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Sensor Calibration and Characterization to Meet Climate Monitoring Requirements

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***Abstract*— The challenge of detecting small changes in the Earth's climate system over decadal and longer time scales places stringent requirements on environmental monitoring systems. Sensors must be well calibrated and maintain their calibration in challenging environments: space, oceans, mountains, tropics, polar regions, and deserts. Additionally, the assembly of regional and global time series for environmental variables, such as sea-surface temperature, vegetation coverage, and soil moisture, requires the integration of measurements from a variety of sensors of different designs, operated by different organizations, and acquired at different times. Success requires sensors that are calibrated and recalibrated against standards tied to the International System of Units (SI) to ensure that measurements are physics-based and comparable between nations, organizations, and over generations. The present talk will provide an overview of research and dissemination efforts at NIST to advance the calibration and characterization of sensors, highlighting satellite-based sensors, for application to measurements in support of climate science.**

Keywords—calibration, climate change, climate research, radiometry, satellite sensor, sensor calibration, traceability

I. Introduction

Despite the finding [1] that the “warming of the climate system is unequivocal” and that “it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century” there remain many questions about the Earth’s climate. How much is the Earth warming and how fast? What is the impact of global warming? How will the regional effects of climate change compare with the global effects? Are there mitigation strategies, and are they working? Are there new, unexpected anthropogenic threats to the climate?

To answer these questions, climate scientists have devised two strategies to help quantify the magnitude and rate of climate change. The first involves understanding what the key climate variables are and how they interact so that climate scientists can create models to predict trends. The second involves extrapolating measured time series from the existing climate data records to determine the trend. The former requires high-quality models that are guided and validated by targeted measurements of climate variables, while the latter requires long-term, continuous measurement of climate variables. These measurements can be used to assemble data records at the global or regional level.

Obtaining the data used for both strategies poses unique challenges to climate scientists. Measurement of climate variables requires extremely high accuracy to detect the small changes indicative of climate change amid the variations in the climate system due to short-term weather phenomena and multi-year oscillations, such as due to El Niño and La Niña. Accuracy is also desired to reduce the time necessary to capture a trend. Furthermore, measurements of climate variables must have low uncertainties to ensure a high level of confidence in climate trends and predictions. The points were clearly illustrated in a recent study by Wielicki *et. al* [2]. They found that reducing the measurement uncertainty (k = 2) for temperature from 0.30 K to 0.06 K, as determined from a satellite-based thermal infrared sensor, reduced the time required to detect a decadal temperature trend of 0.1 K from 40 years to 20 years.

At NIST, we have been attempting to provide the infrared and optical radiation measurement infrastructure necessary for climate scientists to obtain accurate data with low uncertainties. Other national measurement institutes such as the National Physical Laboratory (NPL, UK) and Physikalisch-Technische Bundesanstalt (PTB, Germany) are also active in such efforts. This is a challenging problem that requires a multidisciplinary approach since the measurement chain from raw instrument counts to climate variables to climate models to predicted trends is often long with uncertainties propagating along each step.

The NIST effort encompasses collaborations with NASA and NOAA to establish rigorous traceability of infrared and optical environmental measurements to the International System of Units (SI), development of measurement capabilities to provide high accuracy calibrations of environmental sensors (including satellite sensors), and dissemination of guidance on best practices for acquiring measurements [3]. In this paper, we discuss the importance of establishing traceability to the SI (Section II), provide an example of a measurement requirement for monitoring climate change (Section III), describe examples of how NIST is meeting other measurement requirements (Section IV), and provide a summary (Section V).

II. Traceability in Measurements

Accurate, long-term climate data records require the integration of measurements from multiple instruments and organizations. This process is made particularly robust when all measurements relevant to climate change are traceable to accepted physics-based, absolute scales based on the SI. According to the International Vocabulary of Metrology, traceability is defined as a property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties [4]. Such an unbroken chain is essential for comparing scales and fundamental physics-based models and providing comparability across generations, geographical borders, organizations, and instrument and measurement types. Additionally, traceability facilitates bridging gaps in the climate data record and mitigating gaps when sensor failures occur.

To establish confidence in the traceability chain, management system is recommended for each step of the calibration and measurement process. This system documents the processes used to establish traceability and the methods applied to validate the measurements. Such a system is currently employed by National Metrology Institutes (NMIs) to establish comparability of scales internationally. In accordance with the International Committee for Weights and Measures (CIPM) Mutual Recognition Arrangement (MRA) [5], NMIs document and validate methods of scale realization by various means of peer review. Multi-lateral measurement comparisons are then organized to assess the comparability of scales and uncertainties. Based on these comparisons, NMIs engage in research to further improve their realization methods and lower uncertainties. Climate scientists can leverage the experience and expertise of NMIs to establish traceability throughout their measurement chain.

