Report on the NIST workshop of December 10, 2009: calibration strategies for bridging possible climate data gaps

Raju U. Datla,[a*] Joseph Rice,[a] Catherine Cooksey,[a] Kurtis J. Thome,[b] Robert A. Barnes,[c] Changyong Cao[d]

[a]National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899 USA
[b]Goddard Space Flight Center (NASA), Greenbelt, MD 20771 USA
[c]Science Applications International Corporation, 4600 Powdermill Road, Beltsville, MD 20705 USA
[d]National Oceanic and Atmospheric Administration (NOAA), 5200 Auth Road, Suitland, MD 20746-4304 USA

ABSTRACT

A one-day workshop was held on December 10, 2009 at the National Institute of Standards and Technology to address the issue of data gaps in the time series of satellite measurements. Such gaps can occur due to launch delay, launch failure, inconsistencies, or data jumps in radiometric scales between satellites. The presence of such gaps limit the ability of using measurements to detect the small changes in key environmental variables that result from climate change. Leading experts in the Earth Observation community from the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Adminstration (NOAA), United States Geological Survey (USGS), and academia attended the meeting to prioritize the calibration strategies for bridging and mitigating satellite data gaps for climate change detection. These strategies include establishing SI traceability for satellite sensor calibration and measurements; continuing improvements in prelaunch, onboard, and vicarious calibrations and transfer standards; establishing celestial standards and procedures for intercomparisons; establishing SI traceability for alternative measurement strategies, such as in-situ networks and airborne sensor campaigns; and leveraging international satellite assets. This paper summarizes the workshop and recommendations.

Keywords: Climate data gaps, remote sensing satellite data, SI traceability, calibration

1. INTRODUCTION

Developing and implementing effective strategies for overcoming data gaps that occur in satellite sensor observations require considerable forethought. The requirements for high accuracy in observing climate change are applicable through any data gap and are critical for maintaining irrefutable climate records. Raju Datla of the Optical Technology Division at NIST, Changyong Cao of the Center for Satellite Applications and Research (STAR) of NOAA, and James Butler of NASA Goddard Space Flight Center organized the workshop on December 10, 2009 at NIST on behalf of their respective agencies to address the problem and recommend strategies for future planning. Fifty people attended the workshop. The one-day workshop began with invited talks in the morning and concluded with discussions and consensus recommendations in the afternoon.

Atmospheric and Environmental Remote Sensing Data Processing and Utilization VI: Readiness for GEOSS IV,
edited by Mitchell D. Goldberg, Hal J. Bloom, Proc. of SPIE Vol. 7811, 781105 · © 2010 SPIE
CCC code: 0277-786X/10/$18 · doi: 10.1117/12.861517

2. THE PROBLEM OF DATA GAPS IN CLIMATE MONITORING

The purpose of the workshop was rooted in recent Government Accountability Office (GAO),[1] Office of Inspector General (OIG),[2,3] and National Research Council (NRC)[4] reports that highlight concerns about possible disruptions in data records tied to the NPOESS[5] and NPP[6] operational satellite programs. For example, the OIG report, *Top Management Challenges Facing the Department of Commerce, Final Report No. OIG-19384*, states that such a disruption "could have serious consequences for the safety and security of the nation." The current practice for ensuring continuity in the climate data record relies on time series of overlapping satellite observations. Over the decades required to observe the small signatures expected for climate change, the failure of a sensor or satellite in an overlapping series is inevitable. The resulting gap impairs the assembly of a data records. Thus, the challenge for the participants was to identify strategies to address these possible data gaps.

3. GENERAL SOLUTION – SI TRACEABILITY

The general consensus among the workshop participants was that all remote sensing data for climate should be *Système International d'Unités* (SI) traceable. Such traceability is critical because long-term monitoring of climate change will inevitably involve piecing together data from multiple sources. This assemblage of the data record is made particularly robust when all measurements relevant to climate change are SI traceable to accepted physics-based, absolute scales. SI traceability is essential for bridging gaps across systematic variations of different sensor responses, regardless of temporal overlaps, and in maintaining the integrity of the climate data record. SI traceability needs to be done at both the national and international level since gap-filling may require the use of measurements from other nations.

