteristics and were one of the first professions to understand the potential of GPS and to apply it to their work. Surveying applications are critical to many disparate but economically important sectors, such as construction, land registration, mapping, mining, and infrastructure planning.

Before GPS was available, surveyors used technologies that were effective at achieving high levels of accuracy, but with higher labor costs, longer time frames, and lower productivity levels. Given the sub-cm level accuracy required by surveyors and the high accuracy levels that traditional technologies can achieve, if GPS had not been developed or had not been available it is unlikely that an alternative such as eLoran[76] would have been able to achieve the high-resolution accuracy required by surveyors. With no viable alternative, we estimate that GPS has provided the surveying industry with $48.1 billion of benefits since 1984, and an average of about $2.7 billion per year since 2010.

If GPS became unavailable for 30 days, the surveying industry and the broader economy would experience immediate consequences because most surveyors perform GPS-assisted surveying and rely on the productivity enhancements that it provides. Surveyors would need to switch to more traditional techniques and tools, which would cause delays, higher costs, and productivity losses for surveying activities. Economic sectors that rely on surveying would also be delayed. We estimate the total cost of a 30-day GPS outage to the surveying industry to be $331 million.

12.1 Sector Introduction and Overview

The U.S. Bureau of Labor Statistics (2017) recorded 43,430 people in the United States employed as surveyors in May 2017[77], and accounted for approximately $7.2 billion[78] in revenue. The majority worked in architectural, engineering, and related services, with others in local and state governments and infrastructure construction industries. The industry is characterized by small-scale operators.

Surveyors have widely adopted GPS and incorporated it broadly into surveying techniques; almost all surveyors use GPS in at least some of their work or rely on GPS by accessing geodetic networks[79]. Using geometric calculations and technology, surveying has broad applications in construction, architecture, urban planning, engineering, archaeology, real estate, mining, agriculture, and other industries that rely on accurately identifying and mapping boundaries and land features.

---

[76] Approximate position accuracy is 8 – 20m (26.2 – 65.6 ft) from the GPS Wide Area Augmentation Systems (WAAS) 2008 Performance Standard.
[77] https://www.bls.gov/oes/2017/may/oes171022.htm
[78] Extrapolated from historical revenue – see Table X-2.
[79] A geodetic network or geodetic control network is a system of points represented by physical monuments that are precisely marked and documented. The National Spatial Reference System is an example of geodetic control network across the United States.

GPS brought immense benefits to the surveying field. According to the surveying experts interviewed for this study, GPS enables surveyors to greatly enhance their productivity, compared with traditional surveying. Surveyors can reliably complete more jobs with similar accuracy levels in less time and with less labor.

Traditional surveying methods require a "line of sight" between the topographic points being measured, meaning at least two workers are required to measure points no further apart than can be seen and have no visual obstructions between the points. With GPS, this requirement is eliminated, freeing surveyors to measure distant points that may have obstacles between them. Thus, surveying companies can field smaller teams to do often larger jobs. This fact was one of the big selling points when GPS was introduced to the surveying industry and remains one of the primary benefits today.

Surveying is also one of the sectors that requires the highest levels of accuracy, often less than 1 cm and sometimes even less than 1 mm, depending on the application. While traditional surveying methods can achieve this accuracy, GPS enables surveyors to obtain similar levels of accuracy in less time. In the GPS receiver market, the receivers with the highest accuracy are called "survey grade" to indicate that they can be used for survey purposes.

However, GPS does have some drawbacks. GPS does not always provide improved accuracy over other techniques, especially in situations with interference in the line of sight between receivers on the ground and satellites in the sky (Kizil et al., 2006; DiBiase, n.d.). In heavily forested areas, dense urban locations, or over very short distances, surveyors may use a conventional method rather than GPS. Also, by eliminating the need to survey several points using line of sight, there is also the unintended consequence of sometimes losing the additional geographic detail in between those points.

Surveyors typically use a combination of old and new techniques in their work. Older technologies that are still used today in the United States include the "total station," or "robotic total station," an improved electronic version of a traditional technology called a theolodite (a surveying instrument with a rotating telescope for measuring horizontal and vertical angles). Differential GPS is typically used for surveying applications in the form of real-time kinematic (RTK)[80] observations with permanent base stations. This technology provides the accuracy required for most survey applications.

Few comprehensive reviews of the economic benefits of GPS on surveying in the United States have been conducted. Leveson (2015) assumed 100% adoption of GPS in surveying and productivity gains of 45 to 55% and estimated that GPS provided benefits of between $9.8 and $13.4 billion in 2013 ($10.4 and $14.2 billion in 2017$). Similarly, Pham (2011) estimated the annual benefits of GPS to engineering construction (including heavy and civil and surveying and mapping) to be between $9.2 and $23 billion in 2007 ($10.7 and $26.8 billion in 2017$), based on an adoption rate of 40% and 100% respectively. These studies estimated economic benefits for only 1 year, assumed efficiency gains based on few sources, did

---

[80] RTK is a technique that uses carrier-based ranging to provide positioning information that is much more precise than code-based positioning techniques.
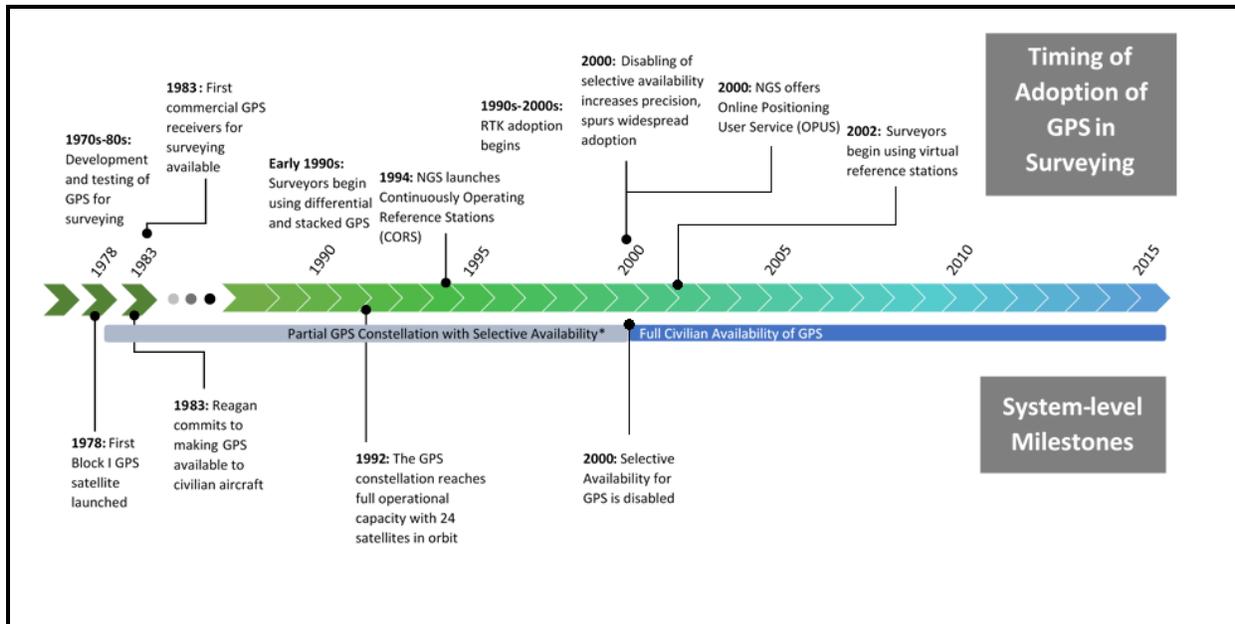
not explicitly account for the costs of GPS-enabled surveying equipment, and did not differentiate between adoption rates or efficiency gains for different surveying applications.

12.2 Timeline of GPS Adoption by Surveyors

Through expert interviews conducted by RTI, surveyors provided a detailed accounting of the timeline and key milestones in the adoption of GPS (see Figure 12-1). The first experimental phases of GPS receiver development occurred in the late 1970s and early 1980s, and surveyors in large firms and organizations like the National Geodetic Survey (NGS) were among some of the first adopters during this time. GPS provides greater returns on large surveying projects, and in its early days, only organizations undertaking large surveying projects found the high costs worthwhile.

Surveyors began widespread adoption in the 1990s as a result of technological development, in particular differential GPS, RTK networks, and NGS's establishment of Continuously Operating Reference Systems (CORS).[81] RTK technology, first introduced in 1992, allowed moment-by-moment GPS updates while in motion, increasing accuracy and speed of data acquisition. Before the full constellation of satellites launched in 1995, a reliable GPS signal was not available 24 hours per day, and surveyors had to plan

Figure 12-1. Timeline of Relevant Events in the History of GPS in Surveying in the United States

---

[81] The Continuously Operating Reference Stations (CORS) is a network of independently owned and operated sites that provide three dimensional positioning for the United States and its territories. NGS oversees the network, which provides highly accurate GPS positioning data relative to the National Spatial Reference System. The Online Positioning User Service (OPUS) relies on CORS to provide any survey grade GPS user with data to link their GPS position with to the NSRS. For more info on CORS and OPUS, visit: https://www.ngs.noaa.gov/CORS/ and https://www.ngs.noaa.gov/OPUS/about.jsp.

around its availability, leading to some impractical late-night availability and discontinuous periods. Benefits of adopting GPS also increased with general technological improvements that made equipment smaller and faster, lowered prices, and increased ease of use. These technologies allowed surveyors to obtain reliable and highly accurate measurements without needing a line of sight to the next survey point. However, GPS equipment was still prohibitively expensive for many surveyors.

Selective availability was turned off in 2000, further facilitating GPS's adoption. By the early 2000s, capital costs fell further, and virtual reference stations became widely available, a technology that allowed surveyors to quickly access a GPS signal from nearly any location. Other sectors that require highly accurate location information such as agriculture, and extractive industries also benefitted from these developments.[82] Through the further expansion of CORS and the incorporation of the GPS into the National Spatial Reference System (NSRS), surveyors could measure absolute locations rather than relative points, so locations from different geographies were on the same system and could be compared with each other. By 2010, surveyors had widely adopted GPS or GPS-assisted technology in their work; one expert remarked that by the late 2000s most surveyors could not afford to *not* use GPS.

The timeline, key trends, and milestones presented here are largely validated by the web-based survey that RTI conducted of National Society of Professional Surveyors (NSPS) membership. Results from the survey show the adoption timeline for survey respondents who had been working in the field since at least 1990 (see Figure 12-2). Close to 20% of these surveyors had adopted GPS by 1990, but this number rose to approximately 70% by the year 2000. The steepest slope of the curve is between 1990 and 2000, when adoption was accelerating most rapidly, reflecting technology improvements. By the time selective availability was turned off in 2000, most surveyors had already adopted GPS and were using it in some capacity. The final wave of GPS adoption occurred after 2000 to the present but at a slower pace than in the 1990s. Today, almost all surveyors use GPS in some capacity, although not for all surveying jobs.

Figure 12-2. GPS Adoption Rate Over Time

Note: Derived from NSPS membership survey. Sample restricted to surveyors working since 1990 or earlier.

---

[82] To avoid double counting, these benefits are not included in the surveying sector analysis of this study but are captured in the related agriculture and mining sections of this report.

12.3 Methodological Notes

To shed light on the different ways that GPS has provided economic benefits to the surveying industry, RTI obtained primary data from fielding a country wide web-based survey, interviewed multiple experts, and through a close collaboration with the National Society of Professional Surveyors (NSPS). NSPS is a national organization that supports surveyors and the surveying profession in the United States.[83] NSPS facilitated access to their membership to enable a web-based survey and to expert licensed surveyors for expert interviews.

The web-based survey was critical to understanding the impact of GPS on the surveying sector. The survey was sent to a random sample of 2,000 of the approximately 17,000 licensed professional surveyors who belong to NSPS. The response rate was slightly greater than 10% (283 respondents). The questions on the survey covered a broad array of topics, including type of surveying conducted, perceptions of GPS, adoption timeline, barriers to adoption, and the quantitative impact of GPS on surveying.

Our analysis was also informed by the qualitative interviews with key stakeholders in the surveying industry, drawn from professional associations, government agencies, and other relevant groups. We conducted 15, hour-long formal interviews with these experts to determine how surveyors use GPS, the benefits of GPS, the timeline of GPS adoption by the surveying industry, counterfactual scenarios, and ways government agencies supported technology transfer to the surveying industry. We conducted additional unstructured interviews to validate the content of the web-based survey, interpret the results, and gather other qualitative information as needed. RTI also attended the North Carolina Society of Surveyors Annual Conference and Trade Show from February 8 through 10, 2018, to discuss the project with surveyors.

12.3.1 *Approach to Quantifying Retrospective Benefits*

Our approach to quantifying retrospective economic benefits of GPS in the surveying industry began with estimating the efficiency gains from using GPS compared with predecessor techniques and technologies (e.g., total stations). We assumed these techniques and technologies, which have advanced over time and are still in use by surveyors, as our counterfactual scenario. Experts agreed that a Loran-based system would not have provided the accuracy requirements to add value to the surveying community in the absence of GPS.

To value efficiency gains, we compared the costs and productivity benefits of GPS-assisted technologies with traditional technologies. We quantified the percentage difference between the costs of GPS-assisted surveying per job completed and the costs of non-GPS-assisted surveying through the web-based survey conducted in partnership with NSPS. We asked surveyors to estimate the percentage share that capital, labor, energy, and materials (KLEM) costs make up of their surveying business and then asked how those costs would change if they used only traditional technologies in each surveying job. In this way, surveyors could reflect on how each factor of production had changed with GPS, rather than trying to estimate cost differences for each factor simultaneously.

---

[83] https://www.nsps.us.com/

After obtaining cost savings of GPS over traditional technologies, we scaled the results to the entire surveying industry in the United States and over time from the date of its first adoption through the present day. To do this, we used four key variables—industry revenues, adoption rates over time, KLEM share of revenue, and efficiency gains over time. Table 12-1 details data sources and assumptions for all data used for the analysis values.

The extrapolation procedure using the variables in Table 12-1 involved six steps:

1. Extrapolated to obtain survey revenues for the years when GPS was adopted (1984 through 2017). Assumed that revenue changed linearly between each data point that was available (1997, 2002, 2007, 2012). Fitted a linear trend to determine values from 1992 through 1997 and for 2012 through 2017. To extrapolate to years prior to 1992, linearly extrapolated the 1992 through 1997 time trend backward to 1984.

2. Removed the share of surveying that services the oil and gas and mining industries to ensure no double-counting for those industries.[84]

Table 12-1. Key Data Sources and Assumptions

Variables	Data Source	Assumptions
Survey industry revenue over time	U.S. Census's Economic Census, from 1997–2012, for North American Industry Classification System (NAICS) code 54137 (Surveying and Mapping [except Geophysical] Services)	Census Bureau data only provide revenue in 5-year time steps. These data are available for 1997, 2002, 2007, and 2012, and we estimated revenue for years where data are missing using linear extrapolation and interpolation. We assumed a perfect market where costs savings = increased revenues.
Surveyor adoption of GPS over time	Web-based survey	Surveyors know when they adopted GPS for the first time and can accurately estimate the cost savings of GPS for the most recent year. Respondents are representative of the surveying industry.
KLEM share of revenues	Web-based survey	Assumed KLEM shares of total revenue as a baseline from which to calculate KLEM-specific efficiency gains.
Costs savings over time	Web-based survey, Total Factor Productivity (TFP) table from Bureau of Labor Statistics, and expert elicitation	Used current costs from the web-based survey and discounted labor by total factor productivity for the industry sector.[85] Assumed labor productivity has increased over time, so benefits for the most recent year are not the same as benefits in previous years. Assumed capital, materials, and energy efficiency gains were the same over time. According to experts, although GPS requires additional capital and other costs than traditional technologies, these additional costs are offset by savings to outfit fewer crews that are needed with GPS.

---

[84] The oil and gas and mining sectors purchase a percentage of services from surveying and mapping. Those percentages were obtained from the IMPLAN model by first calculating the total value that oil and gas and mining sub-sectors purchase from surveying & mapping, an then assuming the sum of those values represented a percentage of the total output of oil and gas and mining from the larger architectural, engineering, and relate services sector. The total percentage was only 0.46%.

[85] Accessed Nonmanufacturing Sector and NIPA–level Manufacturing Industries KLEMS Multifactor Productivity Tables by Industry from https://www.bls.gov/mfp/mprdload.htm. NAICS code 5412-5414. Pulled from Single-Factor Output/Input Ratios.

3. Reduced survey revenues to the portion of the surveying community that had adopted GPS. The adoption curve was based on responses to the web-based survey and conformed with expert feedback.

4. Applied efficiency gains—measured by the cost reduction per survey job completed—to the revenue of the portion of the surveying sector that had adopted GPS. Conducted this separately for capital, labor, energy, and materials (KLEM).

5. Discounted labor savings from GPS by labor productivity for the overall industry NAICS code (5412-5414) from 1984 to the present. In this way, we assumed that the benefits of GPS have increased over time. We cannot assume that the benefits of GPS in 2017 were the same as the benefits of GPS in the 1980s.

6. Summed the KLEM savings for each year to a total value (see Section 1.5.2).

Example calculations:

In general, the benefits of GPS to the surveying industry can be calculated by subtracting the revenue the surveying industry would make if GPS was not adopted at all from the revenue the surveying industry would make if a portion of the industry adopted GPS.

$$GPS\ Benefits_y = \left[\left(\frac{R_y \times A}{1 - |C|} \right) + \left(R_y \times (1 - A) \right) \right] - R_y$$

where

R = Surveying and mapping revenue, by year

A = Percentage of surveyors that adopt GPS, by year (from web-based survey)

C = Percentage reduction in costs from GPS, by year (from web-based survey and expert elicitations)

This equation can be simplified to:

Equation 1: $GPS\ Benefits_y = \frac{R_y \times A}{1 - |C|} - \left(R_y \times A \right)$

As discussed above, we make a few adjustments to this general formula. First, we remove the share of surveying revenue related to the oil and gas and mining industries.

Equation 2:   Total Surveying Revenue of GPS Adopters$_y$ = R_GPS$_y$ = (R$_y$ – S$_y$) * A$_y$

where

S = Share of surveying purchased by extractive industries (from IMPLAN)

We then calculate the benefits for each KLEM separately by plugging Equation 2 into Equation 1 and by accounting for each KLEM's share of annual revenue and using KLEM-specific cost reductions.

Equation 3: GPS Benefits by KLEM$_y$ = ((R_GPS$_y$ * KLEMs) / (1 – |KLEMc$_y$|)) – (R_GPS$_y$*KLEMs)

where

R_GPS = Surveying revenue of GPS adopters by year, calculated above

KLEMs = Share of surveying revenue dedicated to capital, labor, energy, materials (KLEM from web-based survey)

$KLEMc_y$ = Percentage savings, by KLEM and by year, due to GPS, from web-based survey. Labor savings discounted by labor productivity to reflect the fact that present day labor savings are greater that previous years labor savings.

12.4 Retrospective Economic Impact Analysis

Experts and survey respondents described GPS as a technology that revolutionized the surveying industry. Many surveyors today work alone, with sole proprietors accounting for 55.7% of industry operators (O'Connor, 2017). It would be nearly impossible to have this percentage of sole proprietors without GPS, because total stations and pre-GPS surveying usually required at least two people. Today with GPS a single surveyor can complete many jobs in about half the time that it used to take two or three surveyors to do. The benefits of GPS also exhibit returns to scale: as a result of using GPS, costs are reduced for surveying projects covering larger areas; for example, a survey respondent in Alaska reported intense reliance on GPS to complete work in large and remote areas.

12.4.1   Survey Findings

Responses from the web-based survey were consistent with feedback received from the expert interviews. Respondents were all licensed surveyors from throughout the country, many with deep experience in the surveying industry, and almost all were GPS users. More than half were owners or part owners of a surveying business. Those responding to the survey reported using GPS on 86% of jobs, and 66% said they use GPS "all the time"; 32% use it "sometimes," and only 1% never use the technology (see Table 12-2).

More than 94% of surveyors felt that GPS was "very important to their job," and 64% said that GPS enables them to complete jobs that would be impossible to do without GPS. On average, surveyors report that 30% of their revenue comes from jobs that could only be done with the support of GPS. For the relatively small number of jobs for which surveyors did not use GPS, they primarily cited impediments to line of sight to the sky, accuracy limitations, lack of need, and economic reasons (see Table 12-3).

Table 12-2. Use of GPS in Surveying

Do you use GPS technology when you do surveying?	
Yes, all the time	66.2%
Yes, sometimes	32.4%
No, never	1.4%

n=283

Table 12-3. Reasons Surveyors May Not Use GPS

For those jobs where you do not use GPS, why do you not use it? Select all that apply.	
I do not have a line of sight to the sky	55.8%
It does not meet the accuracy requirements to the task	42.4%
I don't need it to do my job	24.7%
It is not economically beneficial to me	18.7%
I don't know how to use GPS technology	0.7%
Other	7.8%
N/A—I use GPS for all surveying jobs	17.3%

12.4.2   *Quantitative Analysis Results*

We asked respondents what percentage of their costs are capital, labor, energy, and materials (KLEM) and then by what percentage their costs in those categories change when using GPS (Table 12-4).[86] We also anticipated that, while GPS in the present day might bring a certain degree of cost savings, it was not as beneficial in its earlier years, so for the time series we discounted labor savings according to labor productivity[87] over time. Capital, materials, and energy savings were not discounted this way and were applied uniformly across years.

Table 12-4. Surveying Cost Structure and Cost Savings from GPS

Cost Category	Percentage of Total Costs	Percentage Reduction in Costs from GPS in 2017[a]
Labor	51.1%[b]	−44.8% (0.19)
Capital	24.6%	−0.5% (0.36)
Energy	8.5%	−7.9% (0.19)
Materials	8.0%	−4.9% (0.18)

[a] Mean answer; standard deviation in parentheses.
[b] Surveyors estimated that labor represented 51.1% of total revenues.

---

[86] We considered that these answers might differ somewhat between surveyors who own their own firms and are thus very familiar with their cost structure and regular employees who might not be familiar, but we found their answers to be extremely similar when aggregated, so we present figures given by both owners and nonowners of surveying firms.
[87] See Section 1.4, Step 5.

We estimate that the benefits of GPS to the surveying sector are $48 billion, with 97% of those benefits coming from labor savings and only 4% from capital, energy, and material cost savings (see Table 12-5).[88] Benefits have increased over time as the surveying industry has grown, GPS adoption has increased, and technology has improved. The average benefit has been $2.7 billion per year since 2010. These are net benefits to surveying, because they implicitly account for the counterfactual, including capital costs, given that surveyors compared savings to their costs in the absence of GPS. The benefits are based on the cost savings of GPS that surveyors reported from the survey. Table 12-5 summarizes total benefits by year to the surveying industry.