The level of effort, and thus amount of resources devoted to establishing and maintaining traceability of measurements, depends on the uncertainty requirements for the measurements and the consequence of not meeting these requirements. As summarized in Fig. 1, a high quality traceability claim that might be required for a climate benchmark satellite sensor, for example, would require significantly more effort establishing and maintaining SI traceability throughout the lifetime of the sensor than the low quality traceability claim for an imaging satellite primarily collecting black and white or color imagery.

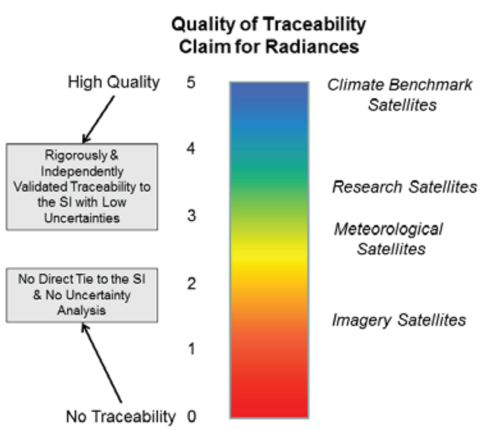

Fig.1. Required quality of traceability claim for radiances from the Earth as measured at the top of the atmosphere for different types of environmental satellite sensors.

III. Measurement Requirement Example: The Earth's Radiative Balance

Establishing the measurement requirements for a given sensor is key to guiding the design of the sensor and developing the calibration requirements for the sensor. Here, we consider the space-based measurement of the Earth's radiative balance as a simple example of determining such requirements and to demonstrate that the requirements are extremely stringent for monitoring the Earth's changing climate.

The change in the surface temperature is related to the radiative forcing through the following expressions [6],

$$\Delta T_s = \lambda \, \Delta F \qquad (1)$$

Where ΔT_s is the change in surface temperature, induced by a climate forcing, ΔF, and λ is the climate sensitivity which varies with model and type of forcing, but is approximated here as 0.8 K W^{-1} m^{-2}. The radiative forcing of the Sun and the Earth's albedo are given approximately by

$$\Delta F_{\mathrm{Sun}} = \tfrac{1}{4}\,(1 - \alpha)\,\Delta S \qquad (2)$$

$$\Delta F_{\mathrm{albedo}} = -\tfrac{1}{4}\,(\Delta\alpha)\,S \qquad (3)$$

where α is the Earth's albedo of $\cong$ 0.3 and S is the solar irradiance of $\cong$ 1361 W m^{-2}. Using these expressions, we find that a 0.1 % change in solar irradiance, on the order of the magnitude of the change during the solar cycle, corresponds to a 0.19 K change in the surface temperature, whereas a 0.1 % change in the Earth's albedo corresponds to a 0.08 K temperature change. To detect a 0.2 K change in the Earth's temperature per decade suggests a measurement requirement for incident solar and reflected solar radiation per year of $\approx$ 0.01 % and $\approx$ 0.03 % respectively. Measurements of incident solar radiation are now approaching this level of accuracy [7].

IV. Meeting the Requirements

Generally, a space-based sensor must be calibrated prior to its launching. There are two approaches to the prelaunch calibration of a satellite sensor, a component-level calibration and a system-level calibration. For the former approach, the individual components of the sensor are calibrated and a model of the optical system is used to obtain the system-level calibration. For the latter approach, the sensor is directly calibrated as a system by using standard radiometric sources to mimic the on-orbit observations. In practice, both approaches should be used to provide a check on each calibration result. Further, a validated component-level model is critical for addressing any issues that may arise post-launch, such as damage to an optical component. Examples of NIST's efforts in enabling these two approaches are described below in parts A and B. In addition to prelaunch calibrations, a strategy should be employed to continually monitor and update the calibration throughout the lifetime of the sensor while on orbit. NIST's effort in this area is described below in part C.

A. *Component-Level Calibration*

At the component level, calibrations important for a space-based sensor may include measurements of filters for transmittance, mirrors for reflectance, and diffusers for the bidirectional reflectance distribution function (BRDF). Diffusers are typically plaques of pressed or sintered polytetrafluoroethylene (PTFE), due its nearly perfect Lambertian reflection properties. They are used as on-board calibrators for visible-to-near-infrared sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), or the Operational Land Imager (OLI). The BRDF of these diffusers is measured relative to BRDF standards whose reflectance values are traceable to NIST or other NMI measurements. An intercomparison to assess the transfer of the NIST BRDF scale from 440 nm to 940 nm to the satellite sensor laboratories, which calibrate the space-bound diffusers, demonstrated a typical level of agreement with the NIST values of better than 2 %, limited, in part, by the measurement uncertainties of the non-NIST instruments [8]. NIST uncertainties over the range studied for a pressed PTFE standard were approximately 0.25 % ($k = 1$). In comparison, the requirements for the near-infrared to visible spectrometer for the proposed Climate Absolute Radiance and Refractivity Observatory (CLARREO) is 0.3 % ($k = 2$) for the Earth's mean reflectance [2].