Building upon this general consensus, the workshop participants then addressed the following questions: 1) What methods are to be used to establish SI traceability on orbit? 2) What are the possible alternative strategies to obtain reference data during failure or launch delay of a satellite sensor? and 3) How can the various U.S. agencies and international partners for climate remote sensing data coordinate their efforts regarding these issues? A series of invited speakers presented reviews of the current efforts to establish SI traceability on orbit, noted lapses, and suggested answers these questions. Their reviews are summarized in the following sections.

4. CURRENT EFFORTS – CLARREO

Bruce Wielicki and Martin Mlynczak, both of NASA Langley Research Center, described the features of the Climate Absolute Radiance and Refractory Observatory (CLARREO). CLARREO will provide benchmark measurements of the Earth's climate to meet the requirements for detecting and tracking the small changes associated with climate change. Success will require robust SI-traceability and high accuracy. CLARREO focuses on long time scales and large spatial scales in providing data to test and improve climate forecasts. The science objectives involve studying the anthropogenic forcing and the response of the climate system. CLARREO will also provide an opportunity for intercalibration with other operational sensors, which is critical for bridging gaps in other satellite observations over the course of the next several decades. The proposed optical sensors for CLARREO will cover the entire spectrum, the reflected solar from 320 nm to 2300 nm and the infrared from 5 microns to 50 microns. The traceability and accuracy achieved on orbit by CLARREO is expected to surpass all other measurements of the reflected or emitted Earth radiation. The CLARREO project team is working closely with NIST in all aspects of calibrations and SI traceable standards.

5. CURRENT EFFORTS – VIIRS: LEGACY OF MODIS

Jack Xiong and James Butler, both of NASA Goddard, reviewed the Earth Observing System's Moderate Resolution Imaging Spectroradiometer (MODIS) sensor and preparations for the next generation sensor, the Visible Infrared Imaging Radiometer Suite (VIIRS). MODIS is currently on-orbit in two satellites, Aqua and Terra, detecting a wide spectral range of electromagnetic radiation from the Earth with varying degrees of spatial resolution. The data obtained by MODIS provides information about land surface temperature and emissivity, land cover, surface reflectance, and vegetation indices that are used in numerous applications in the environmental sciences. At the time of its development, MODIS underwent a fairly comprehensive pre-launch calibration and characterization process, including radiometric calibration and characterization of spatial, spectral, and polarization response. In addition, MODIS has several onboard calibration capabilities, such as a NIST-calibrated solar diffuser and a solar diffuser stability monitor. MODIS measurements are also compared with those of other sensors in orbit. Despite these features, the lack of a system-level calibration, including for all planned measurement geometries, has resulted in poorly estimated uncertainties and difficulties in diagnosing on-orbit temporal changes in the uniformity of the solar diffuser.

VIIRS is expected to continue the scientific data records started by MODIS as part of NASA's NPOESS Preparatory Project (NPP). NASA is taking advantage of its previous collaboration with NIST and their joint experience calibrating and characterizing MODIS to improve the calibration and lower the measurement uncertainties of VIIRS. An example of such an improvement is the development of the NIST-built Flat Plate Integrator (FPI). The FPI is a white diffuser that can be illuminated by NIST Travelling SIRCUS tunable lasers or a Xenon arc source through fiber optic feeds. The FPI will be installed in the VIIRS test chamber where it will act as a tunable source with which to characterize the sensor. It will be used to validate the reflective solar band gains of the sensor after the instrument is on the spacecraft, provide an end-to-end calibration of solar diffuser earth view, and enable measurement of the out-of-band and in-band relative spectral response of the sensor in thermal vacuum. These activities are the first time that calibrations and characterization of this type will be done for a sensor in the solar reflective region. A similar effort is being planned for validating the VIIRS blackbody using NIST's Thermal Infrared Transfer Radiometer (TXR).

