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Sensor Calibration in Support for NOAA's Satellite Mission

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ABSTRACT

Sensor calibration, including its definition, purpose, traceability options, methodology, complexity, and importance, is examined in this paper in the context of supporting NOAA's satellite mission. Common understanding of sensor calibration is essential for the effective communication among sensor vendors, calibration scientists, satellite operators, program managers, and remote sensing data users, who must cooperate to ensure that a nation's strategic investment in a sophisticated operational environmental satellite system serves the nation's interest and enhances the human lives around the world. Examples of calibration activities at NOAA/NESDIS/ORA are selected to further illustrate these concepts and to demonstrate the lessons learned from the past experience.

Key words: calibration, sensors, instruments, satellites, operations, remote sensing

1. Introduction

The National Environmental Satellite, Data, and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA) provides satellite services to the United States and the world for weather prediction and environment monitoring. As part of these services, NESDIS is responsible for the sensor calibration of the "NOAA satellites" consisting of a constellation of the Polar-orbiting Operational Environmental Satellite (POES) and the Geostationary Operational Environmental Satellite (GOES). The Sensor Physics Branch of the Office of Research and Applications (ORA) provides scientific guidance for sensor calibration. Information about the NOAA satellite systems, including the sensor packages and their characteristics, is readily available elsewhere (Rao et al., 1990; Kidwell, 2000; Menzel and Purdom, 1994).

This paper grew out of a presentation at the Third International Chinese Ocean-Atmosphere Conference, 28–30 June 2004, in Beijing, China, which also elaborated on the history, organizational structure, personnel, and operational procedures of sensor calibration at NOAA/NESDIS/ORA. These topics have been largely eliminated in the present paper. Instead, the part on the basics of satellite sensor calibration has been expanded. It is believed that a proper understanding of these basics is essential for the effective communications among sensor vendors, calibration scientists, satellite operators, program managers, and remote sensing data users. It is also a part of the basis for international collaboration among the users of the same satellite system and among the calibration scientists of various satellite systems.

Some examples of the calibration activities were presented at the conference and have been included in this paper. These examples are by no means a comprehensive representation of the calibration activities at the NOAA/NESDIS/ORA for NOAA satellite operations. Mission support for system configuration and requirements, oversight of calibration requirements compliance, review of pre-launch calibration procedure and results, post-launch verification of sensor performance, re-calibration of historical satellite archives, consultation to worldwide users, long-term monitoring of instrument health, international cooperation and collaboration, and many other activities are not adequately covered, if at all. While all

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these are important, they are based on the basic concepts to be discussed.

2. Basics of satellite sensor calibration

2.1 *Definition of sensor calibration*

Sensor calibration can mean different things. First of all, it should be clarified that our attention is on the sensors. It is not uncommon to encounter phrases like "data calibration" or "algorithm calibration", the purpose of which is to make certain data or algorithms to behave in an expected way. There are legitimate reasons for those activities, which can be described as calibration. However, those calibrations are different from the sensor calibration to be discussed in this paper.

There is a great variety of sensors. For a spaceborne passive radiometer, which is a highly specialized and small subset of remote sensing instruments but nevertheless includes all sensors currently on NOAA satellites, sensor calibration can still be further divided into spatial, spectral, and radiometric calibration. The former two determine, respectively, where the signals come from spatially and spectrally; the latter one determines the intensity of the signals. Although these calibrations are not totally independent of each other, this paper primarily focuses on the radiometric calibration, with some consideration of spectral calibration.

Radiometric calibration is the quantification of sensor responses to known signals. The purpose is to infer unknown signals from sensor responses (measurements) during the sensor's duty cycle. There are two central issues in radiometric calibration. One is whether the quantification is in sufficient detail. For example, if a sensor is known to have nonlinear response to signals but is calibrated with only two sources of radiation, or if the calibration cycle is infrequent relative to a sensor's operating environment, the inferred signals will have a larger uncertainty. This paper, however, focuses on the other central issue, i.e., how well-known are the known signals.

2.2 *Complexity of sensor calibration*

The simplest calibration of a linear sensor can be carried out by determining its responses to two known signals, as illustrated schematically in Fig. 1 for a thermometer. While straightforward, sensor calibration can become complicated when one questions about the "known signals". For example, when the thermometer is in a mixture of ice and water to mark the value of 0°C, is the water perfectly pure so its freezing point is indeed 0°C? Similarly, is the atmospheric pressure exactly 1013.25 hPa so that the water's boiling point is 100°C? Is the thermometer's response to varying temperature precisely linear, considering the inside diameter of the tube, the mass of liquid in the bulb, and so on? Is there a temperature gradient within the ice and boiling water? Is the thermometer in thermal equilibrium at each measurement? Questions like these remind us that what we have taken for granted as "know" is in fact uncertain upon close scrutiny. And all these seemingly minor uncertainties could potentially become issues as the requirements on calibration