Table 12-5. Retrospective Economic Benefits of GPS

Year	Adoption Rate of GPS, %[a]	Savings ($ million)				Benefits ($ million)
		Labor	Capital	Energy	Materials	
1984	4%	14	<1	1	<1	15
1985	5%	21	<1	1	<1	23
1986	6%	30	<1	1	1	32
1987	8%	42	<1	2	1	44
1988	15%	91	1	3	2	96
1989	18%	122	1	4	2	129
1990	20%	150	1	5	3	158
1991	24%	188	1	6	3	198
1992	28%	239	1	7	4	251
1993	30%	268	1	8	4	282
1994	34%	325	2	9	5	342
1995	42%	432	2	12	7	454
1996	45%	523	2	14	8	547
1997	53%	686	3	17	10	715
1998	66%	945	4	23	13	984
1999	68%	1,053	4	25	14	1,096
2000	72%	1,210	5	27	15	1,258
2001	74%	1,327	5	29	17	1,378
2002	77%	1,542	6	32	18	1,597
2003	81%	1,805	6	36	20	1,868
2004	83%	2,027	7	40	23	2,097

(continued)

---

[88] Benefits are sensitive to assumptions made about the cost share of labor in surveying. In our survey, surveyors estimated that the labor share of revenue was 51.1%, which is 29% higher than the share of payroll to revenue according to Census Bureau statistics (U.S. Census Bureau, n.d.). This is likely because about half of surveying firms are sole proprietorships; therefore, their labor income is not reported as payroll. In our calculation, we assumed 51.1% over time. If we use the annual labor share of revenue as reported by the Census Bureau, total benefits decrease to $41 billion.

Table 12-5. Retrospective Economic Benefits of GPS (continued)

Year	Adoption Rate of GPS, %[a]	Savings ($ million)				Benefits ($ million)
		Labor	Capital	Energy	Materials	
2005	86%	2,261	8	44	25	2,338
2006	88%	2,391	8	48	27	2,474
2007	91%	2,610	9	52	29	2,700
2008	91%	2,676	9	49	28	2,761
2009	92%	2,537	8	47	27	2,620
2010	95%	2,620	8	46	26	2,701
2011	95%	2,456	8	44	25	2,532
2012	96%	2,328	7	42	23	2,400
2013	97%	2,414	8	44	25	2,490
2014	98%	2,638	8	46	26	2,718
2015	99%	2,759	9	48	27	2,843
2016	99%	2,876	9	50	28	2,963
2017	99%	2,943	9	51	29	3,032
Total		**46,536**	**162**	**912**	**514**	**48,124**

[a] Adoption rate refers to the number of surveyors that have adopted GPS even if they do not use it for all jobs.

The quantitative benefits conform to the informal estimates provided in interviews with surveying experts. Experts agreed that primary benefits provided to GPS are from labor savings. Capital costs could increase or decrease because GPS equipment can be expensive, but these expenses are largely offset by the fact that GPS enables smaller surveying teams and lower capital costs to outfit fewer teams.

Experts also consistently estimated that GPS roughly halves labor costs; responses ranged from a 100% labor savings to a 0% labor savings, and 98.2% of respondents agreed that GPS allowed them to perform the same amount of work in less time. GPS's impact on capital expenditure is somewhat less clear. Anecdotally, experts believe GPS had an ambiguous effect on capital costs for firms for the reasons discussed above and that ambiguity is reflected in the survey data; this item had the highest standard deviation (0.36, see Table 12-5), and responses ranged from some respondents reporting 80% savings on capital costs all the way to a 200% increase in capital costs. Respondents reported small savings in energy and materials, but these categories did not represent large portions of most surveying firms' costs.

Most of the benefits of GPS are going to small business owners rather than big companies. Unlike many industries that benefit from GPS, surveying mainly consists of small-scale operators. In 2018, sole proprietors accounted for 55.8% of all enterprises. Of surveying businesses with a payroll, 84.6% employed fewer than 10 people (O'Connor, 2018).

Note that these estimates do not account for any quality improvements in surveying results, which would tend to underestimate the benefits of GPS to surveying. GPS has enabled surveyors to better communicate and relate their measurements to each other by standardizing them into the National Spatial Reference

System and through the development of CORS. Now surveying measurements are comparable across the country and are very precise as well as more accurate, allowing absolute measurements in different geographies to be comparable. This kind of added value is not captured in our results.

12.5   Potential Impacts of a 30-Day Outage

Experts and survey respondents agreed that a 30-day outage of GPS would be disruptive to the surveying industry, although they disagreed somewhat on what form those disruptions would take and how severe they would be. Experts described the impacts of such a shutoff as "catastrophic," "stunning," and "chaotic"; some suggested all surveying work would stop. They expressed concern that younger surveyors would be unfamiliar with pre-GPS surveying techniques, that surveying firms no longer own the appropriate tools to work without GPS, or that the required additional labor to survey without GPS— some said as much as three to five times as much—would not be available during the outage.

Respondents to the web-based survey agreed that they would be affected but not as severely. While 94% said that such an outage would have an impact on their work, only 7.8% thought it would prevent them from working entirely.[89] Most respondents (86%) thought the outage's biggest impact would be increased time required to complete the same jobs. Very few thought they did not have the right equipment to survey without GPS, that it would take a long time to get the right equipment (5.3% and 6%, respectively), or that they did not know or would need to relearn how to survey without GPS (0.4% and 3.9%, respectively) (Table 12-6). Respondents generally agreed that they have the necessary equipment and knowledge to survey without GPS, but because GPS provides time and labor savings, its outage would result primarily in delays and labor shortages.

Table 12-6. Perceptions about the Impact of a 30-Day Outage

What would be the primary impacts of a thirty-day GPS outage? Select all that apply.	Percentage Selecting Option
It would take longer to complete similar jobs	85.9%
I could not do certain jobs	43.8%
I could not compete for certain jobs	38.9%
Other	6.0%
What are the reasons that the GPS outage would impact your work? Select all that apply.	
There is no way to complete certain jobs without GPS	37.8%
I do not have the right equipment to survey without GPS	5.3%
It would take me too long to acquire the right equipment to survey without GPS	6.0%
I do not know how to survey without GPS	0.4%
It would take me a while to relearn how to survey without GPS	3.9%
It takes longer to complete jobs without GPS	85.9%
Other	8.4%

---

[89] This was in response to the questions: "Would an unplanned GPS outage have any impact on your work?" and "In the event of an unplanned GPS outage that lasted for thirty days, would you be able to continue conducting surveying work in any capacity?"

12.5.1   Approach for Quantifying the Potential Impacts of a 30-Day Outage

Respondents indicated that 31% of their revenue (estimated at $7.2 billion in 2017) comes from jobs that could only be completed with GPS (see Table 12-7). Assuming that surveying earnings are distributed uniformly across the year, a 1-month shutoff of GPS would cost the surveying industry $184 million of revenue just from jobs that could not be completed ($7.2 billion * 30.7%)/12). The jobs that could still be started would be delayed and incur additional labor costs. For those jobs that could be completed, surveyors thought it would take 69% longer to complete them during an outage (see Table 12-7). With 2017 labor costs totaling $3.68 billion ($306.6 million for one month), we estimate total impacts of this delay to be $147.0 million ((306.6 million * 0.69 * 0.69).[90] Adding these losses together (147.0 million + 184.1 million, we estimate total losses from a 30-day outage of GPS to be $331 million.

12.5.2   Discussion of 30-Day Outage Estimates

The calculation of losses only accounts for increased payroll and uncompleted jobs and does not account for secondary impacts. Real estate transactions, construction projects, resource extraction, and other industries rely on land surveys and would be delayed by a GPS outage that stops or slows surveying work. These economic impacts could be quite large but were beyond the scope of this study's analysis.

Some respondents also expressed concern that an outage would require them to significantly increase costs charged to clients. The industries that rely on surveying also benefit from GPS in surveying through purchasing faster, more accurate services at lower costs, and this study does not quantify the consumer surpluses that would be lost in an outage.

Some experts also brought up that GPS is used to tie surveying points into larger coordinate grids, which in some circumstances is legally required. Others also described difficulties with contracts; in a 30-day outage, they might be unable to fulfill work previously contracted in the specified time frame and price. The full impact these interruptions would have is unclear because it is possible that legal requirements might be relaxed given a GPS outage, but they would certainly be disruptive.

Table 12-7. Quantitative Impacts of 30-Day Outage

Question	Mean Response
What percentage of your revenue comes from jobs that could only be done using GPS?	30.7%
How much longer, in percentage terms, would it take you to complete a typical job during a 30-day GPS outage?	69.2%

---

[90] We multiply by 0.69 twice because the first 0.69 reduces the total by the share of jobs that could not be completed at all (31%) and the second 0.69 takes into account the increased time that respondents estimated in the survey.

12.6 Technology Transfer and Federally Supported Infrastructure

As in the development of the satellite constellation that enables GPS itself, the federal government has played a critical and direct role in transferring GPS technology to the surveying industry. In the early years of GPS technology, they provided financing, infrastructure, technical feedback, institutional support, and public outreach to ensure that GPS technology was appropriate for and addressed the needs of surveyors. The federal government has also been at the forefront of developing the legal and regulatory environment that enabled the surveying industry to take advantage of GPS technology. State governments have also played active roles in providing services that benefit the surveying industry.

In the early 1980s, multiple federal agencies were involved in developing the first commercial GPS receivers for surveying, setting the stage for GPS to be used for other industries in later years. In 1981, the Defense Mapping Agency (DMA), the National Geodetic Survey (NGS), and the U.S. Geological Survey joined forces to develop the specifications and award a contract to Texas Instruments to develop what became the TI 4100 (Figure 12-3). Geodesists from NGS also developed the software used to process its data (Hofmann-Wellenhof, Lichtenegger, & Collins, 2012).

Figure 12-3.   TI 4100

Around the same time, scientists at the NASA Jet Propulsion Laboratory developed the technology that led to the development of the Macrometer Interferometric Surveyor. Thus, several federal agencies played an important role in transferring the technology that led to the first commercial GPS receivers, and the legacy is that most features from these early models are found in GPS receivers today.

The Federal Geographic Data Committee (FGDC)[91] provides advisory services and oversight for geospatial initiatives across the government and played a fundamental role in transferring GPS technology to the surveying industry in the early years of GPS. The FGDC's federal interagency "Instrument Working Group" supported survey equipment manufacturers by testing and evaluating their technologies to ensure they met standards and were working properly. They tested the instrumentation, hardware, software, and procedures and provided written feedback on how the equipment performed. FGDC's oversight enabled the private sector to continuously improve GPS technology so that it could store more data, use less power, and cost less. One of the original chairs of instrument testing for this group discussed how manufacturers would bring in their equipment and the subcommittee would present results on Friday of the same week. One of the first portable GPS receivers—the previously mentioned Macrometer—was tested by the FGDC in 1982 (Hothem & Fronczek, 1983). One archived working group report from 1997 (Federal Geodetic Control Subcommittee [FGCS], n.d.) describes tests done for NovAtel, Ashtech, and Zeiss, as well as the first FGCS test of a surveying system that used the Russian

---

[91] https://www.fgdc.gov/

GLONASS satellites. The working group also conducted public workshops to inform the public about technological changes in the surveying community.

In addition to facilitating the transfer of GPS technology directly to industry, the federal government provides the institutional framework and infrastructure so that surveyors and other industries can realize economic benefits from GPS. The National Oceanic and Atmospheric Administration's NGS manages the NSRS, a national coordinate system that underpins the spatial infrastructure of the United States. In recent years, NGS has strengthened this coordinate system by facilitating the development of the CORS network, which is backed by GNSS satellites, including GPS. CORS provides an invaluable tool for surveyors, farmers, and other industries that require spatial data. NGS estimated that there were 10.6 million CORS data downloads in 2008, with a rough estimate of $643 million ($735 million in $2017) in benefits for that year (Leveson, 2009).[92]

Several experts discussed how NGS provides other services to the surveying industry such as antenna calibration. NGS has been conducting antenna calibration at an NGS facility in Corbin, Virginia, since 1994. These calibrations reduce antenna errors and provide survey equipment manufacturers with important information about the quality of their products. NGS publishes the data on their website, enabling the industry to learn from each other's products. NGS provides this service free of charge and ensures compatibility with international GNSS values. According to the NGS (2016) antenna calibration procedures, NGS has conducted more than 500 antennae calibrations for manufacturers since the program started in 1994.

According to several stakeholders, in addition to federal agencies, many state governments play a beneficial role in providing the infrastructure and services needed to ensure that surveyors can use GPS. Some states operate virtual reference stations that can help surveyors improve their measurements and reduce costs. In states where this service is offered, such as North Carolina, surveyors can either pay a small fee or access the virtual reference stations for free. In states where this service is not provided, surveyors can end up paying thousands of dollars a year to access virtual reference stations from private providers.

12.7 Looking Forward

GPS has had an enormous impact on the surveying industry, and some future changes may further increase its benefits. GNSS constellations other than GPS are expected to be completed by 2020, and their full availability will allow greater accuracy and positioning in urban canyons, dense forests, and other locations where the line of sight to the sky is blocked. NGS is also putting into place an International Terrestrial Reference Frame, which will correct for errors caused over time by continental drift.

Experts speculated about the future of surveying and its relationship to GPS. Many expect that GPS will be combined further with unmanned aerial vehicles (drones) and other autonomous vehicles to complete surveying work. Some guessed that service providers might investigate switching to satellite systems that would require less expensive antennas to access, instead of pricey receivers, and sell subscriptions to the

---

[92] Benefits include those provided by NGS's Online Positioning User Service, which is made possible by the CORS network.

systems instead of equipment. Others speculated that receivers will be built in with more reliance on cell towers, rather than GPS for positioning. Most agree that surveyors will continue to derive a great deal of value from GPS in the future.

12.8 Concluding Remarks

The surveying industry was one of the first to see the value of GPS, and many surveyors played a role in its development. Since the earliest years of GPS, surveyors have reaped the benefits of GPS, and we estimate that GPS has provided nearly $48 billion in direct benefits to the surveying industry from 1984 to the present and much higher benefits to the overall economy if one includes the benefits for those sectors that rely on surveying. In the event of a 30-day outage, the industry would lose approximately $331 million, not including economic impacts from delays and disruptions to industries that rely on surveying.

However, these quantitative results do not capture the great impact surveyors have had on the development of GPS applications themselves. The surveying sector has been active in developing GPS-related technologies since its inception, enabling the development of GPS receivers that have benefited many industries. Their commitment to and influence on the development of the technology in the future are likely to continue.

13. Telematics

Telematics is a field of technology that uses in-vehicle equipment to remotely monitor vehicles for a variety of purposes. The high-precision capabilities of GPS are critical to unlocking most of the benefits of telematics. This case study focuses on the use of telematics devices in on-road commercial vehicles to increase operational efficiency, encourage driver behavior change to increase safety, optimize routing, and increase productivity.

The use of GPS in telematics has resulted in net benefits close to $330 billion between 2000 and 2017. In the event of a 30-day GPS outage, telematics users would experience, at a minimum, a loss of some labor and fuel savings benefits. In those industries in which telematics is tightly integrated into core business processes, users may experience a more serious business disruption. We conservatively estimate that the economic impact of a 30-day outage in the telematics sector could be between $3.2 and $6.3 billion.

13.1 Sector Introduction and Overview

Telematics devices gather data from multiple sources to gain insight into the position, direction, speed, and condition of the vehicle being monitored. The enabling data stream is the real-time location data provided by GPS. Other sensors include accelerometers and the internal vehicle computer, which monitors the condition of the vehicle and can also relay information about speed, intensity of acceleration, wheel angle, and whether a vehicle is in reverse. One expert commented that in the absence of GPS other data streams would be in effect "useless" in a matter of minutes.

The most common end users are in industries with large fleets of vehicles, including

- shipping and logistics,
- construction,
- field service sectors (e.g., home repair, plumbing, lawn service, on-demand roadside assistance for freight companies), and
- utilities (e.g., electricity, water, gas, and telecom providers).

Features of telematics services for which GPS generates significant benefits include real-time location awareness, navigation assistance, driver behavior monitoring, and vehicle condition monitoring. Table 13-1 describes these features and their benefits in detail.

Table 13-1. Features and Benefits of Telematics

Feature	Precision Required	Description	Benefit
Driver behavior monitoring	5 m	GPS and other sensors collect data on speed, acceleration, harshness of braking, frequency of reversing, engine idling, and other behaviors that increase fuel consumption and the risk of accidents.	▪ Reduced occurrence of accidents ▪ Reduced fuel consumption and wear on the vehicle through more efficient driving behavior and idle reduction ▪ Reduced insurance premiums
Real-time location awareness	50–100 m	GPS data can help dispatchers know in real time where all their vehicles are, aiding faster, more intelligent decisions about which vehicles to dispatch to which jobs based on their location and the work needs. Additionally, awareness that their location is being tracked can deter drivers from taking personal trips during the workday. Finally, location data can aid in the recovery of stolen vehicles.	▪ Improved productivity ▪ Reduced fuel consumption ▪ Prevention of theft or reduced lost productivity from thefts
Navigation assistance	5 m	Turn-by-turn directions using GPS and digital map services can help drivers navigate to their next destination more efficiently.	▪ Improved productivity ▪ Reduced fuel consumption
Vehicle condition monitoring	5 m	Using GPS and data streams from the internal vehicle computer can help fleet managers anticipate mechanical problems and better manage preventive maintenance.	▪ Reduced work disruptions due to unanticipated breakdowns ▪ Lower maintenance expenses

The first version of a modern telematics device using real-time location data was the OmniTracs system by Qualcomm, which came on the market in 1988 and used a private satellite constellation to provide location data that were accurate to approximately 1,000 feet.[93] The first telematics services to leverage GPS came on the market in the early to mid-1990s, which improved the accuracy of location data. Some of the first companies to offer GPS-based services were Rockwell and HighwayMaster, which used location data to provide automated mileage and route data collection systems (Satellite Today, 1996; TruckingInfo HDT, 1996).

During the early stage of digital telematics adoption, hardware and service costs were high, making it cost prohibitive for smaller fleets to adopt. Additionally, wireless data transfer, if available, was expensive. Telematics users typically relied on downloading data at the end of a shift or trip, meaning that while drivers had real-time location awareness, dispatchers at fleet management offices did not have visibility of their drivers' real-time location. Turn-by-turn navigation, which helps optimize routing and reduce fuel consumption and vehicle miles traveled (VMT), was also not available.

---

[93] Prior to digital telematics, the earliest version of an analog telematics device is the analog tachograph, which used a wax-coated paper disc to record data on the speed, distance, and activity mode of the driver. Typically, a single disc stored 24 hours of data, which could be analyzed after the fact to monitor how many hours a driver worked and provide basic insights into driving behavior.

In 2003, wireless telecom companies began to roll out the first wireless broadband networks, significantly expanding network coverage, reducing the cost of real-time data transfer, and causing an acceleration in telematics adoption. Telematics data are now used by many industries to optimize all aspects of fleet operations.

13.2 Methodological Notes

This section presents methodological notes and information germane to valuing the role of GPS in telematics. It complements the general methodology presented earlier in this report.

13.2.1   *Counterfactual to the Availability of GPS*

In the absence of GPS, the benefits of telematics would be substantially curtailed. Navigation and driver behavior monitoring, which yield some of the most significant benefits of telematics, would not be possible because a high level of precision (less than 5 m) is required.

As in the other case studies, we assumed that in the absence of GPS some other, less accurate positioning technology would be available and used by telematics service providers. This could be something like a Loran-based system or a private satellite or terrestrial PNT system like those used in the telematics sector before the adoption of GPS. Such a system could still deliver some benefits associated with optimized dispatch, which can be achieved with less accurate positioning (e.g., 100 m).

In the event of a 30-day failure of GPS, the fleet management industry would, at the very least, suffer a decrease in productivity and an increase in fuel consumption as it reverts to older methods of allocating resources and planning routes.

For the purposes of this analysis, we assumed that end users lose most of the benefits they gained when adopting telematics, though we expect this is conservative. Businesses that are particularly reliant on GPS may experience more significant disruptions. For example, package delivery companies that rely heavily on GPS to deliver high volumes of parcels every day might experience a greater loss of business than a field service company that has only a small number of stops every day.

13.2.2   *Interviews with Sector-Specific GPS Experts*

To validate existing research and acquire new information about the role of GPS in telematics, we engaged experts from different stakeholder groups through semistructured phone interviews. They also provided reviews of consensus estimates, assumptions, and early analysis results.

Experts were identified through service provider websites, industry association websites, and conference speaker lists. The affiliations of our panel of 10 experts included telematics service providers, end users in shipping and logistics, telematics consulting, industry associations, government, and academia. For end users of telematics, we specifically targeted fleet managers and other individuals who had a role in choosing and implementing a telematics service. For telematics service providers, we worked with companies to identify individuals with the right expertise to speak to our questions. Finally, where possible we relied on referrals from existing contacts in the industry to identify strong candidates for interviews.

13.2.3   *Approach for Quantifying Benefits and the Potential Impacts of a 30-Day Outage*

Table 13-2 details the different categories of benefits included in this analysis and summarizes the metrics used to quantify and monetize each category of benefits. To quantify the benefits outlined therein, we took the steps detailed below.

Characterized the commercial vehicle fleet. Using data from EPA (2016b) and the FHWA (2016),[94] we developed a profile of the population of commercial vehicles on the road from 2000 through 2017, including

- vehicle stock disaggregated by light commercial, single-unit, and combination trucks;

- annual vehicle miles traveled disaggregated by light commercial, single-unit, and combination trucks; and

- average fuel economy for light commercial, single-unit, and combination trucks.

Disaggregating the fleet by vehicle type allows us to estimate fuel savings using fuel economy estimates for specific vehicle types.

Table 13-2. Benefits Quantified

Benefits	Telematics Features Driving Benefits	Technical Impact Metric	Economic Impact Metric
Labor savings	Improved dispatch, navigation aids, and real-time location awareness all contribute to workers accomplishing the same amount of work in less time	Hours of labor saved	Weighted average wage of typical job types associated with telematics users (Source: Bureau of Labor Statistics [BLS], 2018)
Fuel savings	Driver behavior monitoring (for idle reduction and inefficient driving habits), improved dispatch, and navigation aids	Gallons of fuel saved; public health benefits from emissions reductions	Fuel savings monetized using weighted average of gasoline and diesel fuel prices; public health benefits monetized using EPA's COBRA model (Source: EIA, 2017)
VMT reductions	Improved dispatch and navigation aids	Repair and maintenance (R&M) cost savings	Average R&M costs in dollars per mile (Source: American Transportation Research Institute [ATRI], 2017)

---

[94] EPA (2016b) provides population data on light commercial vehicles, while FHWA (2016), Table VM-1 provides population data for medium- and heavy-duty single-unit and combination trucks. In the absence of 2017 stock data, we assume the 2017 stock is the same as 2016. We consider this reasonable because over the long term the truck stock increases, but from year to year it fluctuates up and down. Thus there is not a reliable historical trend with which to project the 2017 stock.

Applied estimated adoption levels. Most estimates of market adoption of telematics technology over time are not publicly available. However, some point estimates of adoption in individual years are available. Pham (2011) refers to multiple studies that estimate a 50% to 86% adoption among fleet vehicles, which is a subset of all commercial vehicles. Other estimates look at adoption of telematics in the context of the full stock of on-road commercial vehicles. Fleetmatics (2014) cites a 2012 Frost & Sullivan study that estimates a 12.6% adoption level of telematics among commercial vehicles in the United States and Canada, which would equate to just over 4 million vehicles in the United States based on the commercial vehicle stock of 32.1 million vehicles in 2012. C.J. Driscoll and Associates (2017) estimated that 8 million vehicles used telematics technology in 2016, which equates to a 24% adoption level of telematics among commercial vehicles.