6. CURRENT EFFORTS – GSICS

Mitch Goldberg of NOAA spoke about the Global Space-based Inter-Calibration System (GSICS), which is an international collaboration launched by the World Meteorological Organization (WMO) and the Coordination Group for Meteorological Satellites (CGMS) to meet accuracy requirements for climate monitoring and improvement of Numerical Weather Prediction (NWP). GSICS plans to intercalibrate critical components of the observing system with climate quality benchmark observations. This will be accomplished by using simultaneous Nadir Observations (SNO) to compare measurements acquired by different satellite sensors when viewing the same Earth scene at the same time. There will be opportunities for measurement institutes, like NIST, to play a critical role in GSICS by establishing SI-traceability and uncertainties, and also for improving the community's understanding of the biases that become apparent during these intercomparisons. Particular opportunities include improving calibrations with the use of SI-traceable transfer standards, establishing SI traceability for lunar absolute calibration, and supporting the calibration of airborne sensors that collect climate data.

7. CURRENT EFFORTS – MOON: THE ROLO MODEL

Thomas Stone of USGS described his agency's efforts to calibrate the Moon in the reflected solar wavelength range. The purpose of the program is to develop a reliable standard for on-orbit radiometric calibration of solar-band instruments to allow the quantification of changes in sensor performance between pre-launch calibration and on-orbit operation. The USGS developed an analytical model to account for variations in the brightness of the Moon due to phase and libration based on observations made from Flagstaff, AZ using the Robotic Lunar Observatory (ROLO).[7] This model has been recognized by the operational programs in the US and in other countries for its value in monitoring the stability of sensors on orbit. For example, NOAA has instituted regular, dedicated observations of the Moon with the GOES satellites and the data is currently being used to improve the quality of the ROLO model. Unfortunately, the SI-traceability of the ROLO model is poor and the absolute uncertainty of the irradiances derived from the ROLO model vary from 5 % to 10 % ($k = 1$).

Developing the Moon as an SI-traceable, absolute reference for space-based radiometers would lower the calibration uncertainty to levels acceptable for long-term monitoring of climate change, and represent a significant improvement over the uncertainties obtained by the current best practices of measurement comparisons against well-characterized ground sites (i.e., vicarious calibration) or the use of an on-board solar diffuser system and stability monitor to measure the degradation of the reflectance of the solar diffuser. Thus, NIST, USGS and others are developing a project called Lunar Spectral Irradiance and Radiance (LUSI).[8] The NIST-led project would involve a multi-year campaign during which specialized instruments, designed and calibrated by NIST, will be used to obtain high accuracy, SI-traceable measurements of the Moon with continuous spectral coverage over the entire reflected solar wavelength range. A ground-based instrument suite, which will undergo regular calibration, will be located at an astronomical observatory site and operate for several years to obtain the necessary time series of lunar measurements. A second instrument suite will be flown on a high-altitude balloon, to acquire absolute lunar measurements above 99 % of the atmosphere. NIST will characterize and calibrate both sets of lunar radiometer instruments prior to deployment and perform pre- and post-flight calibrations for the balloon-based suite. The resulting lunar model will be based on the ROLO irradiance model and aim to achieve an uncertainty of 0.5 % ($k = 1$).

8. CURRENT LAPSES AND CHALLENGES

Microwave sensors observe climate parameters important for maintaining atmospheric temperature, sea-surface temperature, and water-vapor records. However, the development and implementation of transfer standards for the calibration of microwave sensors lags behind that of other sensors, such as those in the solar reflected region. Fuzhong Weng of NOAA spoke about the microwave sensors and their current calibration methodologies, noting that each microwave sensor is different, and that there is lack of community effort to define SI traceability, develop needed reference standards, and establish pre-launch calibration methods.

Establishing standard methods for calibration and intercalibration is becoming increasingly important for NOAA's National Climate Data Center (NCDC) whose mission is to archive and produce weather data and products. John Bates of the NCDC explained that there is interest in creating a climate information record in which the climate data records are applied to particular problem, such as monitoring long-term changes in tropical cyclone intensity or assessing the cycles of water, energy, and carbon. This requires highly accurate measurements over time scales ranging from seasonal to inner-annual to decadal, and that all of the processes involved in retrieving climate variables from fundamental measurements, such as observed radiance, and creating the climate information record must be calibrated and uncertainties propagated through well understood processes.