Efforts are required to both improve the quality of the reflectance measurements used for the prelaunch calibration of space-based diffusers and to find alternative materials for use as reflectance standards. To achieve the former effort, NIST has recently expanded its reflectance capabilities to include measurements of BRDF in the shortwave infrared for limited measurement geometries [9], and NIST is developing a new reflectance facility, which aims to provide measurements at a wider range of reflectance geometries to better match on-orbit geometries and to accommodate larger plaque sizes to shorten the measurement chain [10].

The motivation for the latter effort is based on the observation that PTFE-based diffusers significantly degrade on orbit. The Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) saw degradation levels of as much as 12 % depending on wavelength, over approximately 2000 days of operation, attributed to diffuser degradation [11]. NIST is planning on studying new materials, such as ceramics, to determine how prolonged solar radiation affects their reflectance properties.

B. System-Level Calibration

System-level calibration of an infrared or optical satellite sensor has generally involved the use of either a large-aperture thermal infrared blackbody source for the calibration of Earth-viewing infrared sensors and imagers or a lamp-illuminated, large-aperture, integrating sphere source for visible sensors and imagers.

Generally, the radiance level of a thermal infrared blackbody is traceable through contact thermometry to the International Temperature Scale of 1990 (ITS-90), an operational approximation to the kelvin, as disseminated by NIST and the other NMIs. NIST's thermal-infrared cryogenic Transfer Radiometer (TXR) is used for validating the radiometric performance of these blackbodies. It is calibrated relative to the well-characterized NIST Water-Bath Blackbody (high emissivity with a 10 cm aperture) and is able to measure the brightness temperature of blackbodies used for satellite-sensor calibration to better than 150 mK at 5 µm and 10 µm relative to ITS-90 [12].

In the visible region of the spectrum, NIST calibrates portable, lamp-illuminated integrating spheres for sensor developers, which the developers then use in their calibration process for Earth-viewing sensors. NIST has also developed radiometers, such as the Visible Transfer Radiometer (VXR) [13], that are calibrated at NIST and then deployed to sensor developer sites to validate the radiometric scales used in the calibration of the satellite sensors. An intercomparison of 10 radiance scales between the wavelength range of 411 nm and 777 nm used within the remote sensing community revealed a level of agreement of approximately 2 % for 8 of the participants. The results for two of the participants were significant outliers due to experimental issues discovered through participation in the intercomparison [14].

The challenge with integrating sphere sources for the calibration of sensors and imagers is that the spectral distribution from these sources does not match the spectral distribution of the Earth that the satellite sees on orbit. For example, typical lamp-illuminated integrating spheres produce significantly less short-wavelength radiance compared to the amount that satellites sensors detect when measuring the reflected solar radiation from the Earth. This spectral mismatch thwarts achievement of a desired scenario in radiometry, which is to have the absolute spectral and spatial distribution of the calibration source match as closely as possible that of the eventual target of interest. The absence of such a match can lead to significant calibration errors due, for example, to stray light.

For calibrations with more stringent measurement requirements, NIST has developed the Facility for Spectra Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) [15] to map out the absolute spectral responsivity of a sensor as a function of wavelength as shown and described in Fig. 2. SIRCUS also enables the quantification of wavelength-dependent stray light.

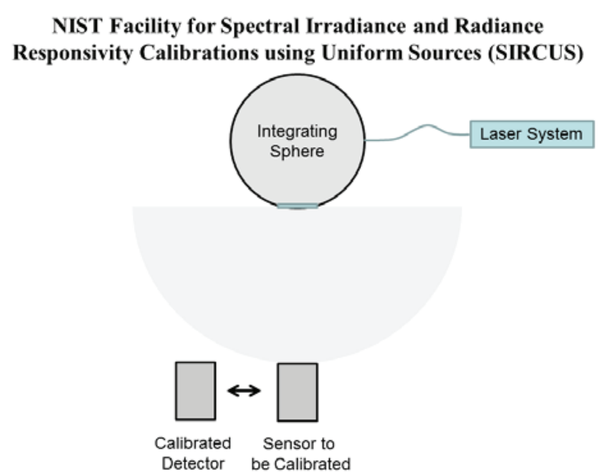

Fig. 2. Schematic of the NIST SIRCUS Facility. A tunable, single-frequency laser illuminates an integrating field to create a source of uniform radiance. The radiance output is calibrated by a detector referenced to a cryogenic radiometer. The sensor to be calibrated also views the source and measures its output. This process is repeated for multiple wavelengths.