We approached our analysis by considering the full stock of commercial vehicles on the road rather than looking only at fleet vehicles.[95] To estimate an adoption curve for telematics, we used data from three sources, which are described in Table 13-3. First, we started with the point estimate of adoption from 2012 and calculated an estimated annual growth rate of 17% to arrive at the C.J. Driscoll and Associates (2017) point estimate of approximately 8 million vehicles. This pace of growth is similar to the GSM Association (2012a) estimate of a 19% growth rate, which increased our confidence that these estimates are reasonable. Subject matter experts interviewed for this analysis concurred with this approach. Note that we apply the 17% growth rate to our estimates of the percent of vehicles that are equipped with telematics (the rate of adoption) rather than the absolute number of vehicles that use telematics. Because the vehicle stock changes from year to year, calculating a percent growth using the estimated number of telematics-equipped vehicles may therefore yield a different percent growth estimate.

Table 13-3. Adoption Estimates

Source	Estimate Type	Year	Value
Frost & Sullivan (2012) cited in Fleetmatics (2014)	Adoption as a percentage of commercial vehicles	2012	12.6% (equivalent to 4.04 million vehicles)
C.J. Driscoll and Associates (2017)	Number of vehicles using telematics	2016	8 million vehicles
GSM Association (2012a)	Growth rate of telematics in commercial fleets	2012–2016	19% CAGR
Expert interview	Point estimate for accelerating the growth of telematics	2003	Telematics growth accelerated when wireless service providers started offering mobile broadband services

---

[95] We took this approach for several reasons. First, the definition of a fleet has shifted several times within our period of study and also varies between light-duty vehicles and trucks, making it difficult to use fleet population data for analysis (Bobit Business Media, 2018). Second, by only considering fleets as potential adopters of telematics, particularly under the more stringent definition that only counts 15 or more vehicles as a fleet, we excluded vehicles that are potential adopters.

Estimating adoption backward from 2012 to 2000 is more uncertain because of the lack of adoption data before 2012. In the absence of better data, we applied the estimated annual growth rate of 17% back to 2004. As mentioned earlier, 2003 marked an acceleration of telematics adoption because of the availability of mobile broadband services. Thus, we estimated a lower growth rate of 10% from 2000 through 2002 and 15% in 2003. Figure 13-1 details estimated annual adoption of telematics from 2000 to 2017.

There are clear limitations to this approach of estimating adoption. The lack of consistent annual data results in a fairly generalized curve. Additionally, the adoption level is for all commercial vehicles and cannot be segmented into different industries or vehicle types. However, this estimated adoption curve was validated by experts as a reasonable proxy for actual adoption. Additionally, we have higher levels of confidence in our estimates from 2012 on, which represents nearly 66% of the estimated net benefits of GPS in the telematics sector, as we explain later in this analysis.

Applied technical impact metrics to estimate benefits. Telematics experts believe that the labor productivity benefits of GPS are between 5% and 10%. By way of comparison, Fleetmatics (2014) estimates labor savings of 20%, and Frost & Sullivan (2016) estimated a range of savings of 20 to 30 minutes per day, which we interpret as 4% to 6% of a workday. The majority of our experts believe that 5% labor savings is reasonable, all else held equal. Two believed that savings could potentially be between 15% and 20%. The consensus estimate was between 5% and 10%. To estimate labor benefits, we assumed one driver per vehicle working 10.6 hours a day for 242 days a year on average based on Fleetmatics (2014) data from the fleets that subscribed to their service.

Figure 13-1. Estimated Adoption of Telematics, 2000–2017

With respect to fuel savings, our experts concluded that 10% to 15% reduction in fuel consumption is reasonable. Frost & Sullivan estimated 20% to 25% reduction in fuel expenditures, while Fleetmatics (2016) cites an Aberdeen Group estimate of 13%, on average. Our experts consider the 20% to 25% reduction to be unlikely.

With respect to VMT savings, our experts were asked to consider VMT savings as a proxy for R&M savings. Our experts concluded that a 5% to 10% reduction in VMT was reasonable as a proxy for R&M savings. Because telematics helps fleet managers be more proactive in maintaining vehicles, experts concluded that fleet managers would likely achieve higher savings than one would imply from reduced VMT. We noted that Frost & Sullivan also estimated a 5% to 10% reduction in travel.

To estimate fuel savings, we used fuel consumption data for commercial vehicles from EPA (2016a). Because VMT fluctuates up and down based on many influencing factors, there was not a clear trend to use to project 2017 data. Therefore, in the absence of 2017 data, we assumed VMT remains the same as 2016. Similarly, we used data on total VMT by commercial vehicle type from FHWA (2016) to estimate VMT reductions.

Estimated environmental benefits. In addition to labor, fuel, and VMT savings, we also developed estimates of environmental benefits associated with reduced fuel consumption. First, we estimated reductions in carbon dioxide (CO_2) emissions using a weighted emissions factor to reflect the fuel mix for commercial vehicles.[96]

Second, we estimated the reductions in criteria air pollutants that are regulated under the Clean Air Act: $PM_{2.5}$, SO_2, NO_x, NH_3, and VOCs. Reductions in criteria air pollutants were estimated using EPA's COBRA screening model, which estimates the economic value of avoided adverse health events associated with reductions in emissions of regulated pollutants (EPA, 2017). Health benefits that are considered by COBRA include general mortality, nonfatal heart attacks, hospital admissions, a variety of respiratory conditions, and lost workdays. See Appendix A for a detailed description of the approach to using COBRA for estimating public health benefits, which is used in both the telematics and LBS sectors.

Monetized estimated benefits. After applying the technical impact metrics, we arrived at a time series of estimated reductions in labor hours, fuel consumption, and VMT from 2000 through 2017. We estimated both fuel consumption and VMT savings because fuel consumption encompasses savings from both reduced VMT and reduced engine idling. Thus, to estimate fuel savings from an estimate of VMT reduction would underestimate fuel savings. VMT reduction estimates were used to calculate savings in R&M costs.

To monetize labor savings, we used data on average wage by occupation from BLS (2018) to calculate a weighted average wage for each year in our analysis. We included 81 job types covering all commercial

---

[96] From 2000 through 2017, on average, commercial vehicles used 55% gasoline and 45% diesel fuel (EPA, 2016). Medium and heavy-duty trucks disproportionately used diesel fuel, but light commercial vehicles and trucks are more likely to use gasoline.

drivers and a range of field service job types (e.g., electricians, utility and telecom technicians, medical equipment repair technicians).

To monetize fuel savings, we calculated a historical weighted average fuel price by year based on the historical distribution of gasoline and diesel consumption in the commercial vehicle fleet. Price data were sourced from EIA (2017). Additionally, fuel savings drive environmental benefits, which were monetized using EPA's COBRA Model.[97]

As mentioned earlier, we used VMT savings as a proxy for a reduction in R&M costs. We used data on the average marginal R&M costs per mile of travel from Table 8 in ATRI's annual analysis of the operational costs of trucking (ATRI, 2017). ATRI publishes data from 2008 to 2016. For 2000 to 2007, we use 2008 data. These cost estimates are most reasonably applied to single-unit and combination trucks; however, we also applied these cost estimates to light commercial trucks because of the lack of R&M cost estimates specific to light-duty trucks.

Estimated cost of telematics adoption (Table 13-4). To account for the cost of telematics adoption faced by users, we used data from several sources and input from subject matter experts on the average costs of different types of telematics services. We disaggregated costs into two categories, grouping together light commercial and single-unit trucks while accounting separately for combination trucks. Combination trucks are most commonly used in the long-haul trucking sector and typically have higher monthly service costs and more expensive hardware requirements.

Estimated net benefits. To estimate the net benefits of telematics from 2000 through 2017, we subtracted the estimated costs of adoption from the monetized benefits.

Limitations. It is important to note that we did not quantify all the benefits of telematics because of a lack of data, including the impact of telematics on insurance rates, recovery of stolen property, vehicle accidents, and fleet investments in new vehicles (capital expenditures).

Table 13-4. Average Cost of Telematics Adoption

Vehicle Type	Average Monthly Service Cost	Average Hardware Cost[a]	Assumed Lifetime of Hardware (years)	Average Monthly Cost w/Hardware
Light commercial and single-unit truck	$20	$200	5	$23
Combination truck	$35	$1100	5	$53

[a] Hardware cost includes the estimated cost of installation.

Source: Expert interviews, Expert Fleet Management (2018), GPS Insight (2018)

---

[97] EPA's COBRA screening model estimates the economic value of health benefits associated with reductions in emissions of regulated pollutants. See Appendix A for a detailed description of the approach to using COBRA for estimating public health benefits.

In the case of a 30-day failure of GPS, we only quantified the loss of the benefits identified in this case study. We did not quantify additional losses associated with business disruption in businesses that are heavily reliant on GPS. Finally, our analysis is limited to estimating a time series of benefits from 2000 through 2017 even though digital telematics services were available in the 1990s as well. Subject matter experts were less certain about the magnitude of benefits in the 1990s, and availability of data on adoption is limited before 2000. Because of these factors, we expect that our estimates of the economic impact in both counterfactual scenarios are conservative.

13.3 Retrospective Economic Benefits Analysis

As described earlier, GPS is essential to modern telematics technology, and the most significant benefits from telematics are because of the precision GPS enables. As summarized in Table 13-5, GPS contributes

- labor savings between 5% and 10%,

- fuel savings between 10% and 15%, and

- VMT reductions between 5% and 10%.

The largest area of benefits is in labor savings where telematics saved 12.2 billion hours of labor from 2000 through 2017, valued at $251.1 billion. We also estimate that telematics users saved 19.7 billion gallons in fuel, valued at $58.0 billion. R&M savings were estimated from the 24.3 billion miles of VMT savings, valued at $21.2 billion. Table 13-6 provides detailed annual estimates of the average benefits of GPS in telematics.

Table 13-5. Telematics Cost Savings Generated by GPS's Precision

Benefit	Units	Lower-Bound Estimate	Upper-Bound Estimate
Labor savings	Percentage reduction in hours of labor	5%	10%
Fuel savings	Percentage reduction in gallons of fuel consumed	10%	15%
VMT reductions	Percentage reduction in annual VMT per vehicle	5%	10%

Table 13-6. Average Benefits of GPS in Telematics

	Labor Savings		Fuel Savings		VMT Savings[a]	Repair & Maintenance[a]
Year	Millions of Hours	$ million	Millions of Gallons	$ million	Millions of Miles	$ million
2000	134	$2,756	293	$603	265	$207
2001	151	$3,094	324	$619	294	$240
2002	165	$3,395	367	$653	328	$280
2003	181	$3,721	420	$847	363	$285
2004	217	$4,458	501	$1,171	426	$324

(continued)

Table 13-6. Average Benefits of GPS in Telematics (Labor, Fuel, Repair, and Maintenance, $2017)
(continued)

Year	Labor Savings		Fuel Savings		VMT Savings[a]	Repair & Maintenance[a]
	Millions of Hours	$ million	Millions of Gallons	$ million	Millions of Miles	$ million
2005	260	$5,339	579	$1,660	499	$378
2006	312	$6,402	677	$2,130	589	$462
2007	388	$7,974	643	$2,132	815	$618
2008	447	$9,194	716	$2,889	954	$734
2009	519	$10,674	799	$2,186	1,048	$944
2010	595	$12,226	950	$3,077	1,238	$961
2011	713	$14,651	1,083	$4,388	1,439	$1,188
2012	848	$17,430	1,261	$5,165	1,612	$1,294
2013	1,003	$20,607	1,489	$5,872	1,931	$1,609
2014	1,191	$24,466	1,834	$6,856	2,285	$1,913
2015	1,414	$29,064	2,147	$5,686	2,716	$2,529
2016	1,686	$34,637	2,587	$5,863	3,465	$3,264
2017	1,972	$40,998	3,027	$6,192	4,054	$3,981
Total	**12,195.3**	**$251,085**	**19,698.1**	**$57,988**	**24,320.8**	**$21,210**

[a] Estimated reductions in VMT were used to calculate savings associated with reduced R&M costs. VMT reductions were not used to estimate fuel savings because a significant amount of fuel savings comes from reduced engine idling, which is not reflected in VMT.

Source: RTI analysis

The volume of avoided fuel combustion translates into emissions reductions and consequently environmental health benefits. The linkages between fuel combustion and human health are clear. Table 13-7 presents the average reductions in metric tons of emissions of CO_2 and criteria air pollutants. Table 13-8 presents the average monetized benefits of these avoided emissions. In total, we value avoided emissions of criteria air pollutants at $13.2 billion.

Table 13-7. Average Environmental Benefits of GPS in Telematics (metric tons of pollutant)

Year	CO_2	$PM_{2.5}$	SO_2	NO_x	NH_3	VOCs
2000	1,037,943	229	870	5,243	118	11,559
2001	1,146,483	252	963	5,784	131	12,801
2002	1,300,238	289	1,083	6,588	147	14,398
2003	1,485,391	324	1,253	7,474	170	16,664
2004	1,770,657	386	1,495	8,908	203	19,872
2005	2,057,331	492	1,697	10,892	230	22,540
2006	2,409,774	607	1,999	13,215	271	26,541
2007	2,326,714	731	1,645	14,187	222	21,746

(continued)

Table 13-7. Average Environmental Benefits of GPS in Telematics (Metric Tons of Pollutant) (continued)

Year	CO_2	$PM_{2.5}$	SO_2	NO_x	NH_3	VOCs
2008	2,590,662	834	1,882	16,191	253	24,879
2009	2,879,838	909	2,252	18,110	304	29,807
2010	3,429,161	1,135	2,686	22,330	362	35,527
2011	3,922,249	1,371	3,050	26,529	411	40,304
2012	4,567,140	1,646	3,620	31,754	487	47,841
2013	5,396,463	2,006	4,359	38,575	587	57,595
2014	6,634,839	2,480	5,623	48,228	757	74,340
2015	7,782,782	3,047	6,604	58,554	889	87,246
2016	9,369,335	3,733	8,228	72,055	1,108	108,726
2017	10,962,122	4,480	9,873	86,467	1,329	130,471
Total	**71,069,121**	**24,952**	**59,183**	**491,085**	**7,977**	**782,857**

Source: CO_2 emissions reductions calculated using emissions factors for diesel and gasoline (EPA, 2016a; EPA, 2017); other environmental benefits estimated using the COBRA model from EPA.

Table 13-8. Monetized Public Health Benefits Associated with GPS in Telematics (millions $2017)

Year	$PM_{2.5}$	SO_2	NO_x	NH_3	VOCs	Total
2000	$33	$48	$69	$3	$18	$170
2001	$37	$54	$77	$3	$20	$189
2002	$43	$61	$88	$3	$22	$217
2003	$48	$71	$101	$4	$26	$250
2004	$58	$85	$121	$5	$31	$301
2005	$73	$95	$146	$5	$35	$354
2006	$88	$111	$174	$6	$40	$420
2007	$105	$90	$184	$5	$33	$416
2008	$118	$101	$207	$5	$37	$468
2009	$126	$119	$228	$6	$43	$522
2010	$155	$139	$276	$7	$51	$628
2011	$184	$155	$322	$8	$56	$726
2012	$217	$181	$378	$10	$66	$852
2013	$260	$214	$451	$11	$78	$1,015
2014	$315	$272	$554	$14	$99	$1,254
2015	$380	$313	$661	$17	$114	$1,486
2016	$458	$383	$799	$20	$139	$1,800
2017	$540	$452	$942	$24	$164	$2,121
Total	**$3,238**	**$2,945**	**$5,779**	**$156**	**$1,071**	**$13,190**

Source: Monetized benefits are an output of the COBRA model from EPA.

For this analysis, we did not monetize the benefits of reducing emissions of CO_2. The most widely accepted approach to valuing CO_2 emissions reductions is the Social Cost of Carbon (SCC), which involves complex intergenerational valuations and is not comparable to the approach used to value emissions of criteria air pollutants using COBRA. Thus, our public health benefits estimates are conservative. However, we did estimate that telematics avoided 71.1 million metric tons of CO_2 emissions from 2000 to 2017, which is equivalent to removing 15.1 million passenger vehicles from the road for 1 year (EPA, 2018).

Table 13-9 provides total estimated benefits described in Tables 13-6, 13-7, and 13-8 and presents lower- and upper-bound estimates for total benefits and net benefits. Lower- and upper-bound estimates were estimated using the ranges of technical impacts detailed in Table 13-5. Additionally, the COBRA model for estimating environmental benefits outputs ranges of benefits.

In total, estimated net benefits of GPS in the telematics sector range from $209.3 billion to $441.1 billion from 2000 through 2017, with a point estimate of $325.2 billion.

Table 13-9. Total and Net Benefits of GPS in Telematics

Year	Total Benefits ($ million)			Estimated Cost of Adoption	Net Benefits ($ million)		
	Low	Average	High		Low	Average	High
2000	$2,476	$3,736	$4,996	$272	$2,204	$3,464	$4,725
2001	$2,781	$4,210	$5,640	$299	$2,482	$3,912	$5,341
2002	$3,045	$4,616	$6,188	$324	$2,721	$4,292	$5,863
2003	$3,431	$5,179	$6,927	$344	$3,088	$4,835	$6,583
2004	$4,215	$6,335	$8,455	$401	$3,814	$5,934	$8,054
2005	$5,229	$7,815	$10,402	$467	$4,762	$7,349	$9,935
2006	$6,369	$9,497	$12,625	$544	$5,825	$8,953	$12,081
2007	$7,470	$11,209	$14,948	$667	$6,803	$10,542	$14,281
2008	$8,945	$13,352	$17,759	$754	$8,190	$12,597	$17,004
2009	$9,524	$14,397	$19,270	$871	$8,653	$13,526	$18,399
2010	$11,290	$16,969	$22,648	$986	$10,304	$15,983	$21,662
2011	$14,066	$21,026	$27,986	$1,150	$12,916	$19,876	$26,836
2012	$16,595	$24,808	$33,021	$1,341	$15,254	$23,467	$31,680
2013	$19,483	$29,164	$38,845	$1,557	$17,926	$27,607	$37,288
2014	$23,062	$34,541	$46,020	$1,819	$21,243	$32,722	$44,201
2015	$25,647	$38,808	$51,970	$2,148	$23,500	$36,661	$49,822
2016	$30,028	$45,599	$61,170	$2,528	$27,500	$43,071	$58,643
2017	$35,009	$53,292	$71,576	$2,902	$32,106	$50,390	$68,673
Total	**$228,666**	**$344,556**	**$460,446**	**$19,374**	**$209,292**	**$325,182**	**$441,072**

Source: RTI analysis

13.4 Potentials Impact of a 30-Day Outage

We estimate that the economic loss associated with a 30-day outage of GPS will range from $2.7 to $5.5 billion at the current level of telematics adoption. Our expert panel indicated that a GPS outage would result in significant loss of productivity because of a loss in GPS-assisted dispatching and navigation.

13.4.1   Summary of Qualitative Findings

Depending on the type of user, the impact of a GPS outage will have varying levels of impact, ranging from inconvenient to disruptive. For field service operations that have a relatively small number of stops in a given day and few last-minute changes in dispatch schedules, a GPS outage would be an inconvenience.

Other sectors rely very heavily on GPS. For example, UPS uses GPS to plan its parcel delivery routes daily. In the absence of GPS, drivers and dispatchers would have to rely on local knowledge and static maps. Given the daily volume of packages that they deliver, such a disruption could lead to significant delays, particularly if an outage occurs during a busy season. In addition to delays, such a business would incur additional fuel consumption costs on the order of millions of gallons. During a testing period for its internal telematics optimization and navigation software (called ORION), UPS saved around 1.5 million gallons of fuel a year using the software on only a portion of its delivery fleet (Konrad, 2013).

The one category of benefits that may be retained in a GPS outage is the fuel savings associated with driver behavior monitoring, which encourages more efficient driving practices and reduced engine idling. While driver behavior monitoring would be lost during a GPS outage, we expect that previous behavior change would be at least somewhat resilient during a GPS outage. Because drivers have been trained and incentivized to change their driving behavior over time, it is unlikely that they would immediately revert to less safe and efficient driving practices in the event of a GPS outage. When posed with this hypothetical scenario, 6 of the 10 experts interviewed for this analysis agreed that it is likely some of these benefits would be retained.

An additional consideration that is not accounted for in our estimates of the impact of a 30-day outage is the reliance of telematics on wireless cellular phone networks. Section 4 examines the impact of a 30-day outage on the telecom sector and concludes that major degradation of service, at a minimum, would occur on wireless networks. Without wireless service, we expect that even further disruption of telematics users would result because they would lose their ability to communicate with dispatchers from the field and telematics devices would not be relaying any data back to dispatchers. Thus, it is reasonable to assume that our estimates of the impact of a 30-day outage are likely very conservative.

13.4.2   Summary of Quantitative Findings

To estimate the quantitative impacts of a 30-day outage, we started with 1 month's worth of benefits—$4.2 billion on average—from 2017. We then considered the difference between the estimated reduction in fuel consumption and the estimated reduction in VMT among telematics users.

We estimated a larger drop in fuel consumption (10 to 15%) than VMT (5 to 10%) to account for reduced engine idling, due to improved driver behavior and less efficient driving behaviors such as rapid acceleration and harsh braking. We assumed that improved driver behavior would likely continue during a GPS outage, meaning that telematics users would retain a portion of the fuel savings benefit and the associated environmental benefits. This results in a projected average economic loss of $4.14 billion during a 30-day outage rather than $4.2 billion. Table 13-10 presents the estimated range of economic loss associated with a 30-day outage of GPS among telematics users.

In addition to idle reduction benefits, we would expect to see some retention of more efficient driving behavior that would reduce fuel consumption during driving (not only while idling), but we do not have data to distinguish between fuel savings attributable to improved driving habits and other sources of fuel savings, such as GPS-assisted navigation. Thus, we might reasonably expect economic losses to be lower than our estimate (or at least more likely to be on the lower bound of $2.7 billion) if losses are truly limited to the benefit categories we define in this analysis.

However, as discussed briefly in Section 13.4.1, we expect a loss of telematics service to affect some telematics users more severely beyond eliminating the benefits described in this analysis. For some users, a loss of telematics may be severely disruptive for businesses depending on how integrated their business processes are with GPS data streams. Thus, rather than overestimating the impact of a GPS outage, we believe we are likely underestimating the impact.

13.5 Future Applications

The ways in which location data from telematics devices are being used continues to evolve, and the dependence of users on telematics and the benefits delivered by telematics will continue to grow in the future. The following uses of telematics are not quantitatively considered in this report and are not yet widely adopted:

- using statistical analysis to identify specific truck models that perform best in different geographic, climatic, and usage conditions to help fleet managers avoid costly acquisition mistakes

- using statistical analysis to help fleets predict when drivers may quit so fleet managers can target driver retention strategies more effectively

Table 13-10. Economic Impact of a 30-Day Outage of GPS ($ million)

Estimate	Lost Labor Savings	Lost Fuel Savings	Lost Repair & Maintenance Savings	Lost Environmental Benefits	Total Loss
Lower bound	$2,196	$266	$213	$73	$2,748
Average	$3,416	$291	$332	$97	$4,137
Upper bound	$4,637	$317	$450	$122	$5,526

■ using equipment built into telematics devices to communicate with connected infrastructure and other vehicles using telematics to optimize traffic flow or increase efficiency (e.g., freight truck platooning)

In addition to increasing the benefits delivered through telematics, three trends are also driving an acceleration in adoption. First, vehicle manufacturers are increasingly including telematics equipment as a standard feature in new vehicles, reducing one of the barriers to adoption—the cost of hardware. Second, telematics services are also increasingly being offered on smartphone platforms, eliminating the requirement for a separate device in the vehicle.