The need for agencies within the US that participate in the development, implementation, and operation of satellites to undertake a more consistent, consolidated approach for improving the calibrations of operational satellites has been recognized. Al Powell of NOAA's Center for Satellite Applications and Research (STAR) described NOAA's proposal to create a National Calibration Center. The center would be designed to encourage cooperative interactions between NIST, NOAA, NASA, and other agencies to identify and implement strategies for the improvement of the calibration of operational satellite systems using expertise from the three agencies.

9. GROUP DISCUSSION AND RECOMMENDATIONS

Changyong Cao of NOAA and Joseph Rice of NIST facilitated the general discussion during which representatives from each breakout group presented the results of their discussion. The breakout groups included: Land Variables led by Kurtis Thome, Atmospheric Variables led by Joe Rice, and Clouds and Oceans led by Robert Barnes. Based on the reports from each discussion group, a list of critical climate variables whose data records are susceptible to data gaps and a list of strategies for managing gaps in the climate data record were compiled. Table 1 summarizes the climate variables identified by each group as well as the corresponding sensor type to measure the variable and required accuracies for climate monitoring. The strategies are provided below in sections 9.1 and 9.2. These activities are varied and applicable to all agencies that have space sensors providing Earth remote-sensing data. Because of NIST's role as a National Measurement Institute and its history as a collaborator in calibrating Earth remote-sensing instruments, there was a natural progression in the discussion of strategies to recommend specific tasks to NIST. These recommendations are provide in section 9.3.

Table 1. Critical climate variables identified by the three breakout groups as susceptible to data gaps. The instruments and accuracy given as a relative uncertainty in percent or as an absolute uncertainty in K or W m^{-2} required to monitor each variable are also listed.[*, †]

Classification	Variable	Instrument	Uncertainty Requirement (k=1)
Land	Vegetation	Vis radiometer	2 %
	Albedo	Vis radiometer	5%
Atmospheric	Temperature	MW or IR radiometer	0.5 K
	Ozone	UV/Vis Spectrometer	3%
	Water vapor	MW radiometer	1.0 K
		IR radiometer	1.0 K
	Precipitation	MW radiometer	1.25 K
	Clouds	Vis/IR radiometer	1 K
	Aerosols	Vis polarimeter	3 % (radiometric)
			0.5 % (polarimetric)
	Greenhouse gases	IR radiometer	3%
Clouds and oceans	TOA radiances	Broad band IR	1 W/m^2
	Sea surface temperature	IR radiometer	0.1 K
		MW radiometer	0.03 K

[*] Ohring, G. et. Al. (2004) "Achieving satellite instrument calibration for climate change," NISTIR 7047.
[†] TOA: top of atmosphere; Vis: visible; MW: microwave; IR: infrared; and UV: ultraviolet.

9.1 Strategies for bridging a gap, i.e. accounting for sensor-to-sensor bias variations

- *Pre-launch calibrations* and *Onboard calibrations* – All spaceborne and aircraft sensors should be required to undergo thorough SI traceable calibrations prior to launch and on-orbit. These calibrations should include component characterization and end-to-end system characterization of the spectral response of the sensor under operational scenarios to build a robust model of sensor performance and should follow the procedures outlined in Reference 10. A sensor-by-sensor study should also be undertaken by respective agencies, before launch, with a risk analysis and impact study to outline strategies for overcoming gaps. Onboard calibration standards should be available for sensors to maintain SI-traceability while on orbit.

- *Celestial standards* – High-resolution spectral calibrations of the Moon and stars, such as Vega, should be made to establish these celestial bodies as on-orbit, absolute reference standards. These standards would enable on-orbit characterization of instruments and could be used to determine any changes resulting from the launch of the instrument. The calibration of sensors against these standards should be integrated into the instrument designs and operational procedures of the sensors. For example, spacecraft in low Earth orbit should have the ability to maneuver to view the Moon through their nadir-viewing optics.

- *Intercomparisons* – Procedures should be established to enable intercomparison of sensors between satellites, both foreign and domestic. Such comparisons are crucial for monitoring and correcting measurement biases in instruments, which often change as the sensors age. The community should support the activities of GSICS (Global space-based inter-calibration system), an international collaboration established to enable inter-satellite calibration and encourage pre-launch characterization and SI-traceable calibration activities.

- *Ground-based vicarious calibrations* – Ground sites should be characterized to provide low-uncertainty, SI-traceable reference data for the calibration of spaceborne and aircraft sensors in the visible and reflected-solar infrared. Mechanisms to ensure the long-term maintenance of these ground sites are needed.

9.2 Strategies for mitigating a gap, i.e. filling the gap with data obtained by alternate means

- *Airborne sensor campaigns* – Airborne sensor campaigns should be considered as an alternative means for collecting data during failures or launch delays of satellites sensors. The sensors should be SI-traceable and calibrated in a manner consistent with their spaceborne counterparts. To improve the uncertainty of data from aircraft campaigns, there should be better characterization of the atmosphere to understand biases in models, such as radiative-transfer models. Agencies with capabilities to undertake airborne campaigns should establish sufficient mission readiness if a data gap occurs and measurements are necessary to ensure continuity in climate data record.

- *Foreign or other satellite assets* – The community should leverage its involvement in GSICS to acquire data from foreign or other satellite assets in the event of the failure of a particular satellite or sensor. These assets should be SI-traceable and calibrated.

- *Radiosonde measurements* – Data provided by *in situ* measurements such as radiosondes, for example, through the GRUAN (GCOS Reference Upper Air Network) network, are critical and should be considered in future plans for mitigating data gaps. Radiosondes measure the important atmospheric climate variables directly and can validate satellite observations. Effort should be made to improve the quality of these measurements and establish their SI traceability.

9.3 Recommendations for NIST

- NIST should develop SI-traceable standards for microwave sensors to include brightness temperature standards and antenna characterization standards. The standards should have uncertainties that meet the requirements for calibrating the microwave sensors at low enough uncertainty to detect the signatures of climate change. The current lack of needed microwave standards increases the risk of not having a SI traceable linkage across a gap to provide data continuity.

- NIST should continue its efforts in improving pre-launch calibrations for space and aircraft sensors and disseminating those calibrations to the aerospace industry. In particular, NIST should facilitate end-to end, system-level calibrations of sensors and actively deploy transfer standards, such as Travelling SIRCUS (Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources) for the reflected-solar region. Additionally, SIRCUS capabilities need to be extended to longer wavelengths in the infrared as infrared laser technology advances. Also, the thermal infrared transfer radiometer (TXR) should be available for easy deployment at user facilities for characterization of the emissivity and validation of the radiance of infrared sources used for calibrating space bound IR sensors.

- NIST should facilitate improvement in on-board calibrations. NIST should provide a service for calibrations of space-deployed solar diffusers. Direct calibrations of onboard artifacts will eliminate intermediate steps in the calibration chain and reduce the onboard artifact calibration uncertainties.

- NIST should develop new on-board standards such as stable lasers and laser diodes for space deployment. An example of the need is seen for the CERES sensor, which would benefit from a temporally, spectrally, and spatially stable, high-accuracy optical radiation standard at 0.4 microns.

- NIST should implement the LUSI project to establish the Moon as an SI-traceable absolute radiometric standard to allow high-accuracy absolute radiometric calibration of sensors and long-term monitoring of the stability of sensors. This project should complement the NIST Stars program, which is developing a set of standard reference stars.

- NIST should be involved in the characterization and calibration of ground sites for vicarious calibrations.

10. SUMMARY

Detecting the small signatures of climate change represents a formidable measurement challenge. Highly accurate and consistent measurements made over long periods of time are required. To minimize disruptions to the climate data record and maintain irrefutable climate records, participants at the workshop agree in the need to improve the SI traceability of remote sensing measurements for climate. Various strategies to ensure SI traceability on orbit and to mitigate data gaps were recommended, and the need to coordinate across agencies to implement strategies was emphasized.

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*rdatla@nist.gov; phone 301-975-2131; fax 301-975-2950

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[5] National Polar Orbiting Environmental Satellite System (NPOESS) is the next generation of low earth orbiting environmental satellites. The program is managed by personnel from NOAA, NASA, and the Department of Defense. (Note: In February 2010, the US Government cancelled the program and a restructuring is underway.)

[6] NPOESS Preparatory Project (NPP) aims to ensure the continuity of climate measurements between heritage sensors and the next generation sensors used by NPOESS.

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