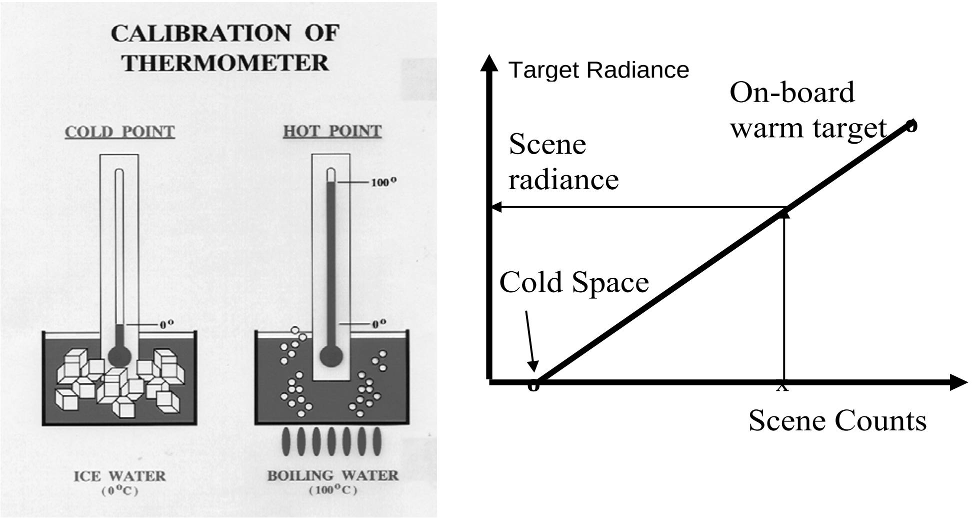

Fig. 1. Schematic illustration of sensor calibration. On the left panel is the calibration of a thermometer in which one puts the un-calibrated sensor into ice water to mark 0°C, into boiling water to mark 100°C, and evenly divides the distance between the marks for other temperature readings. On the right panel is an analogy for calibration of a radiometer.

quality become higher and higher. Surprisingly, many of the issues in this simple illustration have an analogy in real world satellite sensor calibration.

The operation of a sensor is a dynamic process, in which many conditions change with time. A polar satellite typically experiences "day" and "night" about every 100 minutes, and the duration of "day" and "night" and the solar heating all change with season. Meanwhile, the radiation from the earth below also changes with the land-sea distribution and clouds, etc., which can add to the uncertainty if the sensor is not well protected from the earth shine. All such external environment of measurement can be different if the sensor is flown in a different orbit. For a little more complexity, earlier satellites (up to NOAA-14) also suffered from orbit degeneration (drift). For a three-axis-stabilized satellite in a geosynchronous orbit, such as the current GOES system, the diurnal variation of temperature is an order of magnitude larger than that for POES. Finally, all sensors, including their calibration components, age with time. As the vital link between the goal of accurate, precise, and stable scientific data and the actual sensor measurements subject to all these uncertain and changing conditions, sensor calibration is a daunting yet important endeavor.

2.3 *Traceability of sensor calibration*

Traceability of sensor calibration is an often overlooked topic (Johnson, 2004). Ideally, all sensor measurements should be related to a universally accepted standard, such as the Système International (SI), and the relation should be traceable to the artifacts carefully selected by a national authority such as the National Institute of Standards and Technology (NIST). This would enable measurements by all sensors to be comparable with each other, and comparison is often the key objective of an observing and monitoring system.

The practice in the real world is less than ideal due to technological, fiscal, and other constraints. In some cases, for example the visible and near infrared channels of the NOAA satellites and their Chinese counterparts, the sensor is only calibrated before launch but not in orbit. To the extent that the sensor performance is reasonably stable within a short period of time (e.g., during imaging), these measurements are effectively calibrated to an implicit (albeit slowly-changing) reference such that measurements within the image can be compared with each other. These measurements, therefore, are adequate for synoptic analysis of cloud systems or land surface features, in which one compares the radiation intensity among nearby regions measured within a short period of time. Furthermore, vicarious calibration using external references can mitigate some of the deficiencies caused by the lack of onboard calibration for these sensors, although it is difficult to completely remove all these deficiencies for many quantitative applications.

For climate monitoring, one compares radiation intensity in a much extended spatial and/or temporal domain. Stability is of paramount importance in these applications, not only of one sensor over its mission life time but also of series of sensors operated in parallel ("morning" and "afternoon" POES, "east" and "west" GOES) and in succession. Because climate change signals are typically small and detectable only over a long period of time, the requirements on the accuracy and precision of radiometric calibration, as well as on the spectral calibration of the sensors, are extremely high. However, it can still be argued that measurements by one sensor at one time can be chosen as a reference, which is not necessarily traceable to the NIST standard. As long as all measurements can be calibrated through "inter-satellite calibration", they are comparable and the climate can be monitored.

A continuing trend in satellite remote sensing is that the measurements are used for many purposes, some of which were not anticipated before the measurements are made. The Advanced Very High Resolution Radiometer (AVHRR) is a good example (Cracknell, 1997). This means that one has to compare the sensor measurements not only with themselves but also with other quantities. In climate monitoring, it is inevitable to compare satellite measurements with those by other remote sensing or *in situ* systems, some existing at the present time and some being yet to come in the future (for example, the Global-Positioning-System-based climate monitoring system). In data assimilation, one compares satellite measurements with the output of numerical weather prediction models. Clearly, the only way to accommodate all these applications is to calibrate all measurements, including or perhaps starting with the satellite measurements, to a generally accepted absolute standard.