Finally, the most significant trend that will drive growth in the adoption of telematics in the near future is a federal mandate that vehicles used on long-haul routes must be equipped with an electronic logging device to ensure that drivers are complying with hours-of-service requirements designed to increase safety by avoiding driver fatigue (Federal Motor Carrier Safety Administration, 2018). This mandate applies to much of the on-road freight sector and will drive further adoption among heavy-duty commercial trucks.

13.6 Concluding Remarks

Telematics technology uses GPS to unlock significant efficiencies and savings in commercial fleet vehicles at a relatively low cost. Adoption remains at less than half of all commercial vehicles in the United States, suggesting that there is significant room for growth. RTI found that since 2000 telematics has delivered a net economic benefit of $325.2 billion in the United States, on average. In the event of a 30-day outage of GPS, we estimate that telematics users would suffer an economic loss of $2.7 billion to $5.5 billion. We consider these findings to be conservative for several reasons:

■ We did not quantify all the benefits of telematics.

■ During an outage, companies that rely heavily on GPS data to drive business processes may experience more severe disruptions than others, leading to greater losses than we have estimated.

■ We did not attempt to quantify any benefits before the year 2000.

Finally, the private sector continues to innovate new ways to use data streams from commercial vehicles to help fleet managers make better decisions and increase the efficiency and profitability of fleets. We expect that this will drive further adoption and increase the economic value of GPS in telematics in the future.

14. Summary Remarks

The PNT signal provided by GPS enables many of the applications that companies rely on and that are integrated with modern American life. For the United States alone, we estimate that GPS has generated roughly $1.4 trillion in economic benefits (2017$) for the private sector in the years since it was made available for civilian use in the 1980s. Most of those benefits have accrued since 2010.

Our analysis combined insights from nearly 200 experts in the use of GPS for specific applications, surveys of professional surveyors and smartphone users, economic modeling tools, and national statistics. Because of the likelihood of measurement error, we recommended interpreting the point estimate of $1.4 trillion as a rough order of magnitude. The range of benefits to date is between $903 billion and $1.8 trillion. Benefits comprised productivity gains from new and existing products and services, improvements in quality, increases in personal enjoyment, and environmental and public health impacts.

14.1 Retrospective Economic Benefits

Table 14-1 summarizes the benefits we were able to quantify for each of the 10 sectors we analyzed. Benefits are largest for telecommunications, telematics (e.g., fleet management, logistics), and LBS (e.g., location features of smartphones and other personal devices). Relative to total industry size, GPS was particularly transformative for the professional surveying sector. Other industries, such as finance, leverage GPS because of its reliability and ubiquity, although the precision they are afforded is far greater than what is required. Alternatives are or would have been readily available for them.

The magnitude of benefits for telecommunications, telematics, and LBS warrants additional explanation. Precision timing has a critical role in synchronization of telecommunications networks, enabling service providers to more efficiently use available spectrums and deliver high-speed wireless services. Given American society's intensive use of wireless technologies, it is perhaps not surprising that benefits related to telecommunications are substantial. Benefits relating to telematics and LBS have significant positive externalities beyond productivity impacts: improved navigation and fleet management reduces miles driven, generating environmental and public health benefits through reduced fuel combustion. And, of course, Americans enjoy all the location and navigation features of their personal devices.

In looking across the many sectors and applications that require GPS's accuracy and precision, it becomes clear that GPS has some attributes of a utility. The signal is a public good and service provided by the U.S. government that enables productivity, quality, and efficiency benefits that would not otherwise be possible. For many years, it was the only comprehensive PNT signal available. Signals are now available from GLONASS (Russia), Galileo (Europe), and BeiDou (China). The global marketplace means that many devices are increasingly capable of receiving signals from multiple constellations. In the United States, however, critical infrastructure, industries, and applications leverage the GPS signal.

Table 14-1. Summary Economic Benefits of GPS for Private-Sector Use, as of 2017

Sector	Specific Analytical Focus	Benefits ($ million)
Agriculture	Precision agriculture technologies and practices	$5,830
Electricity	Electrical system reliability and efficiency	$15,730
Finance	High-frequency trading	negligible
Location-based services	Smartphone apps and consumer devices that use location services to deliver services and experiences	$215,702
Mining	Efficiency gains, cost reductions, and increased accuracy	$12,350
Maritime	Navigation, port operations, fishing, and recreational boating	negligible
Oil and gas	Positioning for offshore drilling and exploration	$45,922
Surveying	Productivity gains, cost reductions, and increased accuracy in professional surveying	$48,124
Telecommunications	Improved reliability and bandwidth utilization for wireless networks	$685,990
Telematics	Efficiency gains, cost reductions, and environmental benefits through improved vehicle dispatch and navigation	$325,182
Total		**$1,354,830**

Note: Economic benefits were measured relative to a counterfactual that specified that preexisting sources of positioning, navigation, and timing information continued to be available in the absence of GPS. Thus, the relative benefit for some sectors is negligible but substantial for those with applications that have a requirement for GPS's accuracy and precision. We recommend interpreting the $1.4 trillion estimate as a rough order of magnitude. The range of benefits to date is estimated to be between $903 billion and $1.8 trillion.

The economic significance of GPS is growing. About 90% of GPS's benefits have accrued since 2010 (Figure 14-1). Long technology life cycles in some sectors, such as electric utilities, mean that although GPS-enabled equipment has been installed, legacy equipment is still in place. This means that the full potential of GPS functionality has yet to be realized.

14.2 Potential Impacts of a 30-Day GPS Outage

The question of the potential impact of a 30-day outage was added to our scope during our analysis. The duration was specified by the Department of Commerce, and it is not known whether a severe space weather event or nefarious activity by a bad actor would or could cause such a long disruption.

Many technologies can "hold over" timing information or rely on technology alternatives, but a full 30-day outage could potentially have a $30 billion impact (range: $16 billion to $35 billion). If the outage were to occur during critical planting seasons for farmers, the impact could be as high as $45 billion. See Table 14-2.

The impact on Day 1 of an outage would differ from the impact on Day 10 or Day 30. That averages out to about $1 billion in daily loss of use (before accounting for agriculture). As with our retrospective benefits results, this estimate should be interpreted as a rough order of magnitude. If the outage were to occur during April or May, the impact on farmers would be significant, and the impact could be more than $1 billion per day.

Figure 14-1. Time Series of GPS's Economic Benefits for the Private Sector

Table 14-2. Potential Impact of a 30-Day GPS Outage

Sector	Specific Analytical Focus	Potential Losses ($ million)
Electricity	Electrical system reliability and efficiency	$275
Finance	High-frequency trading	Negligible
Location-based services	Smartphone apps and consumer devices that use location services to deliver services and experiences	$2,859
Mining	Efficiency gains, cost reductions, and increased accuracy	$949
Maritime	Navigation, port operations, fishing, and recreational boating	$10,411
Oil and gas	Positioning for offshore drilling and exploration	$1,520
Surveying	Productivity gains, cost reductions, and increased accuracy in professional surveying	$331
Telecommunications	Improved reliability and bandwidth utilization for wireless networks	$9,816
Telematics	Efficiency gains, cost reductions, and environmental benefits through improved vehicle dispatch and navigation	$4,137
Total, Excluding Ag.	**If the outage were not to occur during critical planting seasons**	**$30,298**
Agriculture	Precision agriculture technologies and practices	$15,122
Total, Including Ag	**If the outage were to occur during critical planting seasons**	**$45,420**

Note: Range of potential losses is $16 to $35 billion, before accounting for losses of about $15 billion if a 30-day outage were to occur during critical planting seasons for U.S. farmers.

The maritime sector had technologies and systems available that complemented mariners' skills. GPS's availability meant that the Loran system was no longer necessary, and the signal was turned off. This means that although the historical benefits relative to technology alternatives are negligible, if GPS were lost, there could be more than $10 billion in losses over 30 days. This loss estimate underscores the critical role GPS has come to play in economic activity.

14.3 Final Observations

The comprehensive costs of GPS are difficult to characterize because of the system's emergence from multiple R&D programs over seven decades. Since 2010, expenditures have averaged roughly $1.3 billion per year (2017$).[98] This estimate includes both defense and civilian development, procurement, and operations. A long history of investments, comingling of defense and nondefense funding to sustain and operate the system, and the large number of laboratories and agencies involved make estimation of a benefit-to-cost ratio (or another form of return-on-investment measure) difficult. The Department of Transportation receives appropriations for GPS's civilian use case, but most funding for GPS is provided by Congress to the Air Force.

One could compare GPS's comprehensive costs to only its private-sector benefits for 2010 through 2017. This produces a benefit-to-cost ratio of about 100 to 1.[99] The civilian use portion is a fraction of total expenditure, so the ratio is likely an underestimate. If one assumes that 25% of GPS expenditures were related to civilian use cases, the ratio is about 400 to 1. If one assumes 40%, the ratio is 250 to 1. If one were to guess that the spend on GPS has been more or less constant since President Reagan first permitted civilian use, the ratio is closer to 10 to 1. This does not mean that other investments or programs will have such a high impact; this is simply what we observe within an 8-year window in the 2010s from a program launched in 1973 that itself has roots in programs from the 1960s. It would be a mistake to assume that a comparable investment would achieve these results. The math is less important than the outcome: making GPS available for private-sector use was a good idea.

An important observation from trying to tease out some sense of the return on investment is the relationships between science investments, private-sector innovation, and time. GPS was fully operationally in 1995. It was used by several industries for positioning in the 1980s and 1990s, but the majority of benefits began to accrue during the technology boom starting in the late 1990s. The availability of a reliable, accurate, and extremely precise timing signal meant that innovators had one less barrier to their development of the technologies and applications that are pervasive today and that generate the lion's share of GPS's economic benefits. GPS was a resource whose quality was known, and it took time for innovators to leverage the service. The combination of rapid advances in information technology and GPS was clearly transformative. Excellent examples are telematics and LBS.

---

[98] See https://www.gps.gov/policy/funding/.
[99] Benefits (2017$) for 2010 through 2017 were discounted using a 7% social discount rate, per OMB Circular A-94. Costs for FY2010 through 2017 were adjusted to 2017$ using the real GDP index and discounted. Costs were assumed to be incurred at the beginning of a period and benefits at the end of a period. The benefit-cost ratio is the ratio of the present value of benefits (numerator) to the present value of costs (denominator).

GPS is not just a service; it is also a platform for innovation. With the support of federal agencies, private enterprise has leveraged GPS to deliver value through precision agriculture, advanced logistics and route optimization, high-speed wireless services, and a host of other applications.

For most Americans, the impact of GPS is as near as their smartphone. Maps and navigation tools, social networking, shopping, dating, and relationships are all supported by their phones' location services. GPS is a link between innovation within the national lab system, technology transfer to the private sector, and the tools of their everyday lives.

References

4G Americas. (n.d.). *GSM: Global system for mobile communications*. Retrieved from https://web.archive. Org/web/20140208025938/http://www.4gamericas.org/index.cfm?fuseaction=page&sectionid=242

ACIL Allen. (2013). *Precise positioning in the mining sector—An estimate of the economic and social benefits of the use of augmented GNSS in the mining sector*. Sydney: ACIL Allen Consulting Pty Ltd.

Alliance for Telecommunications Industry Solutions. (2017). *GPS vulnerability*. ATIS technical report. Retrieved from https://access.atis.org/apps/group_public/download.php/36304/ATIS-0900005.pdf

Alliance for Telecommunications Industry Solutions. (2018). *About ATIS—Our work*. Retrieved from http://www.atis.org/01_about/

AlphaBeta. (2016). The economic impact of geospatial services: How consumers, businesses and society benefit from location-based information. Retrieved from https://www.alphabeta.com/wp-content/uploads/2017/09/GeoSpatial-Report_Sept-2017.pdf

American Sportfishing Association. (2018). Freshwater vs. saltwater. Retrieved from https://asafishing.org/facts-figures/angler-participation/anglersurvey-data/freshwater-vs-saltwater/

American Transportation Research Institute. (2017). *An analysis of the operational costs of trucking: 2017 update*. Retrieved from http://atri-online.org/atri-research/operational-costs-of-trucking/

Anderson, M. (2016, January 29). More Americans using smartphones for getting directions, streaming TV. Retrieved from http://www.pewresearch.org/fact-tank/2016/01/29/us-smartphone-use/

Athey, S., & Stern, S. (1998). The adoption and impact of advanced emergency response services. National Bureau of Economic Research Working Paper 6595. Retrieved from https://www.nber.org/papers/w6595

Bellavista, P., Küpper, A., & Helal, S. (2008). Location-based services: Back to the future. *IEEE Pervasive Computing, 7*, 85–89. doi:10.1109/MPRV.2008.34

Bobit Business Media. (2018). Statistics: Fleet industry segments. Retrieved from https://www.automotive-fleet.com/statistics?category=4854

Bobryk, C. W., Myers, D. B., Kitchen, N. R., Shanahan, J., Sudduth, K. A., Drummond, S. T., … Gomez Raboteaux, N. N. (2016). Validating a digital soil map with corn yield data for precision agriculture decision support. *Agronomy Journal, 108*(3), 957–965. doi:10.2134/agronj2015.0381.

Boudette, N. E. (2017, March 2). Building a road map for the self-driving car. *The New York Times*. Retrieved from https://www.nytimes.com/2017/03/02/automobiles/wheels/self-driving-cars-gps-maps.html

Bureau of Labor Statistics. (2018). *Occupational employment statistics*. Retrieved from https://www.bls.gov/oes/tables.htm

Butterline, E., & Frodge, S. (1999). GPS: Synchronizing our telecommunications networks. In *ION GPS'99*, 597–605.

Butterline, E., & Frodge, S. (2001). Telecommunications synchronization and GPS. *GPS Solutions*, *5*(1), 51–54.

Butterline, E., Abate, J., & Zampetti, G. (1988, November). Use of GPS to synchronize the AT&T national telecommunications network. *Proceedings of the 20th Annual Precise Time and Time Interval Systems and Applications Meeting*, Vienna, Virginia, pp. 65–76.

C.J. Driscoll and Associates. (2017). 2016-17 U.S. mobile resource management systems market study, 5th Edition. Retrieved from https://www.cjdriscoll.com/ Reports/15/Details

Carson, R. T. (1991). Constructed markets. In J. Braden and C. Kolstad (eds.), *Measuring the demand for environmental commodities*. Amsterdam: North-Holland.

Carson, R. T. (2000). Contingent valuation: A user's guide. *Environmental Science and Technology, 34*(8), 1413–1418. Retrieved from https://pubs.acs.org/doi/abs/10.1021/es990728j

Celano, T., Carroll, K., Biggs, C., & Lombardi, M. (2003). *Common-view LORAN-C as a backup to GPS for precise time recovery*. San Jose, CA: Symettricom.

Centers for Disease Control and Prevention. (2018). Commercial fishing safety. Retrieved from https://www.cdc.gov/niosh/topics/fishing

Centers for Disease Control and Prevention and National Institute for Occupational Safety and Health. (2015). *Statistics: All mining*. Retrieved from https://www.cdc.gov/niosh/mining/statistics/allmining.html

Corbett, S., & Rayson, M. (1999). Global positioning technologies provide essential exploration tool. *The Oil and Gas Journal*, *97*(26), 54–58.

Curry, C. (2010). Dependency of communications systems on PNT technology. *Dependency of communications systems on PNT technology*. Lydbrook, UK: Chronos Technology.

Curry, C. (2014). *Delivering a national timescale using eLoran*. Lydbrook, UK: Chronos Technology.

Dennehy, K. (2015, April 22). Drones take off for location companies. *GPS World*. Retrieved from https://www.gpsworld.com/drones-take-off-for-location-companies/

DiBiase, D. (n.d.). The nature of geographic information: 25. Summary. State College, PA: The Pennsylvania State University, College of Earth and Mineral Science. Retrieved from https://www.e-education.psu.edu/natureofgeoinfo/c5_p26.html

Energy Information Administration. (2017). *Weekly retail gasoline and diesel prices*. Retrieved from https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm

Erickson, B., Lowenberg-DeBoer, J., & Bradford, J. (2017). *2017 Precision Agriculture Dealership Survey*. West Lafayette, IN: Departments of Agricultural Economics and Agronomy, Purdue University.

Evans, G. (2009, December 8). Miners get spatial awareness. Retrieved from http://www.mining-technology.com/features/feature71335/

Expert Fleet Management. (2018). *GPS fleet tracking costs.* Retrieved from https://www.expertmarket.com/fleet-management/costs

Farnan, T. (2014). How Dwight D. Eisenhower invented the Internet—And the desktop computer. *Forbes*. Retrieved from https://www.forbes.com/sites/realspin/2014/09/02/how-dwight-d-eisenhower-invented-the-internet-and-the-desktop-computer/#4072ba1c2953

Federal Aviation Administration (FAA). (2014a). Satellite navigation—GPS—Space segment. Retrieved from https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/spacesegments/

Federal Aviation Administration (FAA). (2014b). Satellite navigation—GPS—Control segment. Retrieved from https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/controlsegments/

Federal Communications Commission. (2000). In the matter of revision of the Commission's rules to ensure compatibility with enhanced 911 emergency calling systems. (pp. 3). Retrieved from https://transition.fcc.gov/Bureaus/Common_Carrier/Orders/2000/fcc00326.pdf

Federal Communications Commission. (2006). *Auction 66: Advanced wireless services (AWS-1).* Retrieved from https://www.fcc.gov/auction/66

Federal Communications Commission. (2008). *Auction 73: 700 MHz band*. Retrieved from https://www.fcc.gov/auction/73

Federal Communications Commission. (2014). In the matter of wireless E911 location accuracy requirements. (pp. 15). Retrieved from https://www.documentcloud.org/documents/2195636-fcc-third-nprm-february-2014.html#document/p15

Federal Communications Commission. (2015). *Auction 97: Advanced wireless services (AWS-3).* Retrieved from https://www.fcc.gov/auction/97

Federal Communications Commission. (2017). *20th wireless competition report*. Retrieved from https://www.fcc.gov/document/fcc-releases-20th-wireless-competition-report-0

Federal Communications Commission. (2018, March 30). Indoor location accuracy benchmarks. Retrieved from https://www.fcc.gov/public-safety-and-homeland-security/policy-and-licensing-division/911-services/general/location-accuracy-indoor-benchmarks

Federal Communications Commission. (2019). *Report series: Mobile wireless competition*. Retrieved from https://www.fcc.gov/reports-research/reports?field_report_series_tid%5B%5D=1733

Federal Geodetic Control Subcommittee. (n.d.). Geodetic Control Subcommittee. Retrieved from https://www.fgdc.gov/resources/whitepapers-reports/annual%20reports/1997%20annual%20reports/geodetic97

Federal Motor Carrier Safety Administration. (2018). Frequently asked questions (FAQs)—ELD Rule. Retrieved from https://www.fmcsa.dot.gov/hours-service/elds/faqs

Federal Reserve Bank of St. Louis. (2019). FRED economic data: Gross domestic product: Implicit price deflator. Retrieved from https://fred.stlouisfed.org/series/GDPDEF

Federal Reserve Bank of St. Louis. (2019, February 28). Gross domestic product: Implicit price deflator. Retrieved from https://fred.stlouisfed.org/series/GDPDEF#0

Fleetmatics. (2014). Fleetbeat report, Volume 1: From small to large operators: A look across 20,000 service fleets. Retrieved from https://automotivedigest.com/wp-content/uploads/2014/05/FleetBeat_04-22-FINAL.pdf

Fleetmatics. (2016). How GPS fleet tracking can help reduce fuel costs for your business: A Fleetmatics white paper. Retrieved from https://www.fleetmatics.com/resources/ white-papers

Food and Agriculture Organization of the United Nations. (2000). Applications of the contingent valuation method in developing countries: A survey. Retrieved from http://www.fao.org/docrep/003/x8955e/x8955e00.htm#TopOfPage

Franzen, D., & Mulla, D. (2015). A history of precision agriculture. In Q. Zhang (Ed.), *Precision agriculture technology for crop farming* (pp. 1–20). Boca Raton, FL: CRC Press.

Frost & Sullivan. (2016). *Frost & Sullivan's Global Connected Truck Brochure—About 40 million trucks will be connected by 2020.* Retrieved from https://www.slideshare.net/SathyanarayanaK/frost-sullivans-global-connected-truck-brochure-about-40-million-trucks-will-be-connected-by-2020

Gakstatter, E. (2009). RTK networks—What, why, where? Presented at USSLS/CGSIC Meeting. Retrieved from https://www.gps.gov/cgsic/meetings/2009/gakstatter1.pdf

Geneko. (2014). What is GPS and how is it functioning? Retrieved from http://geneko.rs/en/gps-technology.html

Gischig, V., Amann, F., Moore, J. R., Loew, S., Eisenbeiss, H., & Stempfhuber, W. (2011). Composite rock slope kinematics at the current Randa instability, Switzerland, based on remote sensing and numerical modeling. *Engineering Geology, 118*(1–2), 37–53, doi: 10.1016/j.enggeo.2010.11.006

Gohring, N. (2007, November 29). Google "Maps with My Location" service uses cell towers to find users. CIO. Retrieved from https://www.cio.com/article/2437584/mobile/google--maps-with-my-location--service-uses-cell-towers-to-find-users.html

Gopalakrishnan, K. (2016, October 31). The critical need for precision timing in the financial industry. Retrieved from http://www.telecomsync.com/files/pdfs/itsf/2016/day2/1000_CriticalNeedForSecure.pdf

GPS Insight. (2018). *What is the cost of telematics?* Retrieved from https://www.gpsinsight.com/blog/what-is-the-cost-of-telematics/

GPS.gov. *Global positioning system wide area augmentation system (WAAS) performance standard.* Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

Groenfeldt, T. (2016, February 4). Voice is still preferred for trading complex products. Retrieved from https://www.forbes.com/sites/tomgroenfeldt/2016/02/04/voice-is-still-preferred-for-trading-complex-products/2/#efb0bb750947

GSM Association. (2012a). *2025 Every car connected: Forecasting the growth and opportunity*. Retrieved from https://www.gsma.com/iot/wp-content/uploads/2012/03/gsma2025everycarconnected.pdf

GSM Association. (2012b). *Spectrum handbook: Understanding the basics of spectrum policy for mobile telecommunications.* Retrieved from https://www.gsma.com/spectrum/wp-content/uploads/2012/09/Spectrum-GSMA-Spectrum-Handbook-2012.pdf

Hampton, B. (2016, August 1). The history of GPS. FleetTrax. Retrieved from https://fleettrax.net/the-history-of-gps/

Hanemann, W. M. (1999). The economic theory of WTP and WTA. In Bateman, I. & Willis, K. G. *Valuing environmental preferences: Theory and practice of the contingent valuation method in the US, EU, and developing countries* (pp. 96). Oxford University Press.

Hofmann-Wellenhof, B., Lichtenegger, H., & Collins, J. (2012). *Global positioning system: Theory and practice*. Springer Science & Business Media.

Hothem, L. D., & Fronczek, C. J. (1983). *Report on test and demonstration of macrometer model V-1000 interferometric surveyor* (No. FGCC-IS-83-2).

Hummels, D. L., & Schaur, G. (2013). Time as a trade barrier. *American Economic Review*, *103*(7), 2935–2959.

