Time for a Better Receiver

Chip-Scale Atomic Frequency References

John Kitching

CLOCKMAKERS DOWN THROUGH THE AGES have toiled long and hard to improve clock stability — to try to make a clock which keeps constant time, or as constant as possible. The need for such a clock to improve 18th-century navigation led John Harrison to develop a series of marine chronometers, each more stable than the previous. He finally produced the H4, which permitted longitude to be determined with an error of no more than 30 minutes, even after a sea voyage lasting almost half a year.

All clocks contain an oscillator or frequency reference. How well a clock keeps time depends on the stability of this reference. Harrison's oscillating springs and escapements gave way to more accurate quartz crystals and electronic circuitry. Mass-produced quartz-crystal oscillators now are found in virtually every piece of electronic equipment, from wristwatches to GPS receivers. But they are susceptible to environmental factors such as a changing ambient temperature.

INNOVATION INSIGHTS
with Richard Langley

Modern-day John Harrisons are miniaturizing atomic clocks.

The quartz-crystal oscillators in GPS receivers, even if temperature compensated, still have instabilities leading to clock errors that must be estimated by the GPS receiver when computing its fix or otherwise eliminated. What if a GPS receiver's clock was sufficiently error-free that it did not perturb the position fix? The fix could then be obtained with fewer satellite signals — as few as three for a complete three-dimensional fix. Atomic frequency references significantly outperform quartz-crystal oscillators but they are bulky and consume lots of power — hardly an option for a handheld GPS receiver. But just as John Harrison worked to develop a portable clock with a stability approaching that of observatory clocks of his day, so are modern-day John Harrisons working to miniaturize atomic clocks — down to the size of chip on a printed circuit board — so that they can be used in handheld devices such as GPS receivers.

In this month's column, we look at the fabrication and performance of chip-scale atomic frequency references. These new marvels of miniaturization will be moving from the lab to the factory any day now.

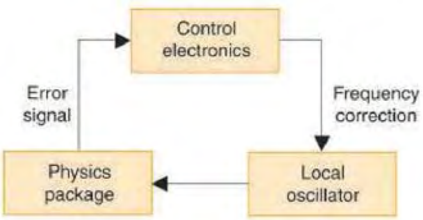
"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 10.

Atomic clocks and precision timing are at the core of almost every aspect of global navigation satellite systems (GNSS). A GNSS receiver determines its position with respect to a subset of the constellation of orbiting satellites by measuring the time taken by a radio frequency (RF) signal to travel the distance between the satellite and the receiver. Through a multilateration process, the receiver is able to determine its three spatial coordinates and clock offset from information from a minimum of four satellite signals. Nanosecond-level timing is typically required for positioning with a precision and accuracy of 1 meter.

In most GNSS receivers, the clock is in the form of a temperature-compensated quartz crystal oscillator (TCXO). These small, low-power and low-cost frequency references are sufficient for most basic GNSS functions and allow the receiver to access, for example, the Standard Positioning Service (SPS) of the Global Positioning System (GPS). In a normal positioning process, the receiver clock is implicitly synchronized to GPS Time by the algorithm that also determines the position.

However, in certain circumstances, it is advantageous to have a receiver reference clock more stable than a TCXO, particularly over long periods. Once initially synchronized, such a clock would allow, for example, positioning with only three satellites since one variable, the receiver time, would already be determined. Several other, more subtle advantages are discussed toward the end of this article.

Over the last six years, the National Institute of Standards and Technology (NIST) and several commercial companies have been funded by the Defense Advanced Research Projects Agency (DARPA) to develop highly miniaturized, low-power atomic frequency references for



▲ **FIGURE 1** The three subsystems of a passive frequency reference and the interaction between them.

use in portable, battery-operated applications such as GNSS receivers. The goals of this program are to develop a fully functional atomic clock with a volume below 1 cubic centimeter (roughly the size of a large integrated circuit "chip"), a power dissipation below 30 milliwatts (mW), and a fractional frequency instability below 10^{-11} at an averaging time of 1 hour. If these goals are achieved, this would represent an improvement by a factor of 100 in size and power dissipation over the current state of the art in compact atomic standards. It also represents an improvement in frequency stability at one hour by over three orders of magnitude over what is typically achieved with a quartz-crystal frequency reference of comparable size and power dissipation.