2.4 *Importance of sensor calibration*

This decade is witnessing a great expansion of environmental satellite programs. The United States is developing the National Polar-orbiting Operational Environmental Satellite System (NPOESS), its new generation of polar system, and the Geostationary Operational Environmental Satellite R Series (GOES-R), its new generation of geostationary system. Similarly, China is developing Feng Yun-3 and -4, its new generation of polar and geostationary systems, respectively. Europe has launched Meteosat Second Generation (MSG), will launch its first polar-orbiting satellite dedicated to operational meteorology MetOp, and is developing its next generation of geostationary satellite (Meteosat Third Generation, MTG). Several East Asian countries are continuing or starting active and viable programs on environmental satellite, for example the Multi-functional Transportation Satellite (MTSAT) and the Communication, Ocean, and Meteorology Satellite (COMS). The sensors on these new satellites are more complicated and sophisticated than the previous generations'. Compared with their predecessors, the new sensors typically have more channels, higher spectral and spatial resolutions, and sometimes a higher temporal resolution (refresh rate). While technology has advanced greatly since the design and procurement of the last generation of satellite systems, so have expectations on the data quality.

On the other hand, the recent focus of scientific, economic, and political attention on climate change and monitoring makes the historical satellite measurements invaluable. No matter how advanced the current or future technology is, there is simply no way to go back in time to make global, continuous, and multiple spectral measurements at reasonable spatial and temporal resolutions, such as those archived by the NOAA satellites. This is an asset we cannot afford to ignore. However, while the earlier satellite systems (including sensors) may be adequate for what they were designed for, they are often inadequate for climate studies. For example, the reflectance channels are not fully calibrated onboard; the spectral characteristics are not completely documented or made consistent among the satellites; and not all satellites are overlapped with their predecessors for inter-satellite calibration. It is important to carefully re-examine the processes of data collection, sensor calibration, and satellite operation to mitigate adverse conditions.

Sensor calibration is a critical link from sensor measurements to scientific data for atmospheric, oceanographic, and climate applications. As China and the U.S. each develops its next generation of polar and geostationary environmental satellite systems, and as the broader scientific community is sifting through historical data for indications and implications of climate change, calibration becomes ever so imperative.

3. Examples of sensor calibration activities at NOAA/NESDIS

Presented in this section are examples of recent calibration activities at the Sensor Physics Branch of NOAA/NESDIS/ORA, each is chosen to illustrate a lesson learned from past experiences. It is not possible, nor intended, to explain each work in detail. Interested readers are referred to the original publications.

3.1 *Scan mirror emissivity*

Shortly after the launch of the first three-axis-stabilized Geostationary Operational Environmental Satellite (GOES-8, in April 1994), it was discovered that, for both the Imager and Sounder and for all channels with wavelengths between 6 and 14 μm, the sensors' responses to a uniform target varied with scan position, as illustrated in Fig. 2. A similar problem was

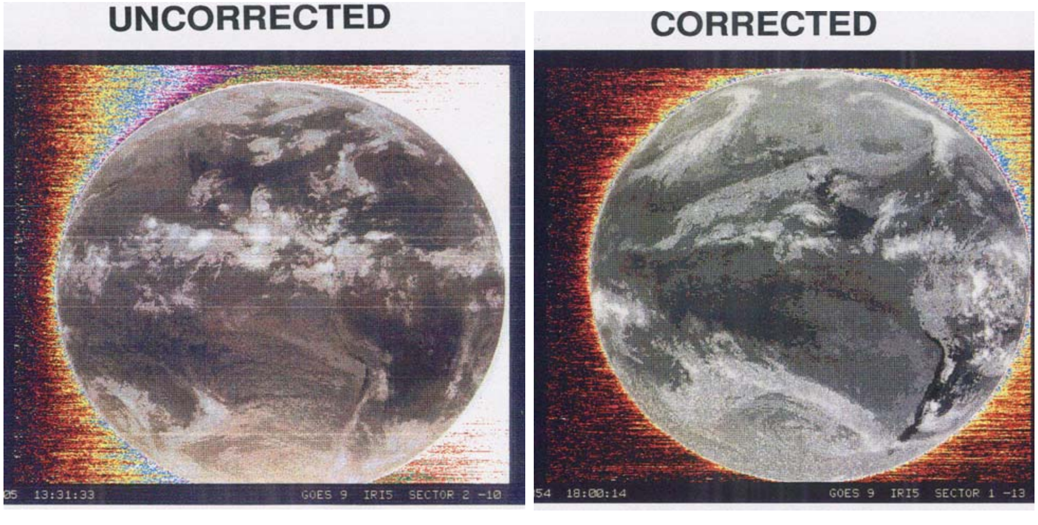

Fig. 2. Demonstration of scan mirror emissivity correction. Before the correction (left panel), sensor output for a space target, which should be uniform, is darker on the west (left) side of the image compared to the east (right) side. This is particularly evident in the scan above the North Pole. After correction (right panel), the asymmetry in the space view is much reduced.