Humphreys, T. (2012). Statement on the vulnerability of civil unmanned aerial vehicles and other systems. Retrieved from https://homeland.house.gov/files/Testimony-Humphreys.pdf

Inforum. (2014). National impact of a west coast port stoppage. Retrieved from https://www.nam.org/Data-and-Reports/Reports/Port-Closure/National-Impact-of-a-West-Coast-Port-Stoppage/

Inkwood Research. (2016). Global automotive navigation system market forecast 2017-2025. Retrieved from https://www.inkwoodresearch.com/reports/automotive-navigation-system-market/#report-summary

Institute for Water Resources, U.S. Army Corp of Engineers. (2012). U.S. port and inland waterways modernization: Preparing for post-panamax vessels. Retrieved from https://www.iwr.usace.army.mil/Portals/70/docs/portswaterways/rpt/June_20_U.S._Port_and_Inland_Waterways_Preparing_for_Post_Panamax_Vessels.pdf

International Maritime Organization. (2019a). AIS transponders. Retrieved from http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx

International Maritime Organization. (2019b). Radiocommunications. Retrieved from http://www.imo.org/en/OurWork/Safety/RadioCommunicationsAndSearchAndRescue/Radiocommunications/Pages/Default.aspx

Johnson, C. W., Shea, C., & Holloway, C. M. (2008). The role of trust and interaction in GPS related accidents: a human factors safety assessment of the global positioning system (GPS). In 26th Annual Conference of the International Systems Safety Society, Vancouver, Canada.

Justice, C., Mason, N., & Taggart, D. (1993, November). Loran-C time management. *Proceedings of the 25th Annual Precise Time and Time Interval Systems and Applications Meeting*, Marina Del Rey, CA. pp. 79–92.

Kaplan, D. (2016, April 26). Overwhelming number of smartphone users keep location services open. Retrieved from http://www.geomarketing.com/overwhelming-number-of-smartphone-users-keep-location-services-open

Kalyani, D. (2018). *IBISWorld Industry Report 48833: Tugboat & shipping navigational services in the US*. IBISWorld.

Kizil, U., Simsek, E., & Yaslioglu, E. (2006). *Performance and accuracy comparisons of GPS and total station in land surveying*. 2006 ASABE Annual Meeting. American Society of Agricultural and Biological Engineers.

Konrad, A. (2013). Meet ORION, software that will save UPS millions by improving drivers' routes. Retrieved from https://www.forbes.com/sites/alexkonrad/2013/11/01/meet-orion-software-that-will-save-ups-millions-by-improving-drivers-routes/#4cb77c844fc7

Lambert, D., & Lowenberg-DeBoer, J. (2000). *Precision agriculture profitability review*. West Lafayette, IN: Site Specific Management Center, School of Agriculture, Purdue University.

Landau, H., Chen, X., Klose, S., Leandro, R., & Vollath, U. (2009). Trimble's RTK and DGPS solutions in comparison with precise point positioning. In *Observing our changing earth* (pp. 709–718). Berlin: Springer.

Langley, R. B. (1998, September). RTK GPS. *GPS World*. Retrieved from http://www2.unb.ca/gge/Resources/gpsworld.september98.pdf

Leite, J. P. (2018, April 9). A brief history of GPS in-car navigation. *NDrive*. Retrieved from https://ndrive.com/brief-history-gps-car-navigation/

Leveson, I. (2009). *Socio-economic benefits study: Scoping the value of CORS and GRAV-D*. Jackson, NJ: Leveson Consulting. Retrieved from https://www.ngs.noaa.gov/PUBS_LIB/Socio-EconomicBenefitsofCORSandGRAV-D.pdf

Leveson, I. (2015). *GPS civilian economic value to the U.S., Interim report*. Prepared for the National Executive Committee for Space-Based Positioning, Navigation and Timing. ASCR Federal Research and Technology Solutions.

Li, B., Saydam, S., Rizos, C., Wang, J., & Wang, Q. (2015). Third generation positioning system for underground mine environments: An update on progress. Retrieved from https://pdfs.semanticscholar.org/f496/f1adfcd99437ff8be50abd1c5c405a2b9c6d.pdf

Lieberman, J. (2009, August 27). Study: GPS systems with real-time traffic can save drivers four days per year, cut emissions by 21%. Retrieved from https://www.autoblog.com/2009/08/27/study-gps-systems-with-real-time-traffic-can-save-drivers-four/

Liu, Y. H., Prince, J., & Wallsten, S. (2018). Distinguishing bandwidth and latency in households' willingness-to-pay for broadband internet speed. *Information Economics and Policy*, *45*, 1–15.

Lohan, E. S., Rusu-Casandra, A., Cramariuc, O., Marghescu, I., & Cramariuc, B. (2011). End-user attitudes towards location-based services and future mobile wireless devices: The students' perspective. *Information, 2*(3), 426–454. doi:10.3390/info2030426

Lombardi, M. (2015, September 14). *Delivering NIST time to financial markets via common-view GPS measurements*. Retrieved from http://www.gps.gov/cgsic/meetings/2015/lombardi.pdf

Lombardi, M. A., Novick, A. N., Neville-Neil, G., & Cooke, B. (2016). Accurate, traceable, and verifiable time synchronization for world financial markets. *Journal of Research of the National Institute of Standards and Technology*, *121*, 436–463.

Lorimer, R. (2010). *Mining Boom Spurs New Positioning Solutions*. GPS World. https://www.gpsworld.com/mining-boom-spurs-new-positioning-solutions/

MarineTraffic. (n.d.). What kind of information is AIS-transmitted? Retrieved from https://help.marinetraffic.com/hc/en-us/articles/205426887-What-kind-of-information-is-AIS-transmitted-

The Maritime Executive. (2018, August 9). Testing underway for next generation straddle carriers. Retrieved from https://www.maritime-executive.com/article/testing-underway-for-next-generation-of-straddle-carriers

Maritime Information Services of North America. (n.d.). Homepage. Retrieved from http://www.misnadata.org/

Markets and Markets. (2018, July). Location-based services (LBS) and real-time location systems (RTLS) market by location type (indoor and outdoor), software (geocoding and reverse geocoding, location and predictive analytics), hardware, service, vertical, and region—Global forecast to 2023. Retrieved from https://www.marketsandmarkets.com/Market-Reports/location-based-service-market-96994431.html

Mölleryd, B. G., & Markendahl, J. (2011). Valuation of spectrum for mobile broadband services: Engineering value versus willingness to pay. *22nd European Regional Conference of the International Telecommunications Society (ITS2011)*, Budapest, Hungary. Retrieved from http://hdl.handle.net/10419/52146

Narins, M. (2004, March). Loran's capability to mitigate the impact of a GPS outage on GPS position, navigation, and time applications. Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate.

Narins, M., Enge, P., Peterson, B., Lo, S., Chen, Y., Akos, D., & Lombardi, M. (2012). The need for a robust and precise time and frequency alternative to global navigation satellite systems. *Journal of Air Traffic Control, 55*(1). Retrieved from https://www.researchgate.net/publication/269411942_The_Need_for_a_Robust_Precise_Time_and_Frequency_Alternative_to_GNSS

National Air and Space Museum, Smithsonian Institution. (2012). Time and navigation. How does GPS work? Retrieved from https://timeandnavigation.si.edu/multimedia-asset/how-does-gps-work

National Archives. (2018). List of fisheries for 2018. *Federal Register*. Retrieved from
https://www.federalregister.gov/documents/2018/02/07/2018-02442/list-of-fisheries-for-2018

National Geodetic Society. (2016). NGS antenna calibration procedures. Retrieved from
https://www.ngs.noaa.gov/ANTCAL/docs/NGSantcalprocedures.pdf

National Institute of Standards and Technology. (2016). *NIST time frequently asked questions (FAQ).*
Retrieved from https://www.nist.gov/pml/time-and-frequency-division/nist-time-frequently-
asked-questions-faq

National Marine Manufacturers Association. (2017). *2017 recreational boating statistical abstract*.

National Mining Association. (2018). *U.S. coal production trends, 1980-2017 (Million Short Tons)*.
Retrieved from https://nma.org/wp-
content/uploads/2018/06/us_coal_production_trends_2017.pdf

National Oceanic and Atmospheric Administration. (2019). Commercial fisheries statistics. Retrieved
from https://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/monthly-
landings/index

National Oceanic and Atmospheric Administration. (n.d.). Vessel monitoring system. Retrieved from
https://www.westcoast.fisheries.noaa.gov/fisheries/management/vms.html

National Transportation Safety Board. (1997). *Marine accident report: Grounding of the Panamanian
passenger ship Royal Majesty on Rose and Crown Shoal near Nantucket, Massachusetts*.
Washington, DC.

Novatel. (n.d.). Resolving errors. In *An introduction to GNSS*. Retrieved from
https://www.novatel.com/an-introduction-to-gnss/chapter-5-resolving-errors/real-time-kinematic-
rtk/

O'Connor, C. (2018). *IBISWorld industry report 54137; Surveying & mapping services in the US*.
IBISWorld.

Pankow, K. L., Moore, J. R., Hale, M., Koper, K. D., Kubacki, T., Whidden, K. M., & McCarter, M. K.
(2014). *GSA Today, 24*(1). doi:10.1130/GSATG191A.1.

Park, J. (2008). The economic impacts of dirty bomb attacks on the Los Angeles and Long Beach ports:
Applying the supply-driven NIEMO (National Interstate Economic Model). *Journal of Homeland
Security and Emergency Management*, *5*(1). doi:10.2202/1547-7355.1312

Petroleum Services Association of Canada. (2019). Industry overview. Retrieved from
https://www.psac.ca/business/industry-overview/

Pew Research Center. (2018, February 5). Mobile fact sheet. Retrieved from
http://www.pewinternet.org/fact-sheet/mobile/

Pham, N. D. (2011). *The economic benefits of commercial GPS use in the U.S. and the costs of potential
disruption*. Washington, DC: NDP Consulting. Retrieved from
http://www.gpsalliance.org/docs/GPS_Report_June_21_2011.pdf

PortVision. (2016). Case studies. Retrieved from https://www.portvision.com/case-studies

Positioning Technology. (n.d.). Indoor atlas. Retrieved from https://www.indooratlas.com/positioning-technology/

Privat, Ludovic. (2007, March 29). TI announced new GPS chip, cost under $5. *GPS Business News*. Retrieved from https://www.gpsbusinessnews.com/TI-announced-new-GPS-chip-cost-under-5_a102.html

Quarles, R. (2017). *2016 recreational boating participation study*. QSA Research and Analytics. Alexandria, VA.

Raquet, J. F. (2013, October 15). *Navigation using pseudolites, beacons, and signals of opportunity*. NATO report STO-EN-SET-197-08.

Recreation Use Values Database. (2016). Corvallis, OR: Oregon State University, College of Forestry. Retrieved from http://recvaluation.forestry.oregonstate.edu/

Resource Analysis. (2017). Tips on selecting the right GPS receiver for your job. Retrieved from http://www.resource-analysis.com/Services/GPS

Ryschka, S., Murawski, M., & Bick, M. (2016). Location-based services. *Business & Information Systems Engineering, 58*(3), 233–237. doi:10.1007/s12599-016-0430-8

Sadlier, G., Flytkjær, R., Sabri, F., & Herr, D. (2017). *The economic impact on the UK of a disruption to GNSS*. Full Report, London Economics.

Satellite Today. (1996). Via satellite briefs. Retrieved from https://www.satellitetoday.com/uncategorized/1996/01/25/briefs/

Schimmelpfennig, D. (2016). *Farm profits and adoption of precision agriculture.* (No. 249773). Washington, DC: U.S. Department of Agriculture, Economic Research Service.

Schimmelpfennig, D., & Ebel, R. (2016). Sequential adoption and cost savings from precision agriculture. *Journal of Agricultural and Resource Economics*, *41*(1), 97–115.

Securities and Exchange Commission. (2006). Rule 6000 Series. Retrieved from https://www.sec.gov/pdf/nasd1/6000ser.pdf

Smink, S. (2018, May 15). Why 911 can't always find you if you call from a cellphone. WPTV. Retrieved from https://www.wptv.com/news/local-news/investigations/why-911-cant-always-find-you-if-you-call-from-a-cell-phone

Spiekermann, S. (2004). General aspects of location-based services. In J. H. Schiller & A. Voisard (eds.), *Location-based services.* San Francisco, CA: Morgan Kaufmann. doi:10.1016/B978-155860929-7/50002-9

Stratmann, T., & Thomas, D. C. (2016). Save time, save lives: The impact of 9-1-1 on lethality and homicides. *SSRN Electronic Journal*. doi:10.2139/ssrn.2773799

Strout, A. (2016, March 10). The future of location-based services. *Marketing Land*. Retrieved from https://marketingland.com/future-location-based-services-167436

Sullivan, M. (2012, August 9). A brief history of GPS. *PC World*. Retrieved from https://www.pcworld.com/article/2000276/a-brief-history-of-gps.html

TechNavio. (2016, November). Global automotive personal navigation systems market 2016-2020. Retrieved from https://www.technavio.com/report/global-automotive-electronics-global-automotive-personal-navigation-systems-market-2016-2020

Tefft, B. C. (2018). American Driving Survey, 2015–2016. AAA Foundation for Traffic Safety. Retrieved from https://aaafoundation.org/american-driving-survey-2015-2016/

The Nautical Institute. (2019). Dynamic positioning. Retrieved from https://www.nautinst.org/en/forums/dynamic-positioning/index.cfm

Tillett, N. D. (1991). Automatic guidance sensors for agricultural field machines: A review. *Journal of Agricultural Engineering Research*, *50*., 167–187. doi:10.1016/S0021-8634(05)80012-5

Titton, L. A., Ratanaubol, C., & Teach, T. (2016). VALUE: A B2B closed bidding game. *Developments in Business Simulation and Experiential Learning, 43*, 185–190.

TruckingInfo HDT. (1996). Fleet management: Communications from the vendor side. Retrieved from https://www.truckinginfo.com/152780/communications-from-the-vendor-side

U.S. Bureau of Economic Analysis. (2017a, March 3). *GDP by industry series (historical).* Gross output by industry. 1990-1996. Retrieved from https://apps.bea.gov/iTable/iTable.cfm?reqid=147&step=2&isuri=1

U.S. Bureau of Economic Analysis. (2017b, November 2). *GDP by industry series.* 1997-2007. Tab: 07NAICS_GO_A_Gross Output. Retrieved from https://www.bea.gov/sites/default/files/2018-04/GDPbyInd_GO_NAICS_1997-2016.xlsx

U.S. Bureau of Economic Analysis. (2018a). GDPbyInd_GO_1947-2017. Retrieved from https://www.bea.gov/sites/default/files/2018-04/GDPbyInd_GO_1947-2017.xlsx

U.S. Bureau of Economic Analysis. (2018b). GDPbyInd_GO_NAICS_1997-2016. Retrieved from https://www.bea.gov/sites/default/files/2018-04/GDPbyInd_GO_NAICS_1997-2016.xlsx

U.S. Bureau of Economic Analysis. (2018c, November 1). *GDP by industry series.* Table U: Gross Output by Industry. 2008-2017. Retrieved from https://apps.bea.gov/iTable/iTable.cfm?ReqID=51&step=1

U.S. Bureau of Labor Statistics. (2017, March). Occupational employment and wages, May 2016: 17-1022 surveyors. Retrieved from https://www.bls.gov/oes/current/oes171022.htm

U.S. Census Bureau. (2017). *USA Trade Online Database*. Retrieved from https://usatrade.census.gov/

U.S. Census Bureau. (n.d.). Industry snapshot: Surveying and mapping (except geophysical) services (NAICS 54137). Retrieved from https://thedataweb.rm.census.gov/TheDataWeb_HotReport2/econsnapshot/2012/snapshot.hrml?NAICS=54137

U.S. Census Bureau, Population Division. (2011, September). Intercensal estimates of the resident population by sex and age for the United States: April 1, 2000 to July 1, 2010 (US-EST00INT-01). Retrieved from https://www.census.gov/data/datasets/time-series/demo/popest/intercensal-2000-2010-national.html

U.S. Census Bureau, Population Division. (2017, December). Annual estimates of the resident population: April 1, 2010 to July 1, 2017. Retrieved from https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=PEP_2018_PEPANNRES&prodType=table

U.S. Coast Guard. (2012). *National Recreational Boating Survey*. Retrieved from http://www.uscgboating.org/statistics/national-recreational-boating-safety-survey.php

U.S. Coast Guard. (2018a). *2017 Recreational Boating Statistics*. Retrieved from https://www.uscgboating.org/library/accident-statistics/Recreational-Boating-Statistics-2017.pdf

U.S. Coast Guard. (2018b). Automatic identification system overview. Retrieved from https://www.navcen.uscg.gov/?pageName=aismain

U.S. Department of Agriculture. (n.d.). NRCS conservation programs: Environmental quality incentives program (EQIP). Retrieved from https://www.nrcs.usda.gov/Internet/NRCS_RCA/reports/fb08_cp_eqip.html

U.S. Department of Agriculture, Agricultural Research Service. (2016). *FY 2016 annual report on technology transfer*. Washington, DC: U.S. Department of Agriculture.

U.S. Department of Agriculture, Economic Research Service. (2019a). Commodity costs and returns. Retrieved from https://www.ers.usda.gov/data-products/commodity-costs-and-returns/

U.S. Department of Agriculture, Economic Research Service. (2019b). Tailored reports: Crop production practices. Retrieved from https://data.ers.usda.gov/reports.aspx?ID=17883

U.S. Department of Agriculture, National Agricultural Statistics Service. (n.d.). QuickStats. Retrieved from https://quickstats.nass.usda.gov/

U.S. Department of Transportation. (2012, September). 3D modeling for construction—Participant workbook part 1. Retrieved from www.fhwa.dot.gov/accelerating/ presentations/3d/3d-work_1.pdf

U.S. Department of Transportation. (2017). Port performance freight statistics program—Annual report to Congress. Retrieved from https://www.bts.gov/learn-about-bts-and-our-work/about-bts/ppfs-annual-report-congress-2016

U.S. Department of Transportation, Bureau of Transportation Statistics. Table 2-17: Motor vehicle safety data (1960-2015). Retrieved from https://www.bts.gov/content/motor-vehicle-safety-data

U.S. Department of Transportation, Federal Highway Administration. (2016). Highway statistics series: Table VM-1. Retrieved from https://www.fhwa.dot.gov/policyinformation/statistics/2016/

U.S. Department of Transportation, Federal Highway Administration. (2018). Highway statistics (2007-2017). Annual vehicle distance traveled in miles and related data, by highway category and vehicle type. Retrieved from https://www.fhwa.dot.gov/policyinformation/statistics/2016/vm1.cfm

U.S. Department of Transportation Maritime Administration. (n.d.). U.S. waterborne foreign container trade by U.S. customs ports 2000–2017. Retrieved from https://www.maritime.dot.gov/data-reports/data-statistics/us-waterborne-foreign-container-trade-us-customs-ports-2000-%E2%80%93-2017

U.S. Energy Information Administration. (1991, December). Performance profiles of major energy producers 1990. Table B22. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (1992, December). Performance profiles of major energy producers 1991. Table B22. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (1994, January). Performance profiles of major energy producers 1992. Table B22. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (1996, January). Performance profiles of major energy producers 1994. Table B22. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (1997, January). Performance profiles of major energy producers 1995. Table B15. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (1998, January). Performance profiles of major energy producers 1996. Table B215 Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (1999, January). Performance profiles of major energy producers 1997. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2000, January). Performance profiles of major energy producers 1998. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2001, January). Performance profiles of major energy producers 1999. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2002, January). Performance profiles of major energy producers 2000. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2003, January). Performance profiles of major energy producers 2001. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2004, February). Performance profiles of major energy producers 2002. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2005, March). Performance profiles of major energy producers 2003. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2006a, March). Performance profiles of major energy producers 2004. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2006b, December). Performance profiles of major energy producers 2005. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2007, December). Performance profiles of major energy producers 2006. Tables B15 and B17. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2008, December). Performance profiles of major energy producers 2007. Tables TS7, TS8, and TS9. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2009, December). Performance profiles of major energy producers 2008. Tables T16 and T18. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Energy Information Administration. (2019a). Annual energy outlook 2019 Table 14. Retrieved from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=14-AEO2019&cases=ref2019&sourcekey=0

U.S. Energy Information Administration. (2019b, February 28). Crude oil production. Retrieved from https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm

U.S. Energy Information Administration. (2019c, February 28). Natural gas gross withdrawals and production. Retrieved from https://www.eia.gov/dnav/ng/ng_prod_sum_a_epg0_fgw_mmcf_a.htm

U.S. Energy Information Administration. (n.d.). Performance profiles of major energy producers 1993. Table B22. Retrieved from https://www.eia.gov/finance/performanceprofiles/

U.S. Environmental Protection Agency. (2016a). *U.S. EPA's inventory of U.S. greenhouse gas emissions and sinks: 1990-2016.* Retrieved from https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016

U.S. Environmental Protection Agency. (2016b). *Population and activity of on-road vehicles in MOVES 2014*. Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100O7VJ.pdf

U.S. Environmental Protection Agency. (2017). *Estimating the co-benefits of clean energy policies: Why use COBRA?* Retrieved from https://www.epa.gov/sites/production/files/2017-10/documents/why_use_cobra_september2017_508.pdf

U.S. Environmental Protection Agency. (2018). *Greenhouse gas equivalencies calculator*. Retrieved from https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

U.S. Geological Survey. (2018). Mineral commodity summaries 2018. Retrieved from
https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf

Wolk, M. (2002). Behind the West Coast port lockout. Retrieved from
http://www.nbcnews.com/id/3073398/ns/business-us_business/t/behind-west-coast-port-
lockout/#.XGHI-DNKjcs

Yonhap News Agency. (2016a, April 5). N. Korea's GP jamming targeted at aircraft navigation systems:
Official. Retrieved from https://en.yna.co.kr/view/AEN20160405008851315

Yonhap News Agency. (2016b, April 6). N. Korea halts GPS jamming: Gov't. Retrieved
fromhttps://en.yna.co.kr/view/AEN20160406007800320

Zafari, F., Gkelias, A., & Leung, K. K. (2017). A survey of indoor localization systems and technologies.
Retrieved from https://arxiv.org/pdf/1709.01015.pdf

Zickuhr, K. (2012, May 11). Three-quarters of smartphone owners use location-based services. Retrieved
from http://www.pewinternet.org/2012/05/11/three-quarters-of-smartphone-owners-use-location-
based-services/

Zickuhr, K., & Smith, A. (2011, September 6). 28% of American adults use mobile and social location-
based services. Washington, DC: Pew Research Center. Retrieved from
http://www.pewinternet.org/2011/09/06/28-of-american-adults-use-mobile-and-social-location-
based-services/

Appendix A:
COBRA

A.1   Approach to Environmental Health Benefits Estimation

Environmental benefits associated with GPS in the telematics and location-based services sectors were quantified on the basis of energy savings. Emissions reductions were quantified by applying emissions factors to energy savings estimates. These emissions reductions were then fed into the Co-Benefits Risk Assessment (COBRA) model, which was developed by EPA to enable users to obtain first-order approximations of benefits due to different air pollution mitigation policies. The COBRA model provides estimates of health effect impacts and the economic value of these impacts resulting from changes in the physical units of emitted pollutants. An overview of the COBRA model and how it works is available from U.S. EPA (2014, 2015). A brief overview of the COBRA model is provided here.

A.1.1   Overview of the COBRA Model

At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in PM concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays. Figure A-1 provides an overview of the modeling steps.

