Achieving Satellite Instrument Calibration for Climate Change

(ASIC^3)

Center for Satellite Applications and Research
National Environmental Satellite, Data, and Information Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

Achieving Satellite Instrument Calibration for Climate Change (ASIC^3)

Report of a Workshop Organized by

National Oceanic and Atmospheric Administration
National Institute of Standards and Technology
National Aeronautics and Space Administration
National Polar-orbiting Operational Environmental Satellite System-Integrated Program Office
Space Dynamics Laboratory of Utah State University

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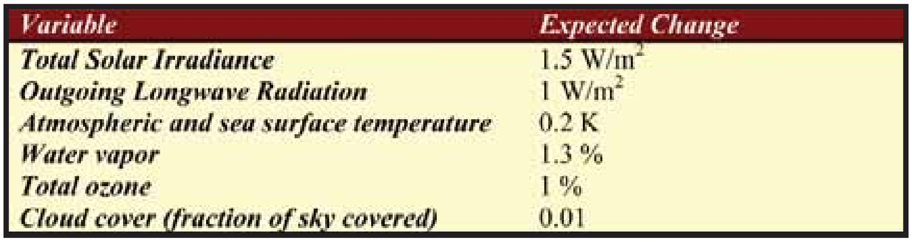
Background

Current satellite systems are, for the most part, not designed to detect the small trends associated with global climate change—an extremely demanding measurement challenge. The trends are indeed tiny, especially in comparison with those of day to day weather fluctuations or even seasonal to inter-annual climate variations. The Table below, based on analyses performed at a previous Workshop on satellites and climate change (Ohring et al., 2004), shows a sample of estimates of expected decadal changes.

Table 1 Expected Decadal Changes (Ohring et al., 2004)



Variable	*Expected Change*
Total Solar Irradiance	1.5 W/m^2
Outgoing Longwave Radiation	1 W/m^2
Atmospheric and sea surface temperature	0.2 K
Water vapor	1.3 %
Total ozone	1 %
Cloud cover (fraction of sky covered)	0.01

For example, the anticipated global temperature change per decade is about 0.2 K. This change is only about 1/10th of typical ENSO temperature variations, and as low as 1/50th of temperature changes of weather events. Measuring these climate change signals from space requires extremely well-calibrated observations to attain the needed high accuracy and stability.

Current long-term climate data records are based mainly on the observations of the operational satellite systems. These satellites are designed primarily to provide measurements for short-term weather and environmental prediction. Instrument calibrations lack traceability to International Standards (SI) units, sensors and onboard calibration sources degrade in orbit, long term data sets must be stitched together from a series of overlapping satellite observations, orbital drift—leading to a changing time of satellite observing time during the satellite's lifetime—introduces artifacts into long term time series, and, most importantly, insufficient attention is paid to pre- and post-launch instrument characterization and calibration. It is no wonder that this system fails to meet the observing challenge of long term climate change.

One may ask: "So what? Is it really important to monitor climate change from space?" Climate change is one of today's most compelling issues, and the single issue that will impact all of humanity. The preponderance of evidence indicates that Earth's climate is changing, and that much of the forcing of the climate change can be attributed to human activity, most notably the human-induced increase of radiatively active "greenhouse" gases such as carbon dioxide and methane in the Earth's atmosphere. The existence of human-induced forcing of climate change is no longer in doubt, but the degree of change is uncertain. Wise, informed decisions on how to prepare for, and respond to, climate change demand quantitative specifics that can be relied upon. Among these specifics are two key informational needs upon which intelligent preparation and response strategies must depend:

- What is the current rate of climate change?
- What will the climate be like in the future?

It's obvious that the answer to the first question depends on accurate observations—our ability to detect small trends rests on high-quality measurements. It is perhaps surprising that credible answers to the second question also rely on highly accurate measurements. Our knowledge of future climate is based on predictions of climate models. But forecasts of future climate differ depending on the model used. For example, predicted temperature changes by the end of the century vary by over a factor of two. How do we know which model to trust? Establishing credibility is critical to decisions on responding to climate change. We can do it the same way we evaluate weather predictions: by checking the forecasts against what really happens. The reliability of climate predictions can be ascertained by testing decadal climate trends predicted by the models against observations. But, as emphasized above, the changes are small, and such tests can only be performed with highly accurate observations. And satellite observations from space provide the only measurements with the needed global perspective.