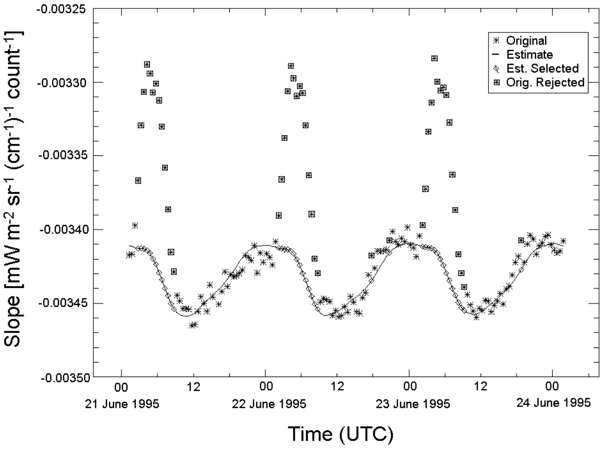

Fig. 3. Example of the midnight blackbody calibration anomaly and correction. The abscissa is time and the coordinate is the slope for GOES-8 Imager Channel 2. Plotted in the graph are original, estimated, rejected, and replaced slope values over a three day period of 21–24 June 1995.

later found in subsequent satellites. The root of the problem was traced to the silicon oxide coating applied to the scan mirror, whose absorption features in the affected range of wavelengths cause the mirror's emissivity to change with the angle of incident radiation. A correction scheme was implemented (Weinreb et al., 1997) that determines the scan mirror emissivity from in-orbit measurements. There was no such problem before because spin-scan radiometers do not employ a scan mirror. A lesson learned from this experience is that each new sensor is likely to adopt some newer technology—as revolutionary as spacecraft attitude control or as evolutionary as mirror coating—that may pose new challenges to sensor calibration. Past performance is no guarantee for future success without continuing efforts in calibration.

3.2 *Midnight blackbody calibration correction*

Another discovery shortly after the GOES-8 launch was that the onboard determination of "slope", or the reciprocal of instrument gain, fluctuates dramatically around the satellite midnight (Fig. 3.). "Slope" is the key calibration parameter that converts sensor response in terms of "count" to physical quantity in terms of radiance, so error in this parameter seriously compromised the sensor's performance. Again, similar problem was found in subsequent satellites, although the pattern of variation differs from satellite to satellite. The root of the problem was traced to the contamination of blackbody radiation. The temperature of some parts of the GOES can rise by as much as 40°K around satellite midnight, when the sun shines directly on the earth side of the satellite. If the blackbody is not perfectly black, some of the radiation from these hot objects can be reflected to the sensor during its calibration cycle. A correction scheme was proposed by Johnson and Weinreb (1996) and implemented in 2003. This is another example that changes in satellite technology and operation can affect sensor calibration in many different ways.

This midnight calibration anomaly has a direct impact on the products based on this sensor's data. Figure 4 is a composite of sea surface temperature (SST) for a ten-day period at eight different times during the day, using the uncorrected GOES-8 data. For the central Gulf of Mexico, the local time is about 0000, 0300, 0600, and 0900 in the left column (from top to bottom), and 1200, 1500, 1800, and 2100 in the right column. The diurnal variation of SST, particularly over the shallow water around Florida, Cuba, and the Bahamas, is apparent. This variation can be attributed to solar heating and, in some instances, to the calm surface wind (Wu et al., 1999). What is puzzling, though, is that the SST at 0600 UTC (local midnight) is cooler than the SST at 0900 UTC (3 a.m. local time). The only explanation is that the midnight calibration anomaly caused a cold bias in the Channel 2 brightness temperatures, which compromised the derived SST product.

3.3 *Lunar contamination of the AMSU calibration*

All space-borne radiometers use the space view as a "cold" or "dark" target in the traditional 2-point calibration method, as illustrated in Fig. 1. Kigawa and Mo (2002) noticed that the moon can enter into the space view of the Advanced Microwave Sounding Unit (AMSU) on POES, as shown in Fig. 5. Similar to the Midnight Blackbody Calibration Correction discussed in 3.2, this is another form of contamination of calibration sources that, without proper correction, will introduce a bias into the calibrated data. Kigawa and Mo (2002) developed and implemented an algorithm to detect and correct the lunar contamination. Other sensors on POES, including the High-resolution InfraRed Sounder (HIRS) and the Advanced Very High Resolution Radiometer (AVHRR), have smaller fields of view. Lunar contamination happens less frequently for these instruments, but it does happen occasionally (Ignatov et al., 2005). These are examples showing that even for sensors that have been in operation for decades (including the Microwave Sounding Unit before the AMSU), improvements are still possible for sensor calibration.