Changes in Emissions → Changes in Ambient PM Concentrations

The user provides changes (decreases) in emissions of pollutants ($PM_{2.5}$, SO_2, NO_x, VOCs, NH_3) and identifies the economic sector from which the emissions are being reduced. For this analysis, the impacted sectors were Residential Distillate Oil Combustion (flame-retention-head oil burner impacts) and Electric Utility Fuel Combustion (advanced refrigeration and heat pump design model and alternative refrigerants research impacts). These changes are in total short tons of pollutants by sector for the U.S. economy for the chosen analysis year. The economic sectors chosen determine the underlying spatial distribution of emissions and hence the characteristics of the human population that is affected.[100]

Figure A-1. COBRA Model Overview

Source: U.S. EPA (2014).

---

[100] The COBRA model has a variety of spatial capabilities. However, for this study there was limited information on the specific location of pollution reductions. Thus, a national analysis was conducted where the national distribution of emissions was used to determine the emission location as input to the S-R matrix.

The S-R matrix consists of fixed transfer coefficients that reflect the relationship between annual average PM concentration values at a single receptor in each county (a hypothetical monitor located at the county centroid) and the contribution by PM species to this concentration from each emission source. This matrix provides quick but rough estimates of the impact of emission changes on ambient PM levels as compared with the detailed estimates provided by more sophisticated air quality models (U.S. EPA, 2015).

Changes in Ambient PM Concentrations→ Changes in Health Effects

The model then translates the changes in ambient PM concentration to changes in incidence of human health effects using a range of health impact functions and estimated baseline incidence rates for each health endpoint. The data used to estimate baseline incidence rates and the health impact functions used vary across the different health endpoints. To be consistent with prior U.S. EPA analyses, the health impact functions and the unit economic value used in COBRA are the same as the ones used for the Mercury and Air Toxics Standards (MATS) Final Rule.

The model provides changes in the number of cases for each health effect between the baseline emissions scenario (included in the model) and the analysis scenario (input by the user). The different health endpoints are summarized in Table A-1 and described briefly below. For additional detail on the epidemiological studies, functional forms, and coefficients used in COBRA, see Appendix C of the COBRA user's manual (U.S. EPA, 2015).

Table A-1. Health Endpoints Included in COBRA

Health Effect	Description
Mortality	Number of deaths (adult or infant)
Acute bronchitis	Cases of acute bronchitis
Nonfatal heart attacks	Number of nonfatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma-, or pneumonia-related hospitalizations
CDV-related hospital admissions	Number of cardiovascular-related hospitalizations
Upper respiratory symptoms	Episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching, or red eyes)
Lower respiratory symptoms	Episodes of lower respiratory symptoms: cough, chest pain, phlegm, or wheeze
Asthma emergency room visits	Number of asthma-related emergency room visits
MRAD	Number of minor restricted activity days (days on which activity is reduced but not severely restricted; missing work or being confined to bed is too severe to be MRAD)
Work loss days	Number of workdays lost due to illness
Asthma exacerbations	Number of episodes with cough, shortness of breath, wheeze, and upper respiratory symptoms in asthmatic children

Mortality researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Krewski et al. (2009) and by a Six-City cohort by Laden et al. (2006). These two studies provide a high and low estimate of mortality associated with changes in ambient PM2.5. COBRA includes different mortality risk estimates for both adults and infants. Infant mortality is based on Woodruff et al. (1997). Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

Nonfatal heart attacks were linked by Peters et al. (2001) to PM exposure. Nonfatal heart attacks were modeled separately from hospital admissions because of their lasting impact on long-term health care costs and earning. COBRA provides a high and low estimate of incidence for nonfatal heart attacks based on differing literature.

Hospital admissions include two major categories: respiratory (such as pneumonia and asthma) and cardiovascular (such as heart failure, ischemic heart disease). Using detailed hospital admission and discharge records, Sheppard et al. (1999) investigated asthma hospital emissions associated with PM, CO, and ozone; Moolgavkar (2000, 2003) found a relationship between hospital admissions and PM. COBRA includes separate risk factors for hospital admissions for people aged 18 to 64 and aged 65 and older.

Acute bronchitis, defined as coughing, chest discomfort, slight fever, and extreme tiredness lasting for a number of days, was found by Dockery et al. (1996) to be related to sulfates, particulate acidity, and, to a lesser extent, PM. COBRA estimates the episodes of acute bronchitis in children aged 8 to 12 from pollution using the findings from Dockery et al.

Upper respiratory symptoms include episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching or red eyes). Pope et al. (2002) found a relationship between PM and the incidence of a range of minor symptoms, including runny or stuffy nose; wet cough, and burning; aching or red eyes.

Lower respiratory symptoms in COBRA are based on Schwarz and Neas (2000) and focus primarily on children's exposure to pollution. Children were selected for the study based on indoor exposure to PM and other pollutants resulting from parental smoking and gas stoves. Episodes of lower respiratory symptoms are coughing, chest pain, phlegm, or wheezing.

Asthma related emergency room visits are primarily associated with children under the age of 18. Slaughter et al. (2003) found significant associations between asthma ER visits and PM and CO. To avoid double counting, hospitalization costs (discussed above) do not include the cost of admission to the emergency room.

Minor restricted activity days (MRAD) in COBRA were based on research by Ostro and Rothschild (1989). MRADs include days on which activity is reduced but not severely restricted (e.g., missing work or being confined to bed is too severe to be an MRAD). They estimated the incidence of MRADs for a national sample of the adult working population, aged 18 to 65, in metropolitan areas. Because this study

is based on a "convenience "sample of nonelderly individuals, the impacts may be underestimated because the elderly are likely to be more susceptible to PM-related MRADs.

Work loss days were estimated by Ostro (1987) to be related to PM levels. Based on an annual national survey of people aged 18 to 65, Ostro found that 2-week average PM levels were significantly linked to work loss days. However, the findings showed some variability across years.

Asthma exacerbations estimates were pooled from Ostro et al. (2001) and Mar et al. (2004) to calculate impacts of changes in air quality on asthmatic children. Cough, wheeze, and shortness of breath are all considered to be exacerbations.

Changes in Health Effects → Monetary Impacts

COBRA translates the health effects into changes in monetary impacts using estimated unit values of each health endpoint. The per-unit monetary values are described Appendix F of the COBRA user's manual (U.S. EPA, 2015). Estimation of the monetary unit values varies by the type of health effect. For example, reductions in the risk of premature mortality are monetized using value of statistical life estimates. Other endpoints such as hospital admissions use cost of illness units that include the hospital costs and lost wages of the individual but do not capture the social (personal) value of pain and suffering. COBRA allows users to choose between a discount rate of 3% or 7% to calculate the present value of health effects that may occur beyond the year 2017.

Limitations

It should be noted that COBRA does not incorporate effects of many pollutants, such as carbon emissions or mercury. This has two potential implications. First, other pollutants may cause or exacerbate health endpoints that are not included in COBRA. This would imply that reducing incidences of such health points are not captured. Second, pollutants other than those included in COBRA may also cause a higher number of incidences of the health effects that are part of the model. This is also not captured in this analysis. Thus, the economic value of health effects obtained from COBRA may be interpreted as a conservative estimate of the health benefits from reducing emissions.

References

Dockery, D. W., Cunningham, J., Damokosh, A. I., Neas, L. M., Spengler, J. D., Koutrakis, P. … Frank E. Speizer F. E. (1996). Health effects of acid aerosols on North American children—Respiratory symptoms. *Environmental Health Perspectives, 104*(5), 500–5.

Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., Turner, M. C., … Tempalski, B. (2009). Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. *Research Report of the Health Effects Institute, 140*, 5–114; discussion 115-136.

Laden, F., Schwartz, J., Speizer, F. E., & Dockery, D. W. (2006). Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard Six Cities Study. *American Journal of Respiratory and Critical Care Medicine, 173*(6), 667–672.

Mar, T. F., Larson, T. V., Stier, R. A., Claiborn, C., & Koenig, J. Q. (2004). An analysis of the association between respiratory symptoms in subjects with asthma and daily air pollution in Spokane, Washington. *Inhalation Toxicology, 16*(13), 809–815.

Moolgavkar, S. H. (2000). Air pollution and hospital admissions for chronic obstructive pulmonary disease in three metropolitan areas in the United States. *Inhalation Toxicology*, *12*(Suppl 4), 75–90.

Moolgavkar, S. H. (2003). Air pollution and daily deaths and hospital admissions in Los Angeles and Cook Counties. In *Revised analyses of time-series studies of air pollution and health*. Boston, MA: Health Effects Institute.

Ostro, B., Lipsett, M., Mann, J., Braxton-Owens, H., & White, M. (2001). Air pollution and exacerbation of asthma in African-American children in Los Angeles. *Epidemiology, 12*(2), 200–208.

Ostro, B. D. (198)7. Air pollution and morbidity revisited: A specification test. *Journal of Environmental Economics and Management, 14*, 87–98.

Ostro, B. D., & Rothschild, S. (1989). Air pollution and acute respiratory morbidity—An observational study of multiple pollutants. *Environmental Research,* 50(2), 238–47.

Peters, A., Dockery, D. W., Muller, J. E., & Mittleman, M. A. (2001). Increased particulate air pollution and the triggering of myocardial infarction." *Circulation, 103*(23), 2810–5.

Pope, C., A., 3rd, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association, 287*(9), 1132–41.

Schwartz, J., & Neas, L. M. (2000). Fine particles are more strongly associated than coarse particles with acute respiratory health effects in schoolchildren. *Epidemiology, 11*(1), 6–10.

Sheppard, L., Levy, D., Norris, G., Larson, T. V., & Koenig, J. Q. (1999). Effects of ambient air pollution on nonelderly asthma hospital admissions in Seattle, Washington, 1987–1994. *Epidemiology, 10*(1), 23–30.

Slaughter, J. C., Lumley, T., Sheppard, L., Koenig, J. Q., & Shapiro, G. G. (2003). Effects of ambient air pollution on symptom severity and medication use in children with asthma. *Annals of Allergy, Asthma & Immunology*, *91*(4), 346–353.

U.S. Environmental Protection Agency (EPA). (2014). Co-Benefits Risk Assessment (COBRA) Screening Model: How COBRA Works. Retrieved from frohttps://www.epa.gov/sites/production/files/2015-11/documents/how-cobra-works.pdf

U.S. Environmental Protection Agency (U.S. EPA). (2015). *User's manual for the Co-Benefits Risk Assessment (COBRA) screening model*. Retrieved from https://19january2017snapshot.epa.gov/sites/production/files/2015-08/documents/cobra-manual.pdf

Woodruff, T. J., Grillo, J., & Schoendorf, K. C. (1997). The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. *Environmental Health Perspectives, 105*(6), 608–612.

Appendix B:
Interview Guides

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating GPS's Impacts on the Agricultural Sector

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

- Quantify the economic impact of GPS.
- Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the agricultural sector.

Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in agriculture.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background.

2. Are you familiar with the use of GPS in the agriculture sector?

SECTION II. How GPS is Used by the Agricultural Sector

3. Where and how is GPS used in the agricultural sector? What are the primary benefits? (e.g. yields, costs, diversification)

4. We plan to use a recent USDA Economic Research Service (ERS) study on the net benefits of precision agriculture to calculate the economic benefits of GPS. The following table summarizes the primary findings of that study. The following questions will refer to this table.

Impacts of precision technologies on net returns and farm operating profit

	GPS soil/yield mapping	Guidance system	VRT
	Percentage change in profits from adopting		
Net returns (incl. overhead) Impact of precision technology	1.8%	1.5%	1.1%
Operating profit impact including farm size scale effect	2.8%	2.5%	1.1%

Note: Percentages in second row have been corrected for the "farm size" effect discussed in the text, using the estimated correlation between the adoption and profit sections of each treatment model. GPS = Global Positioning System; VRT = variable-rate technology.

Source: USDA, Economic Research Service estimates using data from the Agricultural Resource Management Survey (ARMS) Phase II and III.

Source: Schimmelpfennig, D. (2016). *Farm profits and adoption of precision agriculture* (No. 249773). United States Department of Agriculture, Economic Research Service.

    a. Is it appropriate to equate the benefits of precision agriculture (PA) technologies to GPS?

    b. Is it appropriate to categorize the uses of GPS into the same categories as precision agriculture: yield and soil mapping, machinery guidance and control systems, variable-rate application technologies?

    c. Are there other uses of GPS in agriculture you can think of that do not fall into these three categories?

    d. ERS calculated these net benefits for corn, and they assume similar benefits for soybeans. They also have PA adoption rates for cotton, peanuts, soybean, and spring wheat. Is it appropriate to assume that the percentage changes in net benefits of PA for

corn and soybeans are similar to the percentage change in net benefits for cotton, peanuts, soybeans, and spring wheat? If not, how would you expect the net benefits of GPS in PA to be different for cotton, peanuts, soybeans, and spring wheat?

    e.   Are there other crops where you expect that GPS has had a big impact? Which ones?

    f.   In your opinion, to what extent do the net benefits to GPS come from increased yields vs. lower costs? Can you estimate what percentage of the benefits has come from increased yields vs. lower costs?

5. What level of accuracy is required for the different uses of a location technology like GPS to be useful in agriculture? (refer to categories above)

SECTION III. If GPS Were Not Available (refer to Attachment describing counterfactual background)

6. If GPS had not become available, would Loran-C or eLoran have been a viable alternative?

7. Would the decreased accuracy of a Loran-C or eLoran system relative to GPS have an impact on the categories discussed above?

8. If so, can you quantify the impact for each of the PA categories listed above? What percentage of the net benefits could have been realized with Loran-C or eLoran for each category?

SECTION IV. Unanticipated 30-Day Failure of the GPS System

9. Now I am going to ask some questions about what would happen to the agriculture industry if GPS failed for 30 days.
       a.   What would the impacts be for different crops in the spring?

       b.   What would the impacts be for different crops in the fall?

       c.   Can you quantify the impact on farmer revenues? What would be the estimated change in increased costs or lower yields?

10. Is there potential for damage beyond the 30-day failure? (e.g. lower yields effecting commodity markets, loss of confidence in GPS)? Please describe.

SECTION V. Technology Transfer (only for experts that were involved in or knowledgeable about technology transfer related to GPS in agriculture, such as equipment manufacturers)

11. How did government laboratories influence or support the development and/or transfer of GPS equipment for agriculture?

12. Did industry directly collaborate or interact with government laboratories as part of their R&D process?

Section VII. Concluding Questions

13. Do you have any other contacts we should reach out to?

14. Would you be willing to participate in a brief follow-up discussion of your responses to this interview?

THANK YOU for contributing your time and insight to the study.

<u>**COUNTERFACTUAL BACKGROUND**</u>

The Agriculture Industry in the Absence of GPS

In order to accurately assess the benefits of GPS, we consider two counterfactual scenarios: first, the state of agriculture had GPS never been developed, and second, the impact on agriculture if GPS were to fail completely for 30 days.

Counterfactual A: If GPS Were Not Developed

Before GPS was available for commercial use in the mid-1990s, farmers had few technologies that allowed them to proactively manage their fields according to spatial characteristics. Without GPS, we assume many producers would continue to manage their operations as before, planting and harvesting as they have done historically without the benefits of precision agriculture.

Our research shows that while most precision agriculture benefits would be lost absent GPS, a technology called Loran – a land-based position, navigation and timing technology similar to GPS that was also under development at the same time as GPS – might have developed in its stead. We assume that without GPS, precision agriculture would have still progressed with Loran, but it would have taken longer to progress and been much more limited in its applications. Those applications that require a location accuracy of more than 10-20 meters, for example, such as variable rate technology and crop dusting, may have evolved using a Loran-based network.[101]

Additionally, not all precision agriculture technologies rely on GPS or require the high levels of accuracy that GPS offers. We assumed that these technologies would have been developed and adopted by some farmers, corresponding to the level of accuracy required for the specific technology. Thus, the technical counterfactual is the net returns to farming using no precision location technologies or those that would be possible using Loran.

Counterfactual B: 30-Day Catastrophic Failure of GPS

A 30-day GPS outage would likely be a shock to agricultural productions and yields, with farmers who had invested in GPS technologies losing the benefits of their precision agriculture techniques. It is unclear to us what kind of efficiency losses would result from farmers having to retrofit or "relearn" how to operate this equipment without GPS enabled, or return to a conventional farming method. The impacts of a GPS outage also depend on its timing – a failure during planting season would have different impacts than a failure during harvest or winter.

---

[101] Earlier versions of Loran, known as Loran-C, could reliably provide 18-90 meters of positioning accuracy; a newer standard, known as eLoran, can achieve 8-20 meters positioning accuracy

OMB Control #0693-0033
Expiration Date: 06/30/2019

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating GPS's Impacts on the Surveying Sector

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

1. Quantify the economic impact of GPS.

2. Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

Accomplishing these objectives relies on the input from sector stakeholders. This interview guide was developed to capture input from stakeholders from each sector.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the surveying sector. Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in surveying.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background.

2. How are you familiar with the use of GPS in the surveying sector?

SECTION II. How GPS is Used in the Surveying Sector

3. Where and how is GPS used in the surveying sector?

4. Please give a brief background of the surveying industry in general:
    a. What are the main categories of surveying? (e.g. boundary, cadastral, topographic, hydrological, mapping, construction)
    b. What level of accuracy is required for a location technology like GPS to be useful in surveying?

5. What are the primary benefits of using GPS in surveying? (try to link to categories in 4a)

6. What are the tradeoffs between GPS and more traditional technologies such as total stations?

7. How do the benefits of GPS vary by type of surveying or geography?

SECTION III. Timeline of GPS Rollout

8. When did GPS in surveying really take off? What were the breakthroughs? What were the important dates for when GPS was adopted in surveying?

9. How have the enhancements to GPS changed its usefulness to surveying over time (e.g. conventional to differential, differential to real time kinematic, etc.)? When did they occur?

10. Are there any co-technologies that have changed the usefulness of GPS for surveying over time? When did they occur?

11. How did adoption of GPS for surveying change for the changes discussed in questions 8 – 10?

SECTION IV. Counterfactual Questions (please refer to the attachment) and 30-day outage

12. Given the precision and accuracy information in Table 1 of the attachment, would Loran-C or eLoran have provided any benefit to the surveying industry? If not, what level of accuracy would have been required?

13. Loran-C and eLoran, the technologies considered in the counterfactual, are incapable of vertical measurement. How would this impact their usefulness in the surveying industry?

14. What would happen to the surveying industry if GPS failed for 30 days?

15. What percentage of surveyors would be able to continue work and how would their productivity be impacted?

SECTION V. Technology Transfer (depending on specialized knowledge of the interviewee)

16. How did government laboratories influence or support the development of GPS technologies for the surveying sector?

17. What government developed/supported technologies are embedded in private sector products and services?

18. How has industry directly collaborated or interacted with government laboratories as part of their R&D process?

Section VI. Concluding Questions

19. Do you have any other contacts that you recommend we reach out to?

20. Are there any other comments you would like to share?

21. Would you be willing to participate in a brief follow-up discussion of your responses to this survey?

THANK YOU for contributing your time and insight to the study.

ATTACHMENT: *Loran as a Counterfactual in the Absence of GPS*

We hypothesize that, in the absence of GPS, a Loran-based system would have been available and would have evolved over time in performance. The following is a brief background on Loran.

The legacy Loran system, known as Loran-C, was introduced in 1957, operates similarly to GPS in that its primary signal is a timing and frequency message. In the late 1980s and early 1990s, investments were made to expand the coverage of Loran-C to cover the continental U.S and improve the precision and accuracy. However, progress on further upgrades Loran-C stalled as the costs exceeded available funds and as GPS was more widely adopted, eliminating the need for Loran-C in some applications.

In 1994, the U.S. Coast Guard (USCG) ceased operating the international Loran-C chains and the 1994 Federal Radionavigation Plan stated that, by 2000, support for the remaining domestic Loran-C network would end (Narins, 2004). Due to the higher performance capabilities of GPS, it was generally preferred over Loran-C for most applications, which was a key reason for Loran-C gradually falling out of use (Justice et al., 1993).

In the late 1990s, interest in maintaining and modernizing Loran-C rekindled because GPS was recognized as a single point of failure for much of the nation's critical infrastructure. An evaluation conducted by the FAA determined that, with some investment in upgrades, the Loran-C system could indeed function as a suitable backup in the event of a GPS outage (Narins, 2004). Additionally, some research and development was being conducted to standardize an enhanced Loran (eLoran) system, which would have more capabilities and better precision and accuracy.

While eLoran would not be able to achieve the levels of precision and accuracy available from GPS, proponents claim it could perform sufficiently to support many critical applications. Table 1 provides a comparison of the frequency, timing, and positioning capabilities of the different systems.

Table 1. Precision and Accuracy Performance

	Loran-C	*eLoran*	*GPS*
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10-40 ns	10 ns
Positioning (meters)	18-90 meters	8-20 meters	1.6-4 meters*

Sources: Narins et al (2012); Curry (2014); FAA (2008)
*GPS positioning accuracy varies widely by type of receiver and augmentations being applied. The accuracy quoted here is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard

References

Curry, C. (2010). Dependency of communications systems on PNT technology. Lydbrook, UK: Chronos Technology.

Justice, C., Mason, N., & Taggart, D. (1994). Loran-C time management.

Narins, M. (2004). Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications. *Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate, March*.

Federal Aviation Administration [FAA]. (2008). GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard. Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf.

OMB Control #0693-0033
Expiration Date: 06/30/2019

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating the Uses and Benefits of GPS to the Telematics Sector

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

- Quantify the economic impact of GPS.
- Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the telematics and fleet management sector. Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in telematics and fleet management.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background.

2. How familiar are you with the use of GPS in the telematics sector?

SECTION II. How GPS Is Used in Telematics

3. Prior to GPS being widely available, how did commercial fleet operators manage their fleet assets and track their usage?

4. When did the use of GPS devices begin for tracking fleets? At what point did specialized products for telematics and fleet tracking come available?

5. How widely adopted are telematics devices for fleet management?

6. How is GPS used by telematics devices and service providers?

7. How much does a typical telematics solution per vehicle?
    a. For the equipment itself?
    b. For any monthly service agreements with the provider?

8. Besides GPS, what other major sensors make up a telematics device (e.g., ODB interface, accelerometer)?

9. In general, what are the benefits of using telematics for fleet management?

10. A study by Fleetmatics estimated that implementing a telematics solution reduced labor costs by approximately 20% because more efficient operation allowed a crew to complete the same amount of work each day in less time.
    a. Do you agree or disagree with this estimate?
    b. If you disagree, could you provide your own estimate of the impact of a telematics solution on labor costs?

11. The same study by Fleetmatics estimates that a telematics solution, on average, saves $45 per vehicle per month of fuel through reduced idle time, better routing, and slower average speeds. At the time of the study, $45 equated to approximately 12 gallons of gasoline.
    a. Do you agree or disagree with this estimate?
    b. If you disagree, could you provide your own estimate of the impact of a telematics solution on fuel consumption?

SECTION III. If GPS Were Not Available

12. If GPS had not become available, would the telematics sector exist?

13. Would another system (such as Loran, as described in the attachment) with less accurate geolocation information be feasible?

SECTION IV. Unanticipated 30-Day Failure of GPS System

14. If GPS failed unexpectedly, what would the impact be on the functionality telematics services and devices?

15. In the event of a failure, how would companies using telematics services be affected?

16. How would companies manage operations in the absence of a telematics service?

17. Can you characterize and/or quantify the impact of a GPS system outage on:
    a. Ability to complete jobs
    b. Labor costs
    c. Fuel efficiency

SECTION V. Technology Transfer

18. Are you familiar with the technology development history of GPS and devices that use GPS as they relate to the telematics sector?

19. Outside of launching and maintaining the GPS constellation itself, did federally funded research support the development and commercialization of any key GPS components that are used in the telematics sector today?