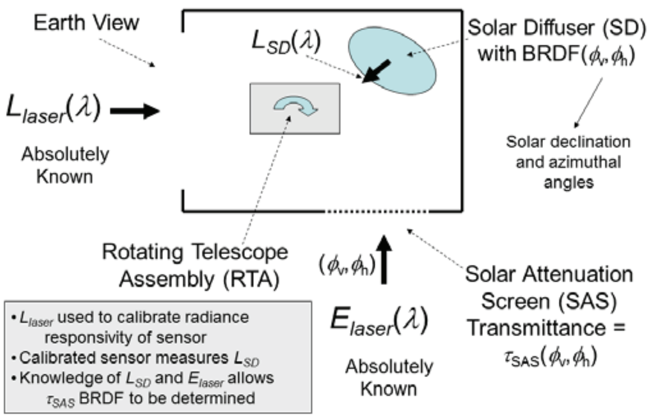

Fig. 3. Schematic diagram showing the SIRCUS-based system-level calibration of the VIIRS sensor. Tunable, single-frequency lasers illuminate an integrating sphere, which provides a source of absolute radiance to mimic the Earth, and feed a collimator, which provides a source of known irradiance to mimic the Sun. The response of the sensor is recorded for each wavelength as it views the Earth port and the solar diffuser.

The SIRCUS capability has been applied to the full system-level calibration of the VIIRS sensor on the Suomi National Polar-orbiting Partnership weather satellite as illustrated in Figure 3 [16]. A laser-illuminated integrating sphere is viewed by the sensor through the Earth view port and a collimated laser is sent through the solar attenuation screen to illuminate the solar diffuser for viewing by the sensor. Data are acquired by the sensor for a range of wavelengths. The measurements allow an assessment of both the in-band and out-of-band response of the sensor and assess the performance of the instrument as a reflectometer.

The next step in complexity for the calibration of an imaging-type sensor is to incorporate the effects of a spatially, spectrally, and temporally varying scene. NIST has developed the Hyperspectral Image Projector (HIP) to provide a dynamic, spatially and spectrally variable scene to an imaging system [17]. The HIP uses micromirror array technology to provide such calibrated scenes to an imaging system. The scene can be the reprojected scene captured using a hyperspectral imaging system, a modified experimental scene to include, for example, a modified water column added using atmospheric radiative-transfer models, or a purely synthetic scene generated from modeling and simulation tools.

C. Space-Based Standards

Earth remote-sensing scientists have long recognized the value of viewing the Moon as a method to track changes in sensor performance [18] and as an on-orbit standard to connect measurements across gaps or interruptions in satellite and sensor coverage [19]. The reflectance of the Moon is constant due to the lack of an atmosphere and plate tectonics. Furthermore, the Moon's surface has not recently experienced any significant impacts and has been exposed to billions of years of solar radiation, so that the chemical composition and thus reflectance is unchanging.

Measurements of the Moon made by the Robotic Lunar Observatory (ROLO) led to the development of the ROLO Lunar Model, which enables the determination of the irradiance at the sensor aperture from the Moon as a function of lunar phase and libration angles [20]. This model has been compared against space-based satellite measurements from SeaWiFS [9]. The Moon, together with the ROLO geometric correction and knowledge of the solar irradiance, has been demonstrated to be an excellent standard for tracking satellite degradation.

However, lunar measurements are not of sufficient accuracy to use the Moon as a standard for the absolute calibration of satellite sensors or for validating the absolute radiometric scales of such sensors. Currently, the uncertainty on the lunar irradiance is estimated at between 5 % and 10 % [21]. To improve the accuracy of measurements of the Moon's irradiance, NIST established a measurement capability at an altitude of 2.4 km on Mt. Hopkins in Arizona [22]. The measurements were made using a 106 mm refracting telescope with a 50.8 mm diameter integrating sphere capturing the light at the focus. The light from the integrating sphere was coupled by an optical fiber to a spectrograph. The irradiance measurement system was calibrated relative to NIST radiometric standards, and atmospheric corrections were modeled using observations at various air masses together with atmospheric models and satellite and weather data. The results have estimated uncertainties of less than 1 % for regions between 420 nm to 1000 nm where atmospheric water vapor and oxygen lines are absent. Future efforts will require observations at additional phase and libration angles, at higher altitudes (such as on Mauna Loa, Hawaii), and validation through balloon or aircraft measurements.

V. CONCLUSION

Detecting the small changes in the Earth's climate system represents a formidable measurement challenge, which requires highly accurate measurements made over long periods of time. To maintain a high level of confidence in climate trends and predictions and minimize disruptions in the climate records, rigorous traceability to the SI is essential. NIST has, and continues, to work with climate scientists to meet the measurement demands of detecting climate change through various strategies such as the development of improved measurement capabilities and guidance on best practices for measurements acquisition.

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