3.4 *HIRS spectral response function*

The importance of a comprehensive characteriza-

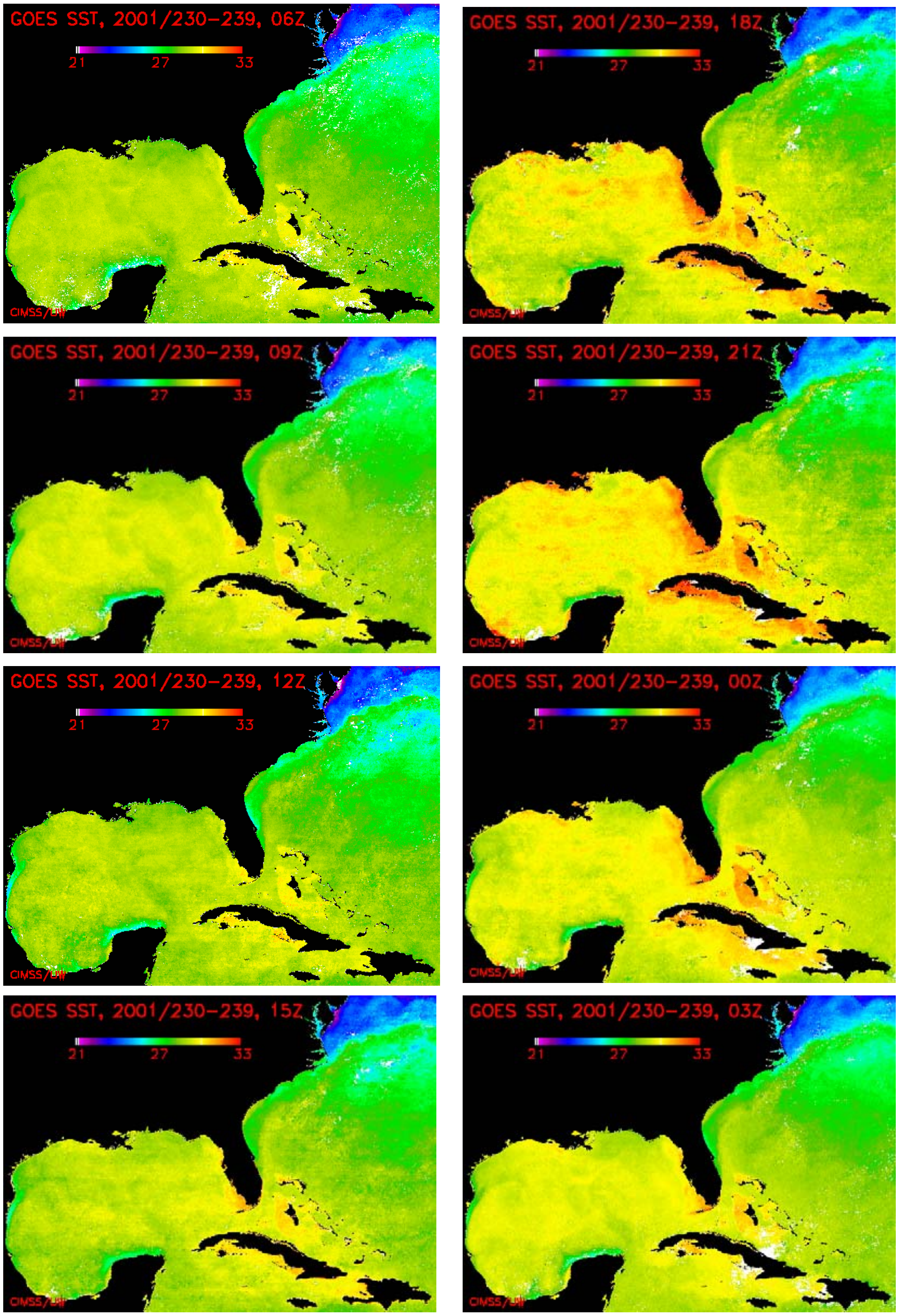

Fig. 4. Ten-day composite (18–27 August 2001) of sea surface temperature (SST) at eight times of the day.

tion of a sensor's spectral response function (SRF) for climate monitoring and data assimilation is well recognized. However, when the current generation of NOAA satellite was conceived in the 1970s, climate monitoring was not among its mission goals, data assimilation was just one of many emerging concepts, and even the retrieval of geophysical parameters from satellite measurements was not quite mature. Therefore the requirements on sensors' SRF were lax by today's standards. To remedy the situation, NOAA/NESDIS, in