Workshop Organization

The Workshop on Achieving Satellite Instrument Calibration for Climate Change (ASIC^3) was organized to formulate a national roadmap for developing the calibration systems to monitor long-term global climate change. Sponsored by the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the National Institute of Standards and Technology (NIST), the Integrated Program Office for the National Polar-orbiting Operational Environmental Satellite System (NPOESS), and the Space Dynamics Laboratory of Utah State University, the Workshop was held at the National Conference Center, in Lansdowne, Virginia, May 16-18, 2006.

ASIC^3 brought together some 100 participants, including instrument calibration experts, metrology scientists from the U.S. and U.K. national standards institutes, remote sensing specialists, and climate data analysts. The Workshop format consisted of plenary sessions with invited papers, and breakout groups that reported to plenary sessions. Invited papers covered the following topics:

- Agency Roles
- Review of Requirements for Measuring Global Climate Change
- Calibration Status for Current Instruments and Plans for Future Instruments
- Concepts and Methodologies for Achieving Calibration of Global Climate Change Measurements

Representatives of the key agencies involved in satellite instrument calibration reviewed their agencies' contributions and commitment to improving satellite measurements. Mary Kicza, NOAA Assistant Administrator for Satellite and Information Services, gave the keynote address. Other agency presentations were made by Katharine Gebbie, Director, Physics Laboratory, NIST; Jack Kaye, Director, Earth Science Division Research, NASA Headquarters; and Al Powell, Director, NOAA Center for Satellite Applications and Research. Their complete presentations, as well as copies of all the invited presentations, may be viewed at the website http://www.asic3.sdl.usu.edu/ with the username guest and password asic32006.

Breakout groups were organized primarily according to the spectral regions used in space-based measurements. They discussed current satellite instrument calibration capabilities, impediments to progress, and recommendations to accelerate progress. Breakout groups were formed on Infrared Instruments; Ultraviolet, Visible and Near-infrared Instruments; Microwave Instruments; Active Instruments (such as radars and lidars); and Broadband Instruments (such as Earth radiation budget and total solar irradiance). Two additional breakout groups were organized: a group on Intercalibration of Instruments focused on techniques for inter-calibrating sensors on different satellites, and a National Roadmap group prepared an outline of a Roadmap to implement the recommendations of the Workshop. Breakout groups reported to plenary sessions where overall coordination and discussions took place.

Overarching Recommendations

The Workshop developed two overarching recommendations as well as a large number of technical recommendations on advancing the state of climate monitoring from satellite instruments.

Overarching recommendation 1: Conduct a set of satellite benchmark missions to create irrefutable records and calibrate other satellite sensors

This is a powerful new paradigm for achieving satellite instrument calibration for measuring long term global climate change. The basic concept is to place in space a series of highly accurate benchmark instruments (see Goody, 2001, for characteristics of climate benchmark measurements) to measure with high spectral resolution the energy reflected and emitted by the Earth. These instruments would provide reliable long term records of climate forcings, response, and feedbacks to monitor climate change. These records would also serve as the validation data needed to test and evaluate climate model predictions. The benchmark instruments would also constitute a reference standard, or calibration observatory, in space to calibrate other environmental satellite sensors–for example, the sensors on operational weather satellites–that are not as well calibrated. Such calibrations can be performed by comparing coincident observations of the benchmark instruments with the other sensors. These spectral instruments would be joined in space by several other critical benchmark measurements.

Specifically, the Workshop recommended the following with respect to benchmark measurements:

- Initiate absolute spectrally resolved measurements of Earth's emission spectrum

  Develop and fly spectrally resolved radiance instruments in the thermal IR that are International Standards (SI) traceable on-orbit and provide climate level accuracy in perpetuity (<0.1 K brightness temperature, a 3-σ value). Such instruments will provide a cross-calibration reference for existing and future research and operational IR satellite-based instruments. This benchmark mission must (1) employ a new generation of absolute temperature scale on orbit, (2) observe blackbody cavity emissivity directly on orbit, (3) observe instrument polarization directly on orbit, (4) test instrument linearity directly on orbit, and (5) test for stray light on orbit.