The field of microelectromechanical systems (MEMS) deals in large part with the fabrication of sub-millimeter physical structures using photolithographic patterning and chemical etching. Many of the tools are similar to those developed for the microelectronics industry but are used to make devices that are mechanically active as well as electrically active. Key technologies made possible by MEMS include the airbag accelerometer and the digital signal processor found in many large-screen televisions. In addition to small size, and correspondingly low thermal power dissipation, MEMS offers the advantage of parallel fabrication of many devices on the same wafer, which can reduce manufacturing costs for large enough instrument volumes.

Chip-scale atomic clock (CSAC) technology combines the use of MEMS processing with innovative atom excitation techniques and a recently developed semiconductor laser technology. These three advances allow miniaturization of the clock physics package by almost a factor of 100 in volume over those of previously developed systems. Complementary improvements in the size and power of gigahertz oscillators and advanced, low-power microprocessing for the implementation of servo systems have allowed the newly developed physics packages to be integrated into complete prototype stand-alone atomic clocks. As reliability and manufacturability of these devices improve, insertion into applications is likely to follow.

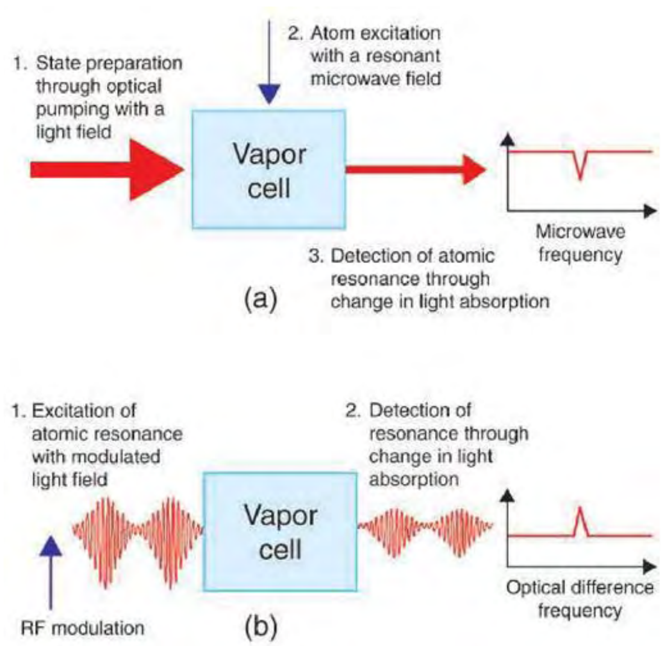
Clock Physics Package

The heart of any atomic clock is the "physics package," which contains the alkali atoms, such as those of rubidium or cesium, that provide the precise periodic oscillation on which the clock is based. Because of the importance of this element in the clock, and because of the role that fundamental physics plays in determining its size, work has focused in large part on this subsystem. However, any complete (passive) frequency reference also requires a local oscillator (LO) to generate the initial (unstable) frequency that interrogates the atoms, and a control system that implements the correction process. The interaction between these three subsystems is illustrated in **FIGURE 1**.

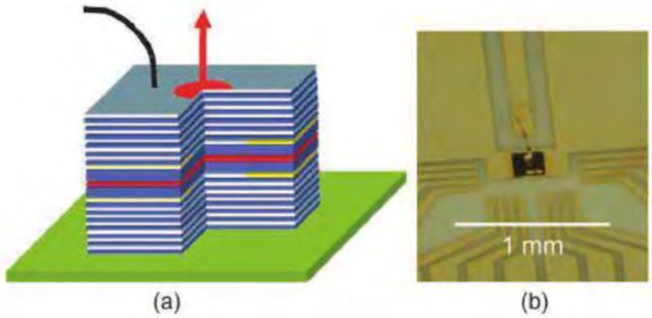
In a conventional vapor cell atomic clock (see **FIGURE 2a**), the atomic transition is excited through the direct application of a microwave field to the atoms. Atoms are first prepared in one of the hyperfine-split ground state sublevels by an optical field from a lamp. The microwave field couples the two hyperfine split ground-state sublevels, generating an oscillating magnetic moment in the atom at the microwave frequency. The change of the atomic state implicit in this oscillating moment is monitored through the change in absorption of the optical field used to prepare the atoms.

One difficulty with this conventional vapor cell clock configuration is that the cell is typically placed inside a microwave cavity; the cavity confines the microwaves in the vicinity of the atoms and reduces Doppler shifts that can be present when a traveling wave microwave field is used. In order to be resonant, the simplest microwave cavities must be no smaller than roughly one half the wavelength of the microwave radiation (3.2 centimeters in the case of cesium). This imposes limits on how small the physics package can be made.

Most designs for microfabricated, chip-scale atomic clock physics packages avoid the difficulty associated with the wavelength of the microwave radiation through the use of coherent population trapping (CPT) excitation of the atomic transition used to stabilize the LO (see **FIGURE 2b**). In this technique, two light fields, separated in frequency by the atomic ground-state hyperfine splitting, are simultaneously



▲ **FIGURE 2** Physical mechanisms involved in (a) conventional microwave-excited vapor cell frequency references and (b) frequency references based on coherent population trapping.



▲ **FIGURE 3** Vertical-cavity surface-emitting lasers. (a) Basic structure showing the upper and lower Bragg mirrors and gain region and (b) photograph of a vertical-cavity surface-emitting laser die mounted to a baseplate.

incident on the atoms. The nonlinear behavior of the atoms generates a coherence (and therefore an oscillating magnetic moment) at the difference frequency of the two optical fields. The amplitude of this coherence can be measured by monitoring the absorption of the atomic sample: When the difference frequency between the optical fields is near the atomic hyperfine splitting frequency, the absorption by the sample decreases.

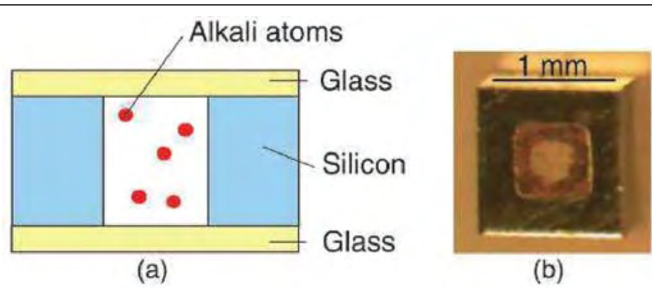
A convenient way of generating the two-frequency optical field is through modulation of the injection current of a diode laser. When locked to the atomic transition, this modulation frequency (generated by the LO) is stabilized over long periods and becomes the output of the atomic clock. Most diode lasers, however, require around 100 mW of electrical power to operate and are difficult to modulate at gigahertz (GHz) frequencies. Vertical-cavity surface-emitting lasers (VCSELs), refined over the last 10 years or so, have very low (sub-milliamp) threshold currents and therefore require very little power to operate. A VCSEL is fabricated by growing layers of materials with differing indices of refraction to form multilayer mirrors called Bragg reflectors above and below a gain region on a wafer. The Bragg reflectors typically have very high reflectivity, which results in a very low threshold current. In addition, many of these lasers were designed for optical communication systems and therefore have high modulation bandwidths, sometimes approaching 10 GHz. A schematic of the laser structure and a photograph of a mounted laser die are shown in **FIGURE 3**.

Atomic clocks based on this CPT excitation mechanism are not restricted in size by the wavelength of the microwave radiation, because no microwave field is applied to the atoms, and no microwave cavity is required. As a result, a highly compact atomic clock can be made with this method. Table-top experiments implementing atomic clocks based on this method have achieved short-term fractional frequency instabilities below 2×10^{-12} for an averaging time of 1 second.

Alkali Vapor Cells

Perhaps the most important way in which MEMS impacts the design of chip-scale atomic clocks is in regard to the alkali vapor cell that confines the atoms. In more conventional atomic clocks, the cell is fabricated by glass-blowing: windows are attached to the ends of a glass tube, a filling tube is attached to the side wall, the system is pumped down, and alkali metal (rubidium or cesium) is distilled into the cell. By contrast, the MEMS alkali vapor cells in most CSACs are made by etching a hole in a silicon wafer a few hundred micrometers thick, and then bonding thin glass wafers on the top and bottom surface. Alkali atoms can be confined in the interior volume of the structure before the second glass wafer is attached. A schematic of the MEMS cell geometry and a photograph of a complete cell are shown in **FIGURE 4**.

Cell fabrication with this method has several critical advantages over the conventional method. First, the method enables the fabrication of cells with very small volumes, since the hole in the silicon wafer is defined by lithographic patterning. Second, the method is highly scalable. The cells typically fabricated for our physics packages are about 1 millimeter in size; however, almost no changes to the basic cell-filling process would be required to make cells of considerably smaller size. Third, the method allows many cells to be made simultaneously on a single wafer stack with the same process sequence. This should lead to a substantial reduction in cost for atomic clock physics packages. Finally, the planar structure allows for easy integration with other optics and electronics. In particular, the light field required for CPT excitation of the atoms can conveniently enter and leave the cell through the glass windows.

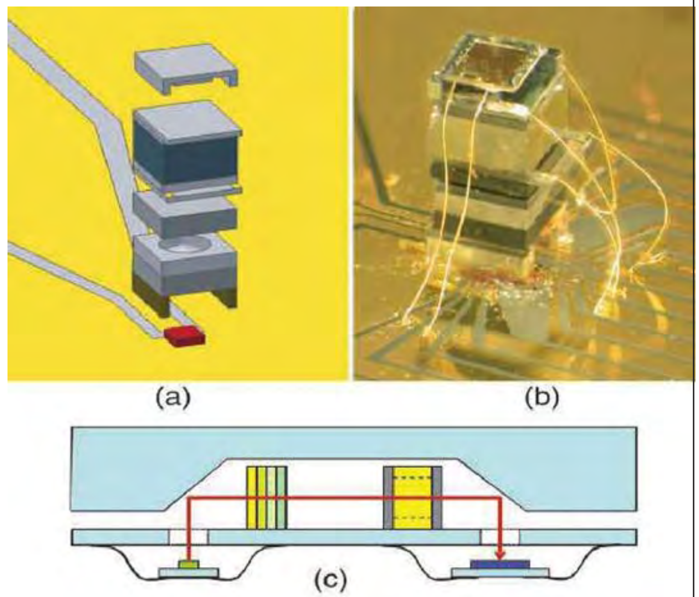


▲ **FIGURE 4** (a) Basic MEMS cell geometry (side view) and (b) photograph of a millimeter-scale cell made at NIST in 2003 (top view).

CSAC Physics Packages

Because of their small size, the cells must be heated to near 100° Celsius in order to have a vapor pressure of alkali atoms sufficient to give a reasonable signal. Cell heaters can be fabricated by depositing a thin (30 nanometer) layer of indium tin oxide (ITO) onto a glass substrate. ITO is a convenient material for this type of heater since it is both transparent and conductive. It therefore allows current to be passed through it (to heat the cell) and also can be placed over the cell windows to make good thermal contact with the cell without obstructing the passage of the light. Alternatively, a thin serpentine trace of metal can be deposited near the edges of the cell to serve as an ohmic heater.

The cell and heaters are integrated with an optics assembly, which generates the light beam used to excite the atoms. The optics assembly typically comprises a VCSEL die, a wave plate to create circular polarization, a neutral density filter to attenuate the light power, sometimes a lens to collimate the light beam, and a polarizer to maintain a constant output polarization. A small photodiode is placed on the side of the cell opposite the laser to detect the transmitted optical power. Two basic geometries are used in the integration. In *vertically integrated* chip-scale atomic clocks, the components (such as laser, optics, and cell) are stacked on top of each other to form a sort of millimeter-scale tower, as shown in **FIGURES 5a** and **5b**. In *horizontally integrated* devices, the light from the laser is first reflected parallel to the wafer surface and the optics and cell are implemented on the surface of the wafer to allow horizontally propagating light to pass through. The light is then reflected back down to the wafer surface into a photo detector. A schematic of a horizontally integrated device is shown in **FIGURE 5c**.



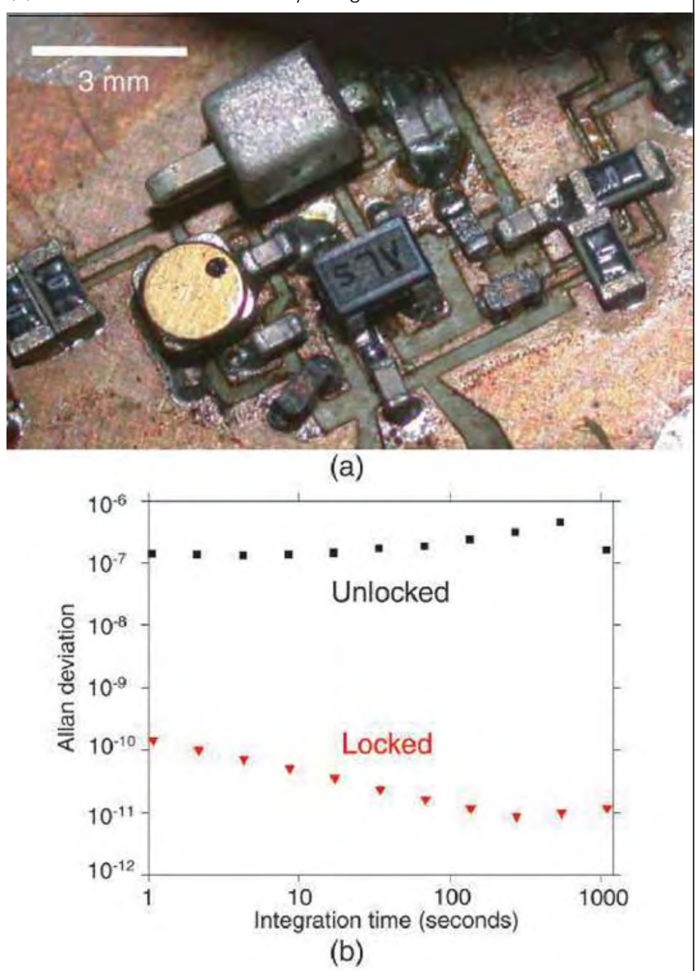
▲ **FIGURE 5** (a) Schematic of a vertically integrated chip-scale atomic clock, (b) photograph of a device fabricated at NIST, and (c) schematic of a horizontally integrated device.

Local Oscillator and Control System

A compact, low-power voltage-controlled oscillator (VCO) capable of generating a signal at a subharmonic of the 6.8 GHz (rubidium) or 9.2 GHz (cesium) atomic resonant frequency is needed to drive the physics package. Commercially available VCOs can be used and consume in the range of 20 to 40 mW. This subsystem can be constructed from individual parts that include commercially available ceramic micro-coaxial resonators with loaded Q-factors in the range of 100.

Thin-film bulk acoustic resonators are another promising resonator technology that promise higher Q-factors at gigahertz frequencies and corresponding reduction in the LO phase noise. The oscillator shown in **FIGURE 6a**, based on a microcoaxial waveguide resonator, operated with a DC power less than 5 mW and was typically run at ~2 mW; at this power level it produced about 0.25 mW of RF power at 3.4 GHz into a 50 ohm load. It could be tuned over ~3 MHz with a weakly coupled varactor diode. When the local oscillator is locked to the atomic resonance, its stability improves significantly, as shown in **FIGURE 6b**. Stabilities in the range of 10^{-10} at one second are typical of most current prototype chip-scale atomic clocks; the stability improves with increasing averaging time to about 10^{-11} at one hour. Often, the VCO is locked with a low-power phase-locked loop (PLL) to a 10 MHz quartz-crystal oscillator; this low-frequency oscillator then serves as the output of the clock. The use of such an oscillator increases the power required to operate the instrument but it improves significantly the phase noise. Also, the 10 MHz output frequency is more suitable for many applications. In addition, the modulation of the LO needed to lock it to the atomic resonance can be generated in the PLL leaving the 10 MHz output unmodulated.

A control system processes the output from the physics package and sends a signal back to the local oscillator to stabilize its frequency. This control system is typically implemented digitally with a low-power microprocessor. In addition to stabilizing the LO frequency, the control system also carries out other functions such as stabilizing the cell (and perhaps the laser) temperature, locking the wavelength of the laser to the center of the optical transition in the atoms, and monitoring parameters critical to the operation of the instrument such as the laser output power (see **FIGURE 7**).



▲ **FIGURE 6** The local oscillator subsystem of the NIST chip-scale atomic clock. (a) Photograph of the local oscillator, which is based on a micro-coaxial resonator at 3.4 GHz. (b) The fractional frequency stability of the local oscillator running both unlocked and locked to a large-scale, high-performance coherent-population-trapping physics package with large control electronics.

Performance

As previously mentioned, most CSACs have frequency instabilities in the range of 10^{-10} at 1 second, integrating down to something below 10^{-11} at 1 hour. The limitations for short integration times (between 1 and 100 seconds) are the rather large transition linewidth (typically several kilohertz at 6.8 GHz or 9.2 GHz) and modest signal size. The linewidth is determined primarily by the size of the vapor cell and is therefore a factor of 10 or more larger than the linewidth in larger vapor cell atomic clocks.

The instabilities at long integration times arise from several sources. Changes in the laser temperature cause time-varying AC Stark shifts (resonance frequency shifts associated with a changing light intensity), while changes in the cell temperature cause shifts due to changing properties of the interatomic collisions. While these shifts can be mitigated to some extent through design, cell and laser temperature stabilities in the 10 millikelvin range are still required over long time periods to maintain the 10^{-11} fractional frequency instability.

Current prototypes have a total volume of about 10 cubic centimeters and run on roughly 100 mW of electrical power. However, it is expected that new designs will reach the 1 cubic centimeter volume goal by the end of 2007. The 30 mW power goal will also probably be reached, but only for instruments without the 10 MHz output. An extra 10–20 mW will probably be needed to generate this 10 MHz output. It is interesting to compare the combined power-stability performance of chip-scale atomic clocks with other types of frequency references. As shown in **FIGURE 8**, a 30 mW CSAC capable of 1 microsecond timing over 1 day would be a significant departure from the tradeoffs that currently exist in the field of precision timing.

Reliability is a serious concern for all atomic clocks, but particularly for instruments that might be used in mission-critical technologies like GNSS. A major source of failure is the VCSEL that is used to drive the atomic resonance. In order to avoid having power-hungry cooling, the VCSEL temperature must be stabilized somewhat above the maximum of the expected range of ambient temperatures, which for some applications might be −40°C to +80°C. Recent results from accelerated lifetime testing have indicated that a VCSEL lifetime of more than six years is possible at an operating temperature of 90°C.

Applications to GNSS

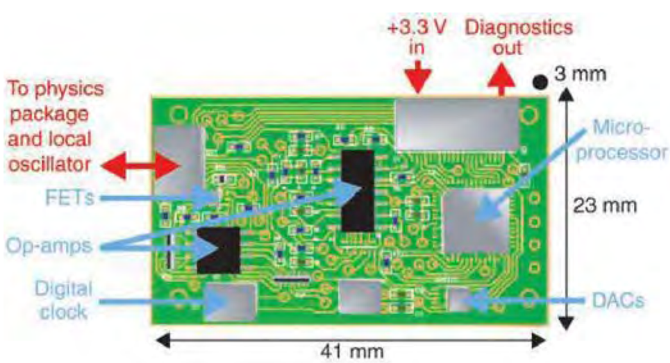
Small low-power atomic clocks could enhance the performance of GNSS receivers in a number of important ways. Perhaps the most significant of these is the enhanced code-acquisition capability that precise long-term timing allows.

In order to acquire a generic GNSS code, the receiver must do a search in both frequency and time and determine the unique receiver frequency and time that gives a high correlation between the receiver-generated code and the code received from the satellite. If the uncertainties in the receiver frequency and time are large, this search can require considerable processing power, particularly when the received signal is weak or when the code is long, as in the case of the GPS P(Y) code.

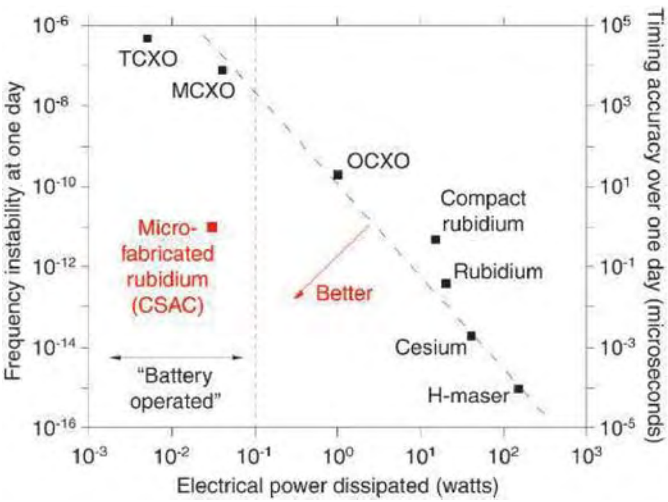
For example, in indoor environments where the signals from the satellites are attenuated by building material, the reduced signal-to-noise implies that a longer integration time is required to determine the correlation function for each time-frequency search bin. This in itself results in a longer code-acquisition time. In addition, a longer integration time means that each frequency search bin is narrower, and therefore that more searches are required to determine the correct receiver frequency offset. A precise knowledge of both frequency and time would enable the receiver to narrow the search window over both quantities and therefore acquire the code in a shorter time.

Similar considerations apply for acquisition of the P(Y) code, even under normal signal strength conditions, and these have implications with regard to sensitivity of the receiver to jamming and interference. For many (especially older) military receivers, P(Y) acquisition is done by first acquiring the C/A code, which has a much shorter code length, determining the time from this signal, and then using this time information to acquire the P(Y) code. While this acquisition process works well under many circumstances, it is considerably disadvantageous in a jamming environment, since the C/A code is broadcast over a much narrower bandwidth than the P(Y) code and is therefore much more susceptible to jamming. If a small clock is available to the receiver and timing to within 1 millisecond can be achieved over long periods, acquisition of the C/A code is not required.

Another advantage of precise time knowledge to GNSS receivers is that position can in principle be determined when fewer than four satellites are in view. Since the receiver time is a known variable, only three unknowns remain in the position-time solution and therefore only three independent pieces of information are required to trilaterate. This might be particularly important in urban environ-



▲ **FIGURE 7** A typical digital control system, noting the interfaces and some components, including operational amplifiers (Op-amps), field-effect transistors (FETs), and digital-to-analog converters (DACs). More highly miniaturized versions are possible by using a more compact layout and smaller components. It is anticipated that an application-specific integrated circuit would be developed for large market volumes.



▲ **FIGURE 8** Comparison of frequency reference timing stability and power requirement for CSACs and other devices including microprocessor-controlled and oven-controlled crystal oscillators.

ments, where buildings and other obstacles regularly impede the receiver's view of satellites.

Finally, a precise clock can allow a receiver on the Earth's surface to better determine altitude. Normally, the vertical component of the position solution is the least well known because of the effect of geometric dilution of precision and uncertainties in modeling atmospheric delay. Since the receiver cannot see satellites below the horizon, the time uncertainty in the receiver is more tightly connected with the vertical uncertainty in position than it is with the horizontal uncertainty.

Conclusion

Chip-scale atomic clocks, with a volume of 1 cubic centimeter and running on 30 mW of power, are nearing commercial reality. These instruments promise fractional frequency stabilities in the 10^{-11} range, allowing microsecond timing over one day and millisecond timing over one year. Atomically precise timebases for portable, battery-operated GPS receivers would allow a range of new capabilities including improved resistance to jamming and interference, faster acquisition time, and more reliable receiver operation.

These instruments are based on a convergence of three disparate fields: atomic physics, microelectromechanical systems, and low-power semiconductor lasers. Other instruments are also being developed based on similar fabrication methods and designs. These include atomic magnetometers with sensitivities approaching those of superconducting quantum interference devices (SQUIDS) and navigation-grade gyroscopes.

Acknowledgment

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