Section VI. Concluding Questions

20. Who else should we contact for this study?

21. Would you like to share any other comments?

22. Would you be willing to participate in a brief follow-up discussion of your responses to this survey?

THANK YOU for contributing your time and insight to the study.

ATTACHMENT: *Loran as a Counterfactual in the Absence of GPS*

We hypothesize that in the absence of GPS a Loran-based system would have been available and would have evolved over time in performance. The following is a brief background on Loran.

The legacy Loran system, known as Loran-C, was introduced in 1957 and operates similarly to GPS in that its primary signal is a timing and frequency message. Up until GPS was available, Loran-C was the de facto standard for PNT services. In the late 1980s and early 1990s, investments were made to expand the coverage of Loran-C to cover the continental United States and improve the precision and accuracy. However, progress on further upgrades to Loran-C stalled as the costs exceeded available funds and as GPS was more widely adopted, eliminating the need for Loran-C in some applications.

In the late 1990s, interest in maintaining and modernizing Loran-C rekindled because GPS was recognized as a single point of failure for much of the nation's critical infrastructure. An evaluation conducted by the FAA determined that with some investment in upgrades the Loran-C system could indeed function as a suitable backup in the event of a GPS outage (Narins, 2004). Additionally, some research and development was being conducted to standardize an enhanced Loran (eLoran) system, which would have more capabilities and better precision and accuracy.

While eLoran would not be able to achieve the levels of precision and accuracy available from GPS, proponents claim it could perform sufficiently to support many critical applications. Table 1 provides a comparison of the frequency, timing, and positioning capabilities of the different systems.

Table 1. Precision and Accuracy Performance

	Loran-C	**eLoran**	**GPS**
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10-50 ns	10 ns
Positioning (meters)	18–90 meters	8–20 meters	1.6–4 meters[a]

Sources: Narins et al. (2004); Curry (2014); FAA (2008)
[a] GPS positioning accuracy varies widely by type of receiver and augmentations being applied. The accuracy quoted here is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

References

Curry, C. (2014). *Delivering a national timescale using eLoran.* Lydbrook, UK: Chronos Technology.

Federal Aviation Administration [FAA]. (2008). GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard. Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

Narins, M. (2004). *Loran's capability to mitigate the impact of a GPS outage on GPS position, navigation, and time application*s. Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate.

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating the Uses and Benefits of GPS to the Location-Based Services Sector

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

- Quantify the economic impact of GPS.
- Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the location-based services (LBS) sector. We are dividing LBS into three broad categories:

1. Personal vehicle navigation (i.e., turn-by-turn driving directions)
2. E911
3. Other apps and services using LBS, including
    a. Traffic information
    b. Personal navigation (walking directions)
    c. Social (including check-in apps and dating apps)
    d. Gaming (e.g., Pokémon Go)
    e. Fitness (e.g., tracking apps for runners)
    f. Search (e.g., searching for something on Google shows local results)
    g. Ride-hailing (e.g., Uber and Lyft)
    h. Smart home

Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in location-based services.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

This collection of information contains Paperwork Reduction Act (PRA) requirements approved by the Office of Management and Budget (OMB). Notwithstanding any other provisions of the law, no person is required to respond to, nor shall any person be subject to a penalty for failure to comply with, a collection of information subject to the requirements of the PRA unless that collection of information displays a currently valid OMB control number. Public reporting burden for this collection is estimated to be 60 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed and completing and reviewing the collection of information. Send comments regarding this burden estimate or any aspect of this collection of information, including suggestions for reducing this burden, to the National Institute of Standards and Technology, Attn: Kathleen McTigue (kathleen.mctigue@nist.gov).

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background.

2. How familiar are you with the use of GPS for LBS, including E911 and personal navigation?

SECTION II. How GPS is Used: Personal Vehicle Navigation

3. What augmentations are used to provide turn-by-turn directions for personal navigation devices or mapping apps on smartphones (e.g. pre-loaded map data)?

4. What level of positioning accuracy is required for personal navigation? Recognizing that different services require different accuracy levels, please elaborate on areas for which you can speak from experience.

SECTION III. How GPS is Used: E911

5. How does the E911 system use GPS location information?

6. Is there a statutorily required level of accuracy for E911?

SECTION IV. How GPS is Used: Other Location-Based Apps and Services

7. What level of positioning accuracy is required for location-based apps, including social, gaming, and local advertising? Recognizing that different services require different accuracy levels, please elaborate on areas for which you can speak from experience.

SECTION V. If GPS Were Not Available

8. In the absence of GPS, how do you think LBS would have developed?

9. Would a Loran-C network with national coverage provide sufficient performance for:
    a. E911?
    b. Personal navigation?
    c. Other location-based apps and services?

10. Would an eLoran network with national coverage provide sufficient performance for:
    a. E911?
    b. Personal navigation?
    c. Other location-based apps and services?

SECTION VI. Unanticipated 30-Day Failure of GPS System

11. If GPS failed unexpectedly, what would be the immediate impact on:
    a. E911 service?
    b. Personal navigation?
    c. Other location-based apps and services?

12. Would E911 continue to function normally as long as wireless networks are able to function?

SECTION VII. Technology Transfer

13. Are you familiar with the technology development history of GPS and devices that use GPS as they relate to the resource extraction sector?

14. Outside of launching and maintaining the GPS constellation itself, did federally funded research support the development and commercialization of any key components that are used in the telecom sector today?

Section VIII. Concluding Questions

15. Who else should we contact for this study?

16. Would you like to share any other comments?

17. Would you be willing to participate in a brief follow-up discussion of your responses to this survey?

THANK YOU for contributing your time and insight to the study.

ATTACHMENT: *Loran as a Counterfactual in the Absence of GPS*

We hypothesize that in the absence of GPS a Loran-based system could have been used by the finance industry to provide some of the frequency and precision timing needs currently being provided by GPS. The following is a brief background on Loran.

The legacy Loran system, known as Loran-C, was introduced in 1957 and operates similarly to GPS in that its primary signal is a timing and frequency message. In the late 1980s and early 1990s, investments were made to expand the coverage of Loran-C to cover the continental United States and improve the precision and accuracy. However, progress on further upgrades to Loran-C stalled as the costs exceeded available funds and as GPS was more widely adopted, eliminating the need for Loran-C in some applications.

In 1994, the U.S. Coast Guard ceased operating the international Loran-C chains, and the 1994 Federal Radionavigation Plan stated that by 2000 support for the remaining domestic Loran-C network would end (Narins, 2004). However, in the late 1990s, interest in maintaining and modernizing Loran-C rekindled because GPS was recognized as a single point of failure for much of the nation's critical infrastructure. An evaluation conducted by the Federal Aviation Administration determined that with some investment in upgrades the Loran-C system could indeed function as a suitable backup in the event of a GPS outage (Narins, 2004). Additionally, some research and development was being conducted to standardize an enhanced Loran (eLoran) system, which would have more capabilities and better precision and accuracy.

While eLoran would not be able to achieve the levels of precision and accuracy available from GPS, proponents claim it could perform sufficiently to support many critical applications. Table 1 provides a comparison of the frequency, timing, and positioning capabilities of the different systems.

Table 1. Precision and Accuracy Performance

	Loran-C	**eLoran**	**GPS**
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10-50 ns	10 ns
Positioning (meters)	18–90 meters	8–20 meters	1.6–4 meters[a]

Sources: Narins et al. (2004); Curry (2014); FAA (2008)

[a] GPS positioning accuracy varies widely by type of receiver and augmentations being applied. The accuracy quoted here is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

References

Curry, C. (2014). *Delivering a national timescale using eLoran.* Lydbrook, UK: Chronos Technology.

Federal Aviation Administration [FAA]. (2008). GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard. Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

Narins, M. (2004). *Loran's capability to mitigate the impact of a GPS outage on GPS position, navigation, and time application*s. Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate.

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating the Uses and Benefits of GPS to the Resource Extraction Sectors

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

- Quantify the economic impact of GPS.
- Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the resource extraction sectors, including open-pit mining and oil and gas exploration.

Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in resource extraction.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background. Is your experience in mining or the oil and gas sector?

2. How familiar are you with the use of GPS in the resource extraction sectors?

SECTION II. How GPS is Used in Resource Extraction

3. Our preliminary research suggests that GPS is used in mining for:
   a. collision avoidance
   b. exploration
   c. mine operations
   d. mine site surveying
   e. autonomous mining and operations control
   f. remote control of vehicles
   g. vehicle tracking and dispatch
   h. loading systems
   i. material tracking along the supply chain
   j. preserving areas of cultural heritage and high environmental value

   Do you agree with this list? Are there any applications you would add?

4. In the mining sector, is the use of GPS primarily limited to open-pit mines? If not, what other types of mining operations should we be including in our analysis?

5. What level of precision is required for these applications?
   a. collision avoidance
   b. exploration
   c. mine operations
   d. mine site surveying
   e. autonomous mining and operations control
   f. remote control of vehicles
   g. vehicle tracking and dispatch
   h. loading systems
   i. material tracking along the supply chain
   j. preserving areas of cultural heritage and high environmental value

6. When was GPS first used in the resource extraction sector? Which application was the first use of GPS?

7. What percent of mining operations use GPS for at least one of these applications?

8. How would you characterize the pace of adoption since GPS was introduced in the resource extraction sectors?

9. Preliminary research suggests that GPS delivers the following categories of benefits:
    a. Improved productivity
    b. Reduced labor requirements
    c. Improved health and safety
    d. Lower environmental impact

    Would you agree or disagree with these categories of savings? Are there any benefit categories that you would add? From your perspective, how would you describe these benefits in a qualitative way?

10. Are you able to make quantitative estimates of the benefits listed in the previous question for the average mining operation?
    a. Overall mine productivity is improved by _____ %
    b. Labor requirements decrease by _____ %
    c. Use of GPS results in _____ % fewer injuries per year in the average mine
    d. Use of GPS decreases waste from operations by _____ %

11. What was used for these positioning needs prior to GPS?

SECTION III. If GPS Were Not Available

12. In the absence of GPS, do you think other technologies would have emerged to fulfill the same applications?

13. Would Loran-C or eLoran (as described in the attachment) be useful in the absence of GPS? If so, how would the resource extraction use such a system, which delivers a less accurate positioning signal?

14. Can you estimate a percentage of the benefits that would be lost due to lower accuracy under a Loran-C or eLoran usage scenario?

SECTION IV. Unanticipated 30-Day Failure of GPS System

15. Can you describe (in a qualitative way) what the impact of a 30-day failure of GPS would be in the resource extraction sectors? For example, would all work stop, or would work continue, but with less efficiency?

16. Are there technologies in use that could serve as backups in the short term? How would these technologies compare to business-as-usual GPS availability?

17. Can you approximate the changes in:
    a. System operating costs (e.g. fuel costs)
    b. Downtime
    c. Labor costs
    d. Other_____

SECTION V. Technology Transfer

18. Are you familiar with the technology development history of GPS and devices that use GPS as they relate to the resource extraction sector?

19. Outside of launching and maintaining the GPS constellation itself, did federally funded research support the development and commercialization of any key GPS components that are used in the telematics sector today?

Section VI. Concluding Questions

20. Who else should we contact for this study?

21. Would you like to share any other comments?

22. Would you be willing to participate in a brief follow-up discussion of your responses to this survey?

THANK YOU for contributing your time and insight to the study.

ATTACHMENT: *Loran as a Counterfactual in the Absence of GPS*

We hypothesize that in the absence of GPS a Loran-based system could have been used by the finance industry to provide some of the frequency and precision timing needs currently being provided by GPS. The following is a brief background on Loran.

The legacy Loran system, known as Loran-C, was introduced in 1957 and operates similarly to GPS in that its primary signal is a timing and frequency message. In the late 1980s and early 1990s, investments were made to expand the coverage of Loran-C to cover the continental U.S. and improve the precision and accuracy. However, progress on further upgrades to Loran-C stalled as the costs exceeded available funds and as GPS was more widely adopted, eliminating the need for Loran-C in some applications.

In 1994, the U.S. Coast Guard ceased operating the international Loran-C chains, and the 1994 Federal Radionavigation Plan stated that by 2000 support for the remaining domestic Loran-C network would end (Narins, 2004). However, in the late 1990s, interest in maintaining and modernizing Loran-C rekindled because GPS was recognized as a single point of failure for much of the nation's critical infrastructure. An evaluation conducted by the Federal Aviation Administration determined that with some investment in upgrades the Loran-C system could indeed function as a suitable backup in the event of a GPS outage (Narins, 2004). Additionally, some research and development was being conducted to standardize an enhanced Loran (eLoran) system, which would have more capabilities and better precision and accuracy.

While eLoran would not be able to achieve the levels of precision and accuracy available from GPS, proponents claim it could perform sufficiently to support many critical applications. Table 1 provides a comparison of the frequency, timing, and positioning capabilities of the different systems.

Table 1. Precision and Accuracy Performance

	Loran-C	**eLoran**	**GPS**
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10-50 ns	10 ns
Positioning (meters)	18–90 meters	8–20 meters	1.6–4 meters[a]

Sources: Narins et al. (2004); Curry (2014); FAA (2008)

[a] GPS positioning accuracy varies widely by type of receiver and augmentations being applied. The accuracy quoted here is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

References

Curry, C. (2014). *Delivering a national timescale using eLoran.* Lydbrook, UK: Chronos Technology.

Federal Aviation Administration [FAA]. (2008). GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard. Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

Narins, M. (2004). *Loran's capability to mitigate the impact of a GPS outage on GPS position, navigation, and time application*s. Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate.

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating the Uses and Benefits of GPS to the Telecom Sector

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

- Quantify the economic impact of GPS.
- Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the telecom sector. For the purposes of this study, we are considering wireline networks, wireless networks, internet service providers, and cable television networks

Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in telecom.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background.

2. How familiar are you with the use of GPS in the telecom sector?

SECTION II. How GPS Is Used in Telecom

3. Please describe the dependence of the telecom sector on GPS for the following:
   a. Wireline network performance
   b. Wireless network performance
   c. Internet service
   d. Cable television

4. When was GPS first used in each of these applications? How has adoption grown over time?

5. How would you characterize the impact of GPS on the telecom sector in the categories listed below? Are you aware of any studies that attempt to quantify the benefits?
   a. Reliability
   b. Security
   c. Bandwidth
   d. Scalability
   e. Other

6. Our preliminary research suggests that a GPS receiver, antenna array, and holdover device are the main pieces of equipment necessary to leverage a GPS signal. Are there any key components that are missing with respect to telecom?

7. Are there any key cost categories that we are missing?

8. At which points within the telecom network infrastructure is GPS equipment installed? Are different types of equipment required at different points within the infrastructure?

9. Can you estimate the cost of procuring each major component of GPS-related equipment?

SECTION III. If GPS Were Not Available

10. In the absence of GPS, what timing and frequency solution do you think the telecom industry would have used in the early 1990s when GPS was first adopted in the industry?

11. Would an eLoran network with national coverage provide sufficient performance for the telecom industry's needs today? What about a Loran-C network?

12. If you answered no in the previous question for either eLoran, Loran-C, or both, please consider the following:
    a. Which part of the telecom network requires more precision than what can be achieved under a Loran solution?
    b. At what point in time did the requirements of the telecom network exceed the capabilities of what Loran-C or eLoran could offer?
    c. In your opinion, what would a telecom network using a Loran system look like in terms of:
        i. Bandwidth (data traffic)
        ii. Capacity (number of devices)
        iii. Reliability
        (If possible, please quantify your estimate—e.g. 20% less bandwidth per device)

SECTION IV. Unanticipated 30-Day Failure of GPS System

13. If GPS failed unexpectedly please describe in a qualitative way how this would affect the telecom network over the timescales below. Please describe the impact in terms of how the outage would affect the different parts of the telecom network delineated in question 3 and in terms of the impact on service quality, network capacity, and service availability.

    a. Immediate impact (within 24 hours)

    b. Intermediate impact (1 day to 1 week)

    c. Beyond 1 week

14. Please review the second attachment, which details holdover estimates for the core and wireless networks. Do you agree or disagree with these estimates?

15. How does an outage in one part of the network affect other parts of the telecom network? For example, if the wireless network were to fail or be significantly affected before the core network, how does this impact the core network?

16. What parts of the network are most vulnerable to a GPS outage? What parts are most resilient?

SECTION VI. Technology Transfer

17. Are you familiar with the technology development history of GPS and devices that use GPS as they relate to the resource extraction sector?

18. Outside of launching and maintaining the GPS constellation itself, did federally funded research support the development and commercialization of any key GPS components that are used in the telecom sector today?

Section IV. Concluding Questions

19. Who else should we contact for this study?

20. Would you like to share any other comments?

21. Would you be willing to participate in a brief follow-up discussion of your responses to this survey?

ATTACHMENT 1: *Loran as a Counterfactual in the Absence of GPS*

We hypothesize that in the absence of GPS a Loran-based system would have been available and would have evolved over time in performance. The following is a brief background on Loran.

The legacy Loran system, known as Loran-C, was introduced in 1957 and operates similarly to GPS in that its primary signal is a timing and frequency message. In the late 1980s and early 1990s, investments were made to expand the coverage of Loran-C to cover the continental United States and improve the precision and accuracy. However, progress on further upgrades to Loran-C stalled as the costs exceeded available funds and as GPS was more widely adopted, eliminating the need for Loran-C in some applications.

In 1994, the U.S. Coast Guard ceased operating the international Loran-C chains, and the 1994 Federal Radionavigation Plan stated that by 2000 support for the remaining domestic Loran-C network would end (Narins, 2004). Because of the higher performance capabilities of GPS, it was generally preferred over Loran-C for most applications, which was a key reason for Loran-C gradually falling out of use (Justice et al., 1993).

In the late 1990s, interest in maintaining and modernizing Loran-C rekindled because GPS was recognized as a single point of failure for much of the nation's critical infrastructure. An evaluation conducted by the FAA determined that with some investment in upgrades the Loran-C system could indeed function as a suitable backup in the event of a GPS outage (Narins, 2004). Additionally, some research and development was being conducted to standardize an enhanced Loran (eLoran) system, which would have more capabilities and better precision and accuracy.

While eLoran would not be able to achieve the levels of precision and accuracy available from GPS, proponents claim it could perform sufficiently to support many critical applications. Table 1 provides a comparison of the frequency, timing, and positioning capabilities of the different systems.

Table 1. Precision and Accuracy Performance

	Loran-C	*eLoran*	*GPS*
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10-50 ns	10 ns
Positioning (meters)	18–90 meters	8–20 meters	1.6–4 meters[a]

Sources: Narins et al. (2004); Curry (2014); FAA (2008)

[a] GPS positioning accuracy varies widely by type of receiver and augmentations being applied. The accuracy quoted here is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

References

Curry, C. (2014). *Delivering a national timescale using eLoran.* Lydbrook, UK: Chronos Technology.

Federal Aviation Administration [FAA]. (2008). GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard. Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf.

Justice, C., Mason, N., & Taggart, D. (1993). Loran-C time management.

Narins, M. (2004). *Loran's capability to mitigate the impact of a GPS outage on GPS position, navigation, and time application*s. Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate.

ATTACHMENT 2: *Telecom Network Holdover Capability (Adapted from Curry, 2010)*

Table 2. Telecom Core Network Traffic Timing—Holdover Capability

Telecom Network Traffic Timing	3 mins	3 hrs	3 days	3 wks	3 mos	3 yrs	>3 yrs
TCXO	X	X	X	X	X	X	X
Low spec OCXO	●	○	X	X	X	X	X
High spec OCXO	●	●	○	X	X	X	X
Low spec Rb	●	●	●	○	X	X	X
High spec Rb	●	●	●	●	○	X	X
1:1 System OCXO and Rb	●	●	●	●	○	X	X
1:1 system + backup timing	●	●	●	●	●	○	○
1:1 system + 24x365 support	●	●	●	●	●	●	●
1:1 system + backup + support	●	●	●	●	●	●	●

Source: Adapted from Curry (2010).

X Failure of GPS would cause failure within the indicated time period.

○ Failure of GPS may cause degradation of service within the indicated time period.

● Failure of GPS would not affect service within the indicated time period.

Table 3. Mobile Base Station Timing—Holdover Capability (FDD Systems)

Mobile Base Station Timing	3 min	3 hrs	3 days	3 wks	3 mos	3 yrs	>3 yrs
TCXO	X	X	X	X	X	X	X
Low spec OCXO	●	○	X	X	X	X	X
High spec OCXO	●	●	○	X	X	X	X
Low spec Rb	●	●	●	○	X	X	X
High spec Rb	●	●	●	●	○	X	X

Source: Adapted from Curry (2010).

X Failure of GPS would cause failure within the indicated time period.

○ Failure of GPS may cause degradation of service within the indicated time period.

● Failure of GPS would not affect service within indicated the time period.

Table 4. Mobile Base Station Timing—Holdover Capability (TDD Systems)

Mobile Base Station Timing	3 min	3 hrs	3 days	3 wks	3 mos	3 yrs	>3 yrs
TCXO	X	X	X	X	X	X	X
Low spec OCXO	●	X	X	X	X	X	X
High spec OCXO	●	○	X	X	X	X	X
Low spec Rb	●	○	X	X	X	X	X
High spec Rb	●	○	X	X	X	X	X
Lo spec OCXO with PTP backup	●	○	○	○	○	○	○
Hi spec OCXO with PTP backup	●	●	●	●	●	●	●

Source: Adapted from Curry (2010).

X   Failure of GPS would cause failure within the indicated time period.

○   Failure of GPS may cause degradation of service within the indicated time period.

●   Failure of GPS would not affect service within the indicated time period.

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating the Uses and Benefits of GPS to the Electricity Sector

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

- Quantify the economic impact of GPS.
- Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the electricity. For example, we are interested in the economic impact (benefits) the electricity services sector gains from the high level of precision timing provided by GPS.

Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in electricity sector.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background.

2. How familiar are you with the use of GPS in the electricity sector?

SECTION II. How GPS is Used by Electric Utilities

3. Where and how is GPS used in the electricity system and what level of timing precision is needed to support each function?
   a. (Y/N) Phasor measurement units (PMUs): _____ milli/micro/nanoseconds
   b. (Y/N) SCADA Networks: __ __ milli/micro/nanoseconds
   c. (Y/N) Fault detection: __ __ milli/micro/nanoseconds
   d. (Y/N) Protective Relays: _____ milli/micro/nanoseconds
   e. (Y/N) Substation control: _____ milli/micro/nanoseconds
   f. (Y/N) Billing and power quality incentives: _____ milli/micro/nanoseconds

4. When was GPS first used in each of these system components/functions and how long did it take for full adoption throughout the system?
   a. What drove the adoption?
   b. What was the influence of government initiatives such as the American Reinvestment and Recovery Act (ARRA).

5. What was used for frequency and precision timing needs prior to GPS?

6. It is our understanding that PMUs have been instrumental in transforming the electricity grid. Do you agree or disagree?
   a. What was the history of the technology development?
   b. Was the R&D conducted by private-sector companies, government laboratories, a combination?
   c. Were there collaborations and/or consortiums?

7. What other GPS-enabled technologies have been important in transforming the electricity grid and what was their history of the technology development?