- Initiate spectrally resolved, highly accurate, measurements of Earth's solar reflectance spectrum

  Develop and fly a hyperspectral benchmark mission observing the Earth's reflectance spectrum from the UV to the NIR that has the ability to view and measure the Moon, additional redundant calibration and validation capabilities and infrastructure to include multiple solar diffusers and onboard lamps, and operational infrastructure to support ground-based measurements, including reference sites and special field campaigns. The spectral and spatial resolution should be sufficient for valid intercomparisons at the resolution of the majority of satellites of interest, and the radiometric accuracy must be close to 0.5%. Ideally, a series of such sensors would be deployed to allow continued long-term overlapping measurements of the Earth necessary to ensure long-term calibration/validation of other satellite sensors and to develop its own highly accurate climate record.

- Ensure continuity of overlapped Total Solar Irradiance observations

  Since the current method of determining potential long-term variations in total solar irradiance relies on continuity and instrument overlap, instrument stability, or *long-term repeatability*, is needed. This can be accomplished by installing a set (e.g., 4) of redundant TSI sensors on the satellite and scheduling pairs to view the Sun simultaneously at progressively lower duty cycles. This permits on-orbit correction of the sensitivity degradation of the primary sensor due to exposure to the Sun and has been successfully implemented on several TSI instruments. Offsets between the multiple channels within an instrument also offer a lower bound to the stated uncertainty in *absolute accuracy* that could be claimed by that instrument. The designs of future TSI instruments are intended to have greatly improved absolute accuracies to establish and maintain a link to the current 28-year Solar Irradiance record. Until such improvements in absolute accuracy are achieved, data continuity of this solar irradiance climate record through continuous, overlapping missions is crucial.

- Ensure continuity of overlapped Broadband Earth Radiation Budget measurements

  Continuous overlapping broadband radiation budget data are critical to determination of cloud feedback and therefore climate sensitivity over the next 2 decades. Eliminate the high risk of a radiation budget climate data record gap by moving the final CERES instrument copy to NPP for launch in 2009/2010 instead of NPOESS C1 in 2013/2014. The current CERES instruments on Terra are already over their 5-year design life, and the remaining fully functional Aqua CERES instrument will exceed its design life by June, 2007. Build follow-on broadband instruments to launch on NPOESS or to fly in formation with the NPOESS imager.

- Ensure continuity of global sea level measurements with overlap of altimeter missions

  Radar altimetry has been shown to be capable of observing the long-term trend of sea level height, a critical climate parameter that acts to integrate many inputs into the climate system, including the global heat budget and hydrologic cycle. Measurements from radar altimeters have been shown to be very stable, but significant intersatellite biases are evident when time series from different instruments are compared. To monitor sea level trends and improve model predictions of sea level rise it is essential to continue the record begun by Jason with additional missions beyond Jason-2 (launching in 2008). Overlap of these future altimeter missions is essential to allow for the correction of systematic biases between satellite instruments and ensure the ability to construct a continuous long-term record of global sea level measurements.

The last three recommendations are especially critical in view of the fact that these instruments have been dropped from the NPOESS program.

Overarching recommendation 2: Establish a U.S. National Center for Calibration (NCC)

This recommendation is based upon the realization that implementation of the recommendations of the ASCIC^3 workshop can only be accomplished through an integrated national effort in instrument calibration involving the two U.S. agencies engaged in environmental satellite observations–NOAA and NASA–and the U. S. agency responsible for establishing measurement standards–NIST. The Center would be a distributed entity, i.e., the Center's program would be conducted at the partner agencies. As demonstrated by the NASA-NOAA-DOD Joint Center for Satellite Data Assimilation, this kind of distributed joint center has been a very successful model for integrating federal activities that cross several agencies.

The mission of the Center would be to advance the state of the art of satellite instrument calibration. Its activities would include carrying out the technical recommendations of the ASIC^3 Workshop, implementing the U.S. Component of the WMO's Global Satellite Inter-Calibration System (GSICS)–an evolving international program to inter-calibrate instruments on different Earth-observing satellites–and championing satellite benchmark measurements for climate monitoring. NOAA plays a leading role in the GSICS, chairing (Mitch Goldberg) its Executive Panel and serving as the GSICS Coordination Center.

Additional Recommendations

The Workshop Breakout Groups made a number of important, detailed recommendations to improve instrument characterization and calibration–recommendations, if adopted, that would lead to a much more robust and reliable climate monitoring system They are summarized in the chapters on Infrared Instruments; Ultraviolet, Visible, and Near-Infrared Instruments; Microwave Instruments; Broadband Instruments; Active Instruments; and Intercalibration of Instruments.

Benefits

The benefits of implementing the Overarching and Additional recommendations would be:

- Early, irrefutable detection of climate change
- Verification of climate model predictions
- Achieving the societal benefit goals of the Global Earth Observation System of Systems (GEOSS), in particular, understanding, assessing, predicting, mitigating, and adapting to climate variability and change
- Ability to make sound policy decisions based on accepted accurate information

These benefits transcend the field of climate. It is quite clear that if we satisfy the stringent observational accuracy requirements of climate change, we will also meet the generally less rigorous accuracy requirements for other environmental applications, such as weather prediction and short term climate forecasting, which have larger observational signals.

A Workshop Summary has been published in EOS (Ohring et al., 2007)

Introduction

1.

Climate change is probably today's most compelling issue since it is the single issue that will impact all of humanity. For the most part, satellite observations of climate are not presently sufficiently accurate to establish a climate record that is indisputable and hence capable of determining whether and at what rate the climate is changing, and of testing the long term trend predictions of climate models. Space-based observations do provide a clear picture of the relatively large signals associated with inter-annual climate variations such as ENSO, and they have also been used to diagnose gross inadequacies of climate models, such as their cloud generation schemes. They have also contributed to substantial improvements in weather prediction: satellite observations comprise more than 90% of the input to numerical weather prediction models, and today's 5-day forecasts are as accurate as 3-day predictions were just 25 years ago. However, satellite contributions to measuring long term change have been limited, and, at times, controversial, as in the case of differing atmospheric temperature trends derived from NOAA's microwave radiometers.

Measuring long-term global climate change from space is a daunting task. The climate signals we are trying to detect are extremely small: e.g., temperature trends of only a few tenths of a degree C per decade, ozone changes as little as 1%/decade and variations in the Sun's output as tiny as 0.1%/decade or less. Current satellite systems are not up to the task. Sensors and onboard calibration sources degrade in orbit, measurements are not traceable to international standards, long term data sets must be stitched together from a series of overlapping satellite observations, orbital drift introduces artifacts into long term time series, and insufficient attention is paid to meeting the high accuracy, high stability instrument requirements for monitoring global climate change.

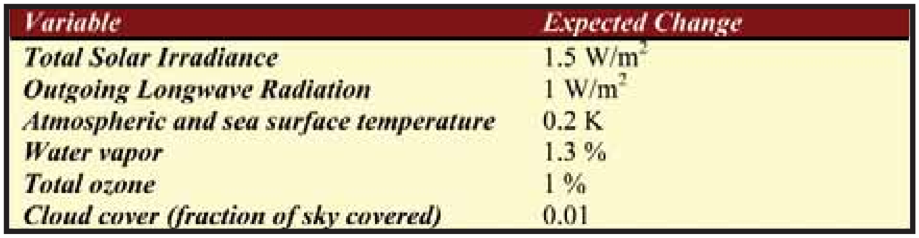
Calibration is the process of quantitatively determining an instrument's response to known controlled signals inputs.

The Workshop on Achieving Satellite Instrument Calibration for Climate Change (ASIC^3) was a follow-up to a 2002 Workshop (Ohring et al., 2004; Ohring et al., 2005) that had developed the measurement requirements for a number of global climate variables. The 2002 Workshop defined the absolute accuracies and long-term stabilities of global climate data sets that are needed to detect expected trends, assessed needed satellite instrument accuracies and stabilities, and evaluated the ability of then current observing systems to meet these requirements.

The major objective of the ASIC^3 workshop was to formulate a national roadmap for developing the calibration systems needed to monitor long-term global climate change from space. The Workshop brought together some 100 participants, including experts in satellite instrument calibration, metrology scientists from the U.S. and U.K. national standards institutes, remote sensing specialists, and climate data analysts. The Workshop format consisted of plenary sessions with invited papers, and breakout groups that reported to plenary sessions. Invited papers covered the following topics: Agency Roles, Review of Requirements for Measuring Global Climate Change, Calibration Status for Current Instruments and Plans for Future Instruments, and Concepts and Methodologies for Achieving Calibration of Global Climate Change Measurements. Copies of the invited workshop presentations may be viewed at http://www.ASIC3.sdl.usu.edu/ using the username guest and the password ASIC32006. Breakout groups were formed to discuss current calibration capabilities, impediments to progress, and recommendations to accelerate progress. The 2002 Workshop had focused on passive satellite sensors that make observations in spectral bands ranging from the ultraviolet to the microwave; ASIC^3 added some representation from the expanding field of active satellite sensors, such as radars and lidars. The breakout groups were organized primarily by spectral region. In addition there were groups on Active Sensors, Intercalibration of Instruments, and Development of a National Roadmap for Achieving Satellite Instrument Calibration for Climate Change.

Table 2 illustrates the challenge of measuring global climate change. Based on the 2002 Workshop, this table lists the expected decadal changes for several climate variables. These changes are indeed small, and observing systems must have measurement uncertainties that are even lower to enable detection of these signals.

Table 2 Expected Decadal Changes (Ohring et al., 2004)



Variable	*Expected Change*
Total Solar Irradiance	1.5 W/m^2
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This report is based on discussions at the Workshop with much of the writing being done after the Workshop concluded.

The report opens with a review of the motivation and urgency for obtaining authoritative climate observations. This is followed by a section on the goals and desired attributes of a climate monitoring system, including a discussion of traceability of measurements to the International System of Units (SI), definitions of accuracy, bias, precision, and stability, and a strategy for achieving the desired climate quality records. The following sections discuss Infrared Instruments; Ultraviolet, Visible and Near-Infrared Instruments; Microwave Instruments; Broadband Instruments, such as those used for measuring total solar irradiance and the Earth's Radiation budget; and Active Instruments. These are followed by a section on the Intercalibration of Satellite Instruments to determine systematic differences between satellite sensors. The Workshop Report concludes with a section devoted to a Roadmap for Establishing a National Center for Calibration (NCC) to implement the recommendations of the ASIC^3 Workshop.

Workshop participants developed two sets of recommendations: high level initiatives and additional recommendations. High level initiatives focused on the satellite programs and national infrastructure needed to implement a new, powerful paradigm for monitoring global climate change. The additional recommendations centered on more detailed technical aspects of instrument calibration, characterization, and intercalibration.

The benefits of achieving satellite instrument calibration for climate change transcend the field of climate. It is quite clear that if we satisfy the stringent observational accuracy requirements of climate change, we will also meet the generally less rigorous accuracy requirements for other environmental applications, such as weather prediction and short term climate forecasting, which have larger observational signals.

One may ask whether workshop reports such as this have any impact. Does anyone act on the recommendations in these documents? The report on the previous calibration workshop, Satellite Instrument Calibration for Measuring Global Climate Change (Ohring et al., 2004), developed required accuracies and stabilities of satellite instruments to monitor decadal scale changes for a number of climate variables. These requirements have now been incorporated in plans for the Global Climate Observing System, which is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the United Nations Environment Program (UNEP) and the International Council for Science (ICSU). They have also been used in the planning of NOAA's next generation geostationary satellite program, GOES-R. The report's recommendations also led to greater engagement of the NIST in satellite instrument calibration issues, resulting in significant enhancements of the nation's capabilities. Hopefully, the present report will also generate actions by the relevant agencies to implement its recommendations.

ASIC^3 was organized by the National Oceanic and Space Administration, the National Institute of Standards and Technology, the National Aeronautics and Space Administration, the National Polar-orbiting Operational Environmental Satellite System-Integrated Program Office, and the Space Dynamics Laboratory of Utah State University and was held at the National Conference Center, Lansdowne, VA, in May 2006.

2.

Motivation for Authoritative Climate Observations

Climate change has the potential to lead to unprecedented social, economic, and demographic changes, particularly if the most extreme predictions from climate models are realized. In 2007, the preponderance of evidence indicates that Earth's climate is already changing, and possibly changing much more rapidly than has been predicted (see, for example, Rahmstorf et al., 2007). Much of the forcing of the climate change can be attributed to human activity, most notably, the human-induced increase of radiatively active "greenhouse" gases such as carbon dioxide and methane in the Earth's atmosphere. The existence of human induced forcing of climate change is no longer in doubt, but the degree of change—with respect to the rate, the consequences and the economic impact—demands quantitative specifics that can be relied upon. Accurate climate records and credible long-term climate forecasts form the basis for wise decisions on mitigation and adaptation policies that address water resources, human health, energy management, civilian and military communications, insurance infrastructure, and international negotiations.

The magnitude and impact of climate change are not, at present, clearly defined. We do not presently observe Earth's climate system with sufficient accuracy to establish a climate record that is tested and trusted, nor are climate observations in place that can adequately constrain climate model predictions.

Current climate records from satellites are, for the most part, not accurate enough to measure the small signals associated with global climate change. This is illustrated by the case of the Microwave Sounding Unit (MSU). MSUs have flown on NOAA's POES satellites for more than 25 years and provide the best measurements of atmospheric temperatures from space. Yet, as shown in Figure 1, analyses of the MSU observations by different investigators yield differing atmospheric warming rates. One result indicates that the atmosphere is heating up faster than the Earth's surface, the other shows the opposite. It is important to nail this down for the attribution problem: analyses of the effects of radiative forcing agents on the climate system and the results of climate model simulations indicate that the troposphere should warm faster than the surface. It is very likely that the most important source of uncertainty in microwave sounding temperature trends is due to inter-satellite calibration offsets, and calibration drifts that are correlated with the temperature of the calibration target (Karl et al., 2006). Improved instrument calibration would permit construction of authoritative records of the rate of global warming, as well as that of other climate variables, enabling informed decisions on mitigation and adaptation.

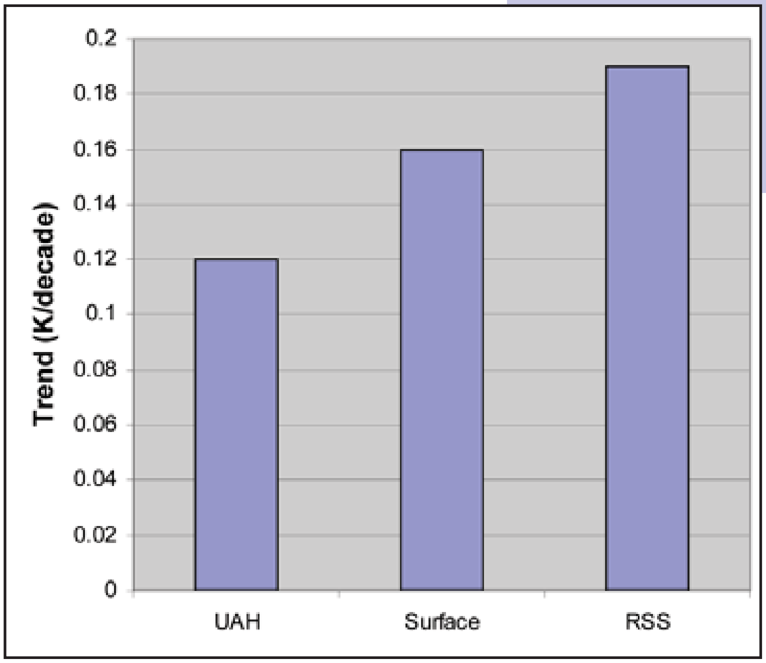

Figure 1 Observed global temperature trends since 1979 at the surface (NOAA and NASA) and lower troposphere (UAH: University of Alabama Huntsville and RSS: Remote Sensing Systems) (After Karl et al., 2006)

Decisions on actions to deal with climate change must be based not only on reliable information about the current rate of change but also on credible predictions of future climate. Climate predictions are founded on numerical climate models that use as input estimated future rates of increase of greenhouse gases. A number of research groups around the world have developed such models. The problem is that the predicted climate varies considerably, depending on the model. Figure 2 shows the predicted global warming from these models out to the year 2100, all based on the same greenhouse gas emissions scenario. The increase in temperature by 2100 ranges from less than 2 deg C to over 3 deg C—or by almost a factor of 2. Credibility of the forecasts thus takes on great importance—particularly the rate of change and the regional impacts. The credibility of models to predict long term changes in climate can be best established by verifying forecasts against observations. But due to the small changes over decadal