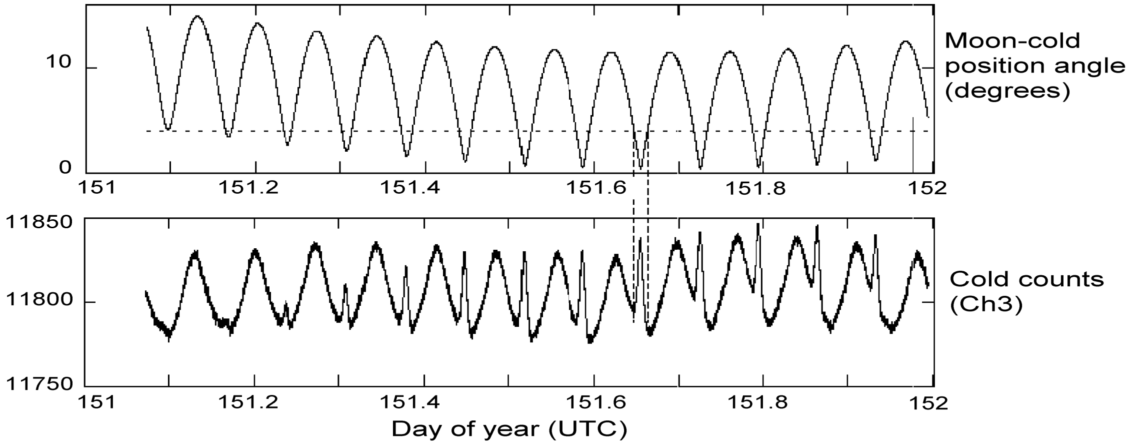

Fig. 5. Time series of the angle between the views to the moon and to the space (upper panel) and the Channel 3 space counts (lower panel) of the NOAA-16 AMSU on May 31, 2001. Lunar intrusion occurs when the angle is less than the threshold value, which was depicted as the dashed line in the upper panel. This causes a short yet sharp increase in the space counts, as seen in the lower panel.

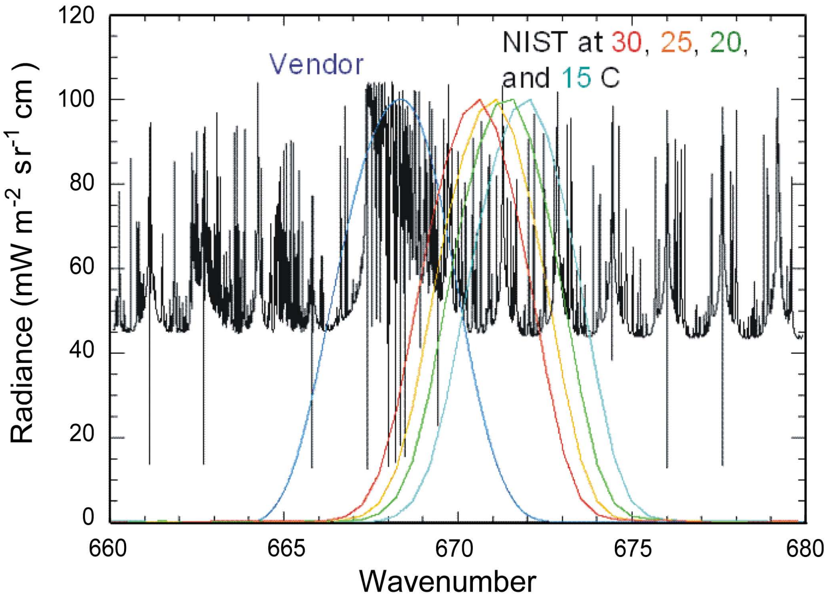

Fig. 6. Atmospheric absorption lines (black) superimposed with the spectral response functions (color curves) of the Channel 1 filter for the HIRS to be flown onboard NOAA-N'. The blue curve to the left is based on vendor measurements, which covers the Q-branch of the CO_2 absorption as required for this channel. The other curves are based on NIST measurements at various temperatures as marked, which shows that the witness sample may have largely missed the Q-branch.

collaboration with NIST, examined a filter witness sample for the HIRS instrument to be flown on NOAA-N' (Cao et al., 2004a). The agreement between the vendor measurements of the flight part and the NIST measurements of the witness sample was good in general; however significant differences existed for some channels. Figure 6 is one result from the comparison study, which shows that a large uncertainty in the sensors' SRF's may exist that can lead to large errors. This is an example of how calibration requirements

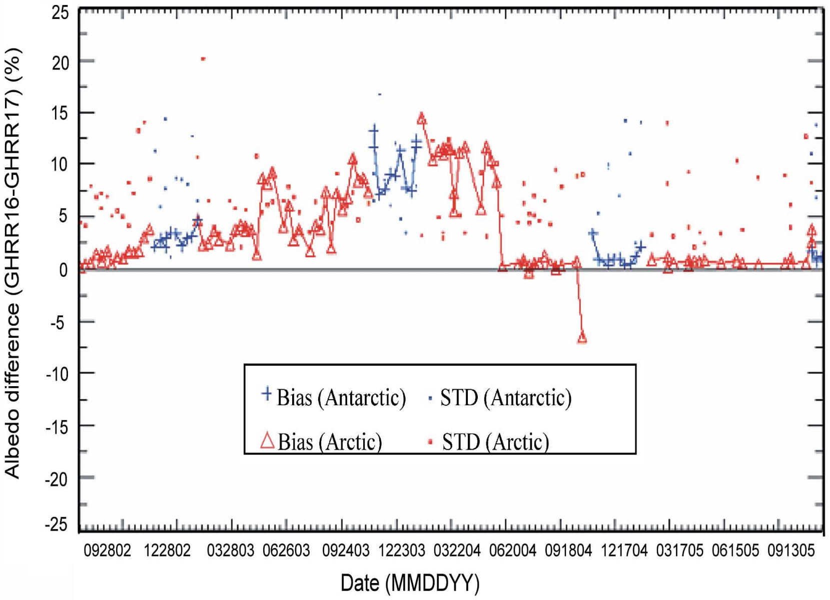

Fig. 7. Time series of the difference between the reflectance measurements by Channel 2 of the AVHRR onboard NOAA-16 and NOAA-17. Note the gradual increase of the difference before May 2003, followed by a rapid increase that was abruptly reduced to nearly zero after June 2004. See text for details.

change with the advances of science and the intended uses of the measurements. Careful characterization and independent verification of a sensor's spectral response functions have become an important requirement in the acquisition of future satellite sensors.

3.5 *Cross calibration*

So far the examples have been focused on the verification of the self-consistency of a single sensor's calibration subsystem. Another powerful tool is the comparison of the measurements by different sensors on the same or different satellites. Cross calibration, also referred to as inter-calibration, can verify the proper functioning of each sensor, reveal deficiencies, quantify the measurement uncertainty, and monitor sensor performance over time. The Coordination Group for Meteorological Satellites (CGMS) has identified the importance of cross calibration of satellite radiance measurements.

Cross calibration has been carried out for more than 20 years by NOAA/NESDIS scientists stationed at the University of Wisconsin (Menzel et al., 1981; Gunshor et al., 2004; and references therein). Most of these cross calibrations are between similar sensors on POES and GOES, although lately a hyperspectral sensor (AIRS) has been used to cross calibrate the GOES (Gunshor et al., 2003) and POES (Ciren and Cao, 2003) sensors. Recently, a web-based, continuous, and near real-time cross calibration tool based on Simultaneous Nadir Overpass (SNO) over the polar regions was implemented at NOAA/NESDIS (Cao et al., 2004b). As an example, Fig. 7 shows a time series of the difference between the reflectance measurements by Channel 2 of the AVHRR onboard NOAA-16 and NOAA-17. Since neither sensor was calibrated before May 2003, the gradual increase of the difference over time simply indicates that NOAA-17 degradation was faster than NOAA-16. A calibration update for NOAA-16 (beginning in May 2003) accelerated the increase of the difference between NOAA-16 and NOAA-17 until June 2004, when a calibration update for NOAA-17 brought the difference to nearly zero. This example shows how cross calibration can be used to continuously monitor instrument performance and to independently verify sensor calibration. In the near future, this tool will be expanded to include GOES/POES cross calibration as well.

Though not obvious, an important lesson in this example is the role played by the internet technology that makes it possible to obtain in a timely fashion the parameters necessary to predict the intersection of satellite orbits and to disseminate the results like Fig. 7 to broad users. In other words, sensor calibration can and should benefit from technology advances in other area.

3.6 *Vicarious calibration*

A unique problem for the visible and near-infrared

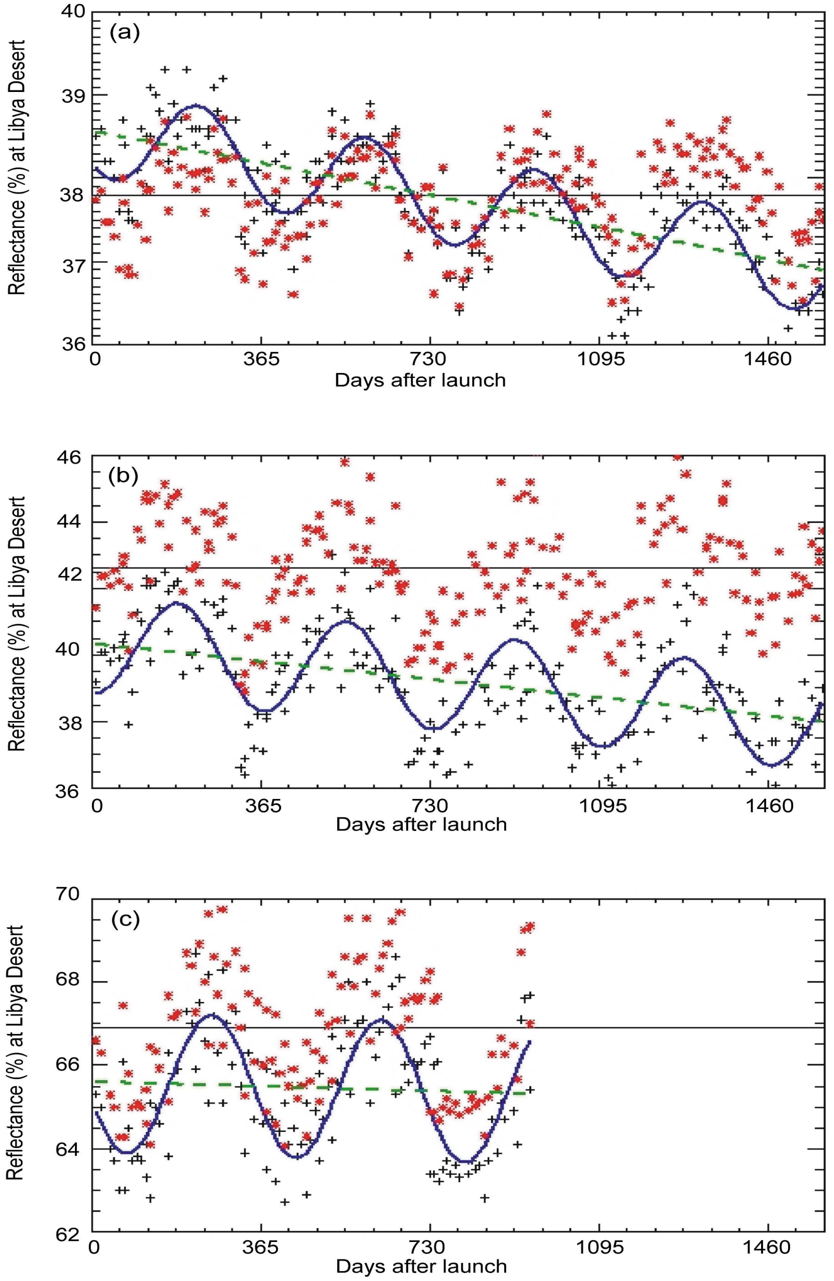

Fig. 8. Desert-based vicarious calibration of NOAA-16 AVHRR Channel 1 (upper panel), 2 (middle panel), and 3A (lower panel). In each panel, the crosses are the target reflectance using pre-launch calibration; the solid curve is a fit to those data that accounts for the bidirectional reflectance distribution function (BRDF), among other things; the thin horizontal line is the expected mean target reflectance; the dashed line is the measured mean target reflectance with the BRDF factor removed; and the stars are the target reflectance derived with the post-launch vicarious calibration.

channels of POES and GOES is the lack of an onboard calibration device. These channels can only be calibrated vicariously in orbit, i.e., using external references. A popular choice of reference is desert that is bright and stable (Rao and Chen, 1995, 1999). Figure 8 shows recent improvements (Wu, 2004) that account for, among other things, the Bidirectional Reflectance Distribution Function (BRDF) of the target surface.

Other references have been used in vicarious calibration of the visible and near-infrared channels of GOES and POES, including the Empirical Distribution Function of earth observations (Crosby et al., 2005) and star measurements (Bremer et al., 1998; Chang et al., 2005). Of particular interest is the use of a well-calibrated space-borne radiometer such as the MODerate Resolution Imaging Spectroradiometer (MODIS), which gives not only the trend of degradation but also an absolute calibration. It was used for AVHRR on POES (Heidinger et al., 2002), but it has been more successful for the Imager on GOES because of the more frequent co-locations of observations by these two satellites (Wu, 2003; Wu and Sun, 2005).

Figure 8 also showed the importance of recalibration. As part of the calibration support to NOAA's satellite mission, calibration coefficients for the visible and infrared channels of the AVHRR were updated regularly and disseminated through the Level 1b data stream in real time. Those updates were the best estimates based on the satellite measurements available at the time, subject to the inherent noise in the data. Statistically speaking, the longer the satellite has been in operation, the more data it has collected, and the better the sensor can be characterized (including its degradation). It would be difficult to assess the sensor responsivity degradation from Fig. 8 when the sensor has been launched into orbit, say, less than one year, and the best time to assess the sensor degradation is to re-calibrate the sensor after all the data have been collected.

4. Summary

Radiometric calibration is the quantification of sensor responses to known signals, with the purpose of inferring unknown signals from sensor responses (measurements) during the sensor's duty cycle. One of the central issues is how well the "known signals" are actually known. Further complication arises from the fact that the operation environment of the satellite sensor is dynamic, making the sensor calibration even more challenging. Nevertheless, sensor calibration is a critical link from sensor measurements to scientific data for atmospheric, oceanographic, and climate applications. As China and the U. S. each develops its next generation of polar and geostationary environmental satellite systems, and as the broader scientific community is sifting through historical data for implications of climate changes, sensor calibration becomes ever so imperative.

It is best to calibrate all sensors to SI units with verifiable traceability to the NIST standards. This will greatly enhance the utility of the sensor measurements because it enables the comparison of measurements by different sensors, of similar or different measurement principles, either currently used, no longer available, or to be invented. A well established sensor calibration traceability is also the basis for infusing data from observing and simulation systems. However, traceability is not always properly enforced in practice, especially in the past. Some of the weaknesses in sensor calibration are well known, while others can be appreciated only upon close examination. Although this does not render the measurements useless, the limitation of the utilitiy of the measurements imposed by the calibration shortcomings should be recognized.

A few examples of sensor calibration activities at NOAA/NESDIS/ORA have been presented in this paper to demonstrate that new sensors are likely to adopt new technology that may affect sensor calibration directly or indirectly. Even for sensors that have been in operation for decades, improvements in calibration are still possible. With advances in science that expand the utility of the sensor measurements, requirements for sensor calibration may change and pose new challenges. On the other hand, advances in technology can offer new opportunities for sensor calibration. Finally, re-calibration should be a part of scientific data stewardship, as it has the advantage of hindsight.

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