SECTION III. If GPS Were Not Available

8. If GPS had not become available, how would the electricity system have evolved/adapted?
   a. Would utilities have relied on existing SCADA systems?
   b. Would utilities have supported their own system of quartz or atomic clocks?
   c. Would Loran-C or eLoran (as described in the attachment) been a viable alternative if GPS had not been made available?
   d. Other _____

9. What would have been the technical impact on the electricity system if GPS had never been made available and no alternative system had been deployed?
   a. No significant impact on operation or efficiency
   b. Transmission and distribution (T&D) losses would be _____ % greater.
   c. The probability of blackout or brownout events would increase by _____%.
   d. Fault detection and correction would take _____% longer.
   e. Other _____

10. What would have been the cost system implication from not having GPS?
   a. Negligible – little to no cost increase in providing today's quality of service to customers.
   b. Increased fuel costs associated with T&D losses - _____ %
   c. Increased generation capital costs associated with decreased capacity utilization - _____%
   d. Increased cost associated with location and correction of faults - _____%
   e. Increased costs associated with meeting precision timing and frequency using alternative methods
      i. For example, purchase and installation of atomic clocks and/or fiber systems for synchronization.
      ii. Ongoing operating costs associated with alternative system.
   f. Other increased operation costs? _____

SECTION IV. Unanticipated 30-Day Failure of GPS System

11. If GPS failed unexpectedly, what precision timing and frequency equipment/systems are in place for holdover?
   a. How long could the required frequency and precise time be maintained? _____hours, _____days?

12. What would happen to the electricity system under a 30-day failure of GPS?
   a. No significant impact on operation or efficiency
   b. Transmission and distribution losses would be _____ % greater.
   c. The probability of blackout or brownout events would increase by _____%.
   d. Fault detection and correction would take _____% longer and cost _____% more to correct.
   e. Increased power quality issues (please describe)
   f. Other _____

13. Can you approximate the changes in system costs over the course of a 30-day blackout?
   a. _____% increase in fuel costs?
   b. _____% increase in operating costs (non-fuel)?
   c. Other _____

14. Is there potential for damage to the existing infrastructure that would need to be repaired/replaced in the event of a 30-day failure of GPS? If so, what would be the cost in terms of damage to assets?
    a. Negligible probability of damage to system assets.
    b. ____% loss in generation assets resulting from damage.
    c. ____% loss in T&D assets resulting from damage.
    d. Other _____

Section IV. Concluding Questions

15. Would you like to share any other comments?

16. Would you be willing to participate in a brief follow-up discussion of your responses to this survey?

THANK YOU for contributing your time and insight to the study.

ATTACHMENT: *Loran as a Counterfactual in the Absence of GPS*

We hypothesize that in the absence of GPS a Loran-based system could have been used by the electricity industry to provide some of the frequency and precision timing needs currently being provided by GPS. The following is a brief background on Loran.

The legacy Loran system, known as Loran-C, was introduced in 1957 and operates similarly to GPS in that its primary signal is a timing and frequency message. In the late 1980s and early 1990s, investments were made to expand the coverage of Loran-C to cover the continental United States and improve the precision and accuracy. However, progress on further upgrades to Loran-C stalled as the costs exceeded available funds and as GPS was more widely adopted, eliminating the need for Loran-C in some applications.

In 1994, the U.S. Coast Guard ceased operating the international Loran-C chains, and the 1994 Federal Radionavigation Plan stated that by 2000 support for the remaining domestic Loran-C network would end (Narins, 2004). However, in the late 1990s, interest in maintaining and modernizing Loran-C rekindled because GPS was recognized as a single point of failure for much of the nation's critical infrastructure. An evaluation conducted by the Federal Aviation Administration determined that with some investment in upgrades the Loran-C system could indeed function as a suitable backup in the event of a GPS outage (Narins, 2004). Additionally, some research and development was being conducted to standardize an enhanced Loran (eLoran) system, which would have more capabilities and better precision and accuracy.

While eLoran would not be able to achieve the levels of precision and accuracy available from GPS, proponents claim it could perform sufficiently to support many critical applications. Table 1 provides a comparison of the frequency, timing, and positioning capabilities of the different systems.

Table 1. Precision and Accuracy Performance

	Loran-C	**eLoran**	**GPS**
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10-50 ns	10 ns
Positioning (meters)	18–90 meters	8–20 meters	1.6–4 meters[a]

Sources: Narins et al. (2004); Curry (2014); FAA (2008)
[a] GPS positioning accuracy varies widely by type of receiver and augmentations being applied. The accuracy quoted here is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

References

Curry, C. (2014). *Delivering a national timescale using eLoran.* Lydbrook, UK: Chronos Technology.

Federal Aviation Administration [FAA]. (2008). GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard. Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

Narins, M. (2004). *Loran's capability to mitigate the impact of a GPS outage on GPS position, navigation, and time application*s. Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate.

Interview Guide: NIST Economic Impact Assessment of GPS
Evaluating the Uses and Benefits of GPS to the Financial Sector

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS).

The study has two objectives:

- Quantify the economic impact of GPS.
- Quantify the economic impact of an unexpected 30-day failure of the current GPS system.

As part of this study, RTI identified an alternative scenario, or counterfactual, to describe what we expect might have happened in the absence of GPS being developed and leveraged for commercial applications. Preliminary research and expert interviews suggest that in the absence of GPS the terrestrial PNT system known as Loran-C would have likely evolved over time to meet some of the needs filled by GPS. Some background on the Loran-C and Enhanced Loran (eLoran) systems are provided in an attachment.

Your perspective will help us quantify the benefits of GPS to the financial sector. For example, we are interested in the economic impact (benefits) the financial services sector gains from the increased precision timing from using GPS.

Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to discuss any proprietary or confidential business information, but rather your professional opinion about the role of GPS in financial sector.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
- Kathleen McTigue, Technology Partnerships Office, NIST, kathleen.mctigue@nist.gov

Interview Questions

SECTION I. Respondent Background

1. Please give a brief description of your background and how familiar you are with the use of GPS in the financial services sector.

SECTION II. How GPS is Used by the Financial Services Sector

2. What is the role of precision timing in the financial services sector (select all that apply)?
   a. Providing time stamps for trades
   b. Enabling the benefits of High Frequency Trading (HFT) in terms of latency arbitrage and liquidity, factors that may increase financial market efficiency.
   c. Other _____

3. Where and how is GPS used in the financial services sector?
   a. What are the alternative or competing precision timing systems that are either used or available?
   b. What backup systems are in place?

4. What was used for precision timing needs prior to GPS?

5. For each of the applications within the financial services sector, when was GPS first used? How long did it take for full adoption throughout the system? What drove the adoption?

6. It is our understanding that the current timing system of choice in financial sites is NISTDC.
   a. What was the history of the technology development
   b. Was R&D done by private-sector companies, government laboratories
   c. Were there collaborations and/or consortiums?

SECTION III. If GPS Were Not Available

7. If GPS had not become available, how would the processes for financial transactions have evolved or adapted?
   a. Would stock exchanges have supported their own system of quartz or atomic clocks?
   b. If atomic clocks were the selected alternative to replace GPS, how many atomic clocks would be needed to provide precision timing to the entire financial sector?
      a. Where would they be located?
      b. What would be the incremental labor cost associated with operating and maintaining them?

8. What would have been the impact on financial services from not having GPS?
   a. No significant impact on trading methods or volume
   b. Current trading volumes could not be supported without GPS and would be _____ % less.
   c. The introduction of HFT would have been delayed by _____ years, but not significantly changed.
   d. Other _____

9. What would have been the approximate cost impact from not having GPS
    a. Negligible – little to no increase in costs associated with providing financial services.
    b. If costs would be greater without GPS, how much money do you think you are saving by using NISTDC based on GPS
    c. If costs would be greater without GPS, alternative systems would have an incremental cost of $_____ to purchase/install and $_____ to operate per year

10. Would Loran-C or eLoran (as described in the attachment) been a viable alternative to support NISTDC?

11. Would the decreased precision of a Loran-C or eLoran system relative to GPS have an impact on key activities such as High-Frequency Trading (HFT) and time stamping? If so, can you quantify the impact, in terms of:
    a. Decrease in trading volume - _____%?
    b. lost revenue - _____$$ (annual)?
    c. Increased vulnerability to fraud (yes/no)? please describe.

SECTION IV. Unanticipated 30-Day Failure of GPS System

12. If GPS failed unexpectedly, what equipment/systems are in place for precision timing holdover?
    a. How long could the required level of time stamp precision be maintained - _____hours or _____Days?

13. Would financial exchanges be ordered to shut down HFT because they cannot precisely time stamp these trades?
    a. Yes – after _____ hours or _____days.
    b. No – Holdover is sufficient with backup systems to keep HFT operating for 30 days at the required level of precision.

14. What would be the economic impact to the financial system from the 30-day failure?
    a. No impact regular operations,
    b. Decrease in trading volume - _____%?
    c. lost revenue - _____$$ (annual)?
    d. Increased vulnerability to fraud (yes/no)? please describe.
    e. Reduced/delayed availability of financing, or other financial services. Please describe.

15. What would be the impact in operating costs or efficiency?
    a. _____% increase in cost per trade.

16. Is there potential for damage to the existing infrastructure that would need to be repaired/replaced, thus leading to impacts past the 30-failure?
    a. _____% loss in capital assets, resulting from damage to computers and software.

Section IV. Concluding Questions

17. Would you like to share any other comments?

18. Would you be willing to participate in a brief follow-up discussion of your responses to this interview?

THANK YOU for contributing your time and insight to the study.

ATTACHMENT: *Loran as a Counterfactual in the Absence of GPS*

We hypothesize that in the absence of GPS a Loran-based system could have been used by the finance industry to provide some of the frequency and precision timing needs currently being provided by GPS. The following is a brief background on Loran.

The legacy Loran system, known as Loran-C, was introduced in 1957 and operates similarly to GPS in that its primary signal is a timing and frequency message. In the late 1980s and early 1990s, investments were made to expand the coverage of Loran-C to cover the continental United States and improve the precision and accuracy. However, progress on further upgrades to Loran-C stalled as the costs exceeded available funds and as GPS was more widely adopted, eliminating the need for Loran-C in some applications.

In 1994, the U.S. Coast Guard ceased operating the international Loran-C chains, and the 1994 Federal Radionavigation Plan stated that by 2000 support for the remaining domestic Loran-C network would end (Narins, 2004). However, in the late 1990s, interest in maintaining and modernizing Loran-C rekindled because GPS was recognized as a single point of failure for much of the nation's critical infrastructure. An evaluation conducted by the Federal Aviation Administration determined that with some investment in upgrades the Loran-C system could indeed function as a suitable backup in the event of a GPS outage (Narins, 2004). Additionally, some research and development was being conducted to standardize an enhanced Loran (eLoran) system, which would have more capabilities and better precision and accuracy.

While eLoran would not be able to achieve the levels of precision and accuracy available from GPS, proponents claim it could perform sufficiently to support many critical applications. Table 1 provides a comparison of the frequency, timing, and positioning capabilities of the different systems.

Table 1. Precision and Accuracy Performance

	Loran-C	**eLoran**	**GPS**
Frequency	1×10^{-11} frequency stability	1×10^{-11} frequency stability	1×10^{-13} frequency stability
Timing	100 ns	10-50 ns	10 ns
Positioning (meters)	18–90 meters	8–20 meters	1.6–4 meters[a]

Sources: Narins et al. (2004); Curry (2014); FAA (2008)
[a] GPS positioning accuracy varies widely by type of receiver and augmentations being applied. The accuracy quoted here is from the GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard.

References

Curry, C. (2014). *Delivering a national timescale using eLoran.* Lydbrook, UK: Chronos Technology.

Federal Aviation Administration [FAA]. (2008). GPS Wide Area Augmentation System (WAAS) 2008 Performance Standard. Retrieved from https://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

Narins, M. (2004). *Loran's capability to mitigate the impact of a GPS outage on GPS position, navigation, and time application*s. Prepared for the Federal Aviation Administration Vice President for Technical Operations Navigation Services Directorate.

Appendix C:
Survey for Professional Surveyors

Survey on the Impact of GPS on the Surveying Sector

Introduction

RTI International is working with the National Institute of Standards and Technology (NIST) to conduct an economic impact assessment of the nation's precision, navigation, and timing (PNT) services provided through the Global Positioning System (GPS). The study has two objectives:

> **Quantify the economic impact of GPS.**

> **Quantify the economic impact of an unexpected 30-day failure of the current GPS system.**

As part of this study, RTI is soliciting your input to better understand the economic impact of GPS on the surveying industry. Your participation is voluntary and confidential; only aggregated information will be included in any deliverables or communications. Additionally, we do not wish to know any proprietary or confidential business information, but rather your professional opinion about the role of GPS in surveying. Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in early 2019 and these will be shared with you as soon as they are released.

If you have questions, please contact:

Alan O'Connor, Principal Investigator, RTI, oconnor@rti.org
Kathleen McTigue, Technology Partnerships Office,
NIST, kathleen.mctigue@nist.gov

Background on GPS

Validation: Must be numeric

ID: 2

1) How many years have you been in the surveying industry?

_____

ID: 24

2) Are you a licensed surveyor?

( ) Yes

( ) No

Validation: Min = 0 Max = 100 Must be numeric

ID: 3

3) Please estimate the percentage of your time you spend on each type of surveying.

_____Cadastral

_____Topographic

_____Mapping

_____Hydrologic

_____Construction

_____Boundary

_____Other

Logic: Show/hide trigger exists.

ID: 4

4) Do you use GPS technology when you do surveying?

( ) Yes

( ) No

Logic: Hidden unless: #4 Question "Do you use GPS technology when you do surveying?" is one of the following answers ("Yes")

ID: 26

5) How important is GPS to your job?

( ) Very unimportant   ( ) Somewhat unimportant   ( ) Neutral   ( ) Somewhat important   ( ) Very important

Logic: Hidden unless: #4 Question "Do you use GPS technology when you do surveying?" is one of the following answers ("Yes")

ID: 22

6) When did you adopt GPS technology for surveying for the first time?

( ) 1975

( ) 1976

( ) 1977
( ) 1978
( ) 1979
( ) 1980
( ) 1981
( ) 1982
( ) 1983
( ) 1984
( ) 1985
( ) 1986
( ) 1987
( ) 1988
( ) 1989
( ) 1990
( ) 1991
( ) 1992
( ) 1993
( ) 1994
( ) 1995
( ) 1996
( ) 1997
( ) 1998
( ) 1999
( ) 2000
( ) 2001
( ) 2002
( ) 2003
( ) 2004
( ) 2005
( ) 2006
( ) 2007
( ) 2008
( ) 2009

( ) 2010

( ) 2011

( ) 2012

( ) 2013

( ) 2014

( ) 2015

( ) 2016

( ) 2017

( ) 2018

Validation: Min = 0 Max = 100 Must be percentage
Logic: Hidden unless: #4 Question "Do you use GPS technology when you do surveying?" is one of the following answers ("Yes")
ID: 5

7) In what percentage of your jobs do you utilize GPS technology when you conduct surveying activities (not including using GPS for driving directions)?

_____

ID: 6

8) For those jobs where you do not use GPS, why do you not use it? Select all that apply.

[ ] I do not have a line of sight to the sky.

[ ] It is not economically beneficial to me.

[ ] I don't know how to use GPS technology.

[ ] I don't need it to do my job.

[ ] Other: _____

[ ] N/A - I use GPS for all surveying jobs

Cost Structure of Surveying

We are now going to ask some questions regarding the cost structure of your surveying business. If you do not know the cost structure, please make your best guess.

9) Are you the owner or part-owner of a surveying business?

( ) Yes

( ) No

10) Please estimate the percentage of surveying expenditures by the following cost categories.

_____Labor (includes time and benefits to complete jobs, gather and analyze data, etc)

_____Capital costs (office space and equipment, including GPS receivers, total stations, vehicles used for surveying work, other data gathering tools, etc.)

_____Material costs (markers, stakes, batteries, etc.)

_____Energy costs (including vehicle fuel, electricity)

_____Professional liability insurance

_____Other

Impacts of GPS on surveying

What are the primary impacts of GPS on the categories mentioned previously?

Use the slide bar to estimate how much GPS changes the amount of time that it takes a surveyor to complete the same job, compared to using traditional technologies (e.g. total stations) over the course of the last year.

A negative number means that GPS reduces the amount of time it takes to complete a job by that

percentage, and a positive number means that GPS increases the amount of time it takes to complete a job by that percentage. Zero means there is no change.

Validation: Min = -100 Max = 100

ID: 10

11) Labor

Includes labor time spent on both data acquisition and data analysis as well as other work. For example, if GPS allows you to complete the same job with one person that would take two people otherwise, set the slider to -50.

-100 _____[__]_____ 100

Validation: Min = -100 Max = 100

ID: 11

12) Capital

Includes expenditures on office space, vehicles, equipment, etc. For example, if you spend 50% more on capital with GPS than you did before you used GPS, set the slider to 50.

-100 _____[__]_____ 100

Validation: Min = -100 Max = 100

ID: 12

13) Materials

Includes stakes, markers, batteries, etc. For example, if you spend 25% less on materials using GPS than you would without it, set the slider to -25.

-100 _____[__]_____ 100

Validation: Min = -100 Max = 100

ID: 13

14) Energy
Includes fuel for vehicles, electricity for offices, etc. For example, if you drive 25% less on a project using GPS than you would for a project without GPS, set the slider to -25.

-100 _____[__]_____ 100

15) Does GPS enable you to complete jobs that would not have been possible without GPS?

( ) Yes

( ) No

16) What percentage of your revenue comes from jobs that would not have been possible to do without GPS?

0 _____[__]_____ 100

Impacts of a 30-day GPS Outage

This section of the survey will pose a series of questions about the potential impacts of a 30-day unexpected failure of the GPS system and how it would affect your work. You can assume that all of your GPS devices would not work during this time period, and that it occurs during a time of year when you have an average workload.

17) In the event of an unplanned GPS outage that lasted for thirty days, would you be able to continue conducting surveying work in any capacity?

( ) Yes

( ) No

18) Would an unplanned GPS outage have any impact on your work?

( ) Yes

( ) No

19) What would be the primary impacts of a thirty day GPS outage? Select all that apply.

[ ] It would take longer to complete similar jobs.

[ ] I could not do certain jobs.

[ ] I could not compete for certain jobs.

[ ] Other: _____

20) What are the reasons that the GPS outage would impact your work? Select all that apply.

[ ] There is no way to complete certain jobs without GPS

[ ] I do not have the right equipment to survey without GPS

[ ] It would take me too long to acquire the right equipment to survey without GPS

[ ] I do not know how to survey without GPS

[ ] It would take me a while to re-learn how to survey without GPS

[ ] Other: _____

21) How much longer, in percentage terms, would it take you to complete a typical job during a thirty day GPS outage?

_____

22) What percentage of jobs would you be unable to complete at all during a thirty day GPS outage?

_____

23) What percentage of jobs would you be unable to compete for during a thirty day GPS outage?

_____

Final Thoughts

24) Is there anything else you would like to tell us about your work?

_____

_____

_____

_____

Thank You!

Thank you for taking our survey. Your response is very important to us.

Appendix D:
Survey for Location-Based Services

Location-Based Services User Survey v2.2

Introduction

This survey asks you about how you value location-based services for a variety of applications and services. The results of this survey will be used to estimate the economic impact of location-based services provided using GPS signals.

Location-based services enable mobile devices like your phone or tablet to determine your location, usually to within a few feet. If you have ever used your phone to locate nearby attractions or get turn-by-turn walking or driving directions, you have used location-based services.

This collection of information contains Paperwork Reduction Act (PRA) requirements approved by the Office of Management and Budget (OMB). Notwithstanding any other provisions of the law, no person is required to respond to, nor shall any person be subject to a penalty for failure to comply with, a collection of information subject to the requirements of the PRA unless that collection of information displays a currently valid OMB control number. Public reporting burden for this collection is estimated to be 3 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed and completing and reviewing the collection of information. Send comments regarding this burden estimate or any aspect of this collection of information, including suggestions for reducing this burden, to the National Institute of Standards and Technology, Attn: Kathleen McTigue (kathleen.mctigue@nist.gov).

OMB Control #0693-0033
Expiration Date: 06/30/2019

Do you use location-based services on a mobile device?

ID: 3

1) Do you use location-based services on any of the following devices?*

[ ] Smartphone (e.g., iPhone or Android mobile phone)

[ ] Tablet

[ ] GPS navigation device (e.g., TomTom or Garmin)

[ ] Built-in navigation system in a vehicle

[ ] None of the above

How do you use location-based services?

ID: 4

2) In what ways do you use location-based services? Check any that you use at least once a month:*

[ ] Traffic information

[ ] Turn-by-turn driving and walking directions

[ ] Social (e.g., check-in apps and dating apps)

[ ] Gaming (e.g., Pokemon Go)

[ ] Fitness (e.g., tracking distance walked, run, or biked)

[ ] Searching for nearby attractions, like stores or restaurants

[ ] Ride-hailing (e.g., Uber or Lyft)

[ ] Geofencing (e.g., get reminders to run an errand when you leave work)

[ ] Other - Write In (Required): _____*

Turn-by-turn driving and walking directions

This question asks about your willingness to give up the use of location-based services for *turn-by-turn driving and walking directions* only.

Validation: Min = 0 Max = 10000 Must be currency

ID: 157

3) What is the smallest amount of money you would accept in exchange for giving up the ability to use location-based services to get *turn-by-turn driving and walking directions* for *one month*?*

_____

Validation: Min = 0 Max = 10000 Must be currency

ID: 182

4) What is the smallest amount of money you would accept in exchange for giving up the ability to use location-based services to get *turn-by-turn driving and walking directions* for *two months*?*

_____

Validation: Min = 0 Max = 10000 Must be currency

5) Imagine your ability to use location-based services to get *turn-by-turn driving and walking directions* **is going to be** *taken away for one month* **unless you pay an extra fee. What is the most you would pay to avoid losing this ability for one month?***

_____

Validation: Min = 0 Max = 10000 Must be currency

6) Imagine your ability to use location-based services to get *turn-by-turn driving and walking directions* **is going to be** *taken away for two months* **unless you pay an extra fee. What is the most you would pay to avoid losing this ability for two months?***

_____

Page entry logic: This page will show when: #2 Question "In what ways do you use location-based services? Check any that you use at least once a month:" is one of the following answers ("Traffic information","Turn-by-turn driving and walking directions","Social (e.g., check-in apps and dating apps)","Gaming (e.g., Pokemon Go)","Fitness (e.g., tracking distance walked, run, or biked)","Searching for nearby attractions, like stores or restaurants","Ride-hailing (e.g., Uber or Lyft)","Geofencing (e.g., get reminders to run an errand when you leave work)","Other - Write In (Required)")

All Location-Based Services

This question asks about your willingness to give up the use of location-based services for *all of the things you use them for***.**

Validation: Min = 0 Max = 10000 Must be currency

7) What is the smallest amount of money you would accept in exchange for giving up the ability to use location-based services *for one month***?***

_____

Validation: Min = 0 Max = 10000 Must be currency

ID: 191

8) Imagine your ability to use location-based services is going to be *taken away for one month* **unless you pay an extra fee. What is the most you would pay to avoid losing this ability for one month?***

_____

Validation: Min = 0 Max = 10000 Must be currency

ID: 192

9) Imagine your ability to use location-based services is going to be *taken away for two months* **unless you pay an extra fee. What is the most you would pay to avoid losing this ability for two months?***

_____

Validation: Min = 0 Max = 10000 Must be currency

ID: 193

10) What is the smallest amount of money you would accept in exchange for giving up the ability to use location-based services *for two months***?***

_____

Thank You!

ID: 1

Thank you for taking our survey. Your response is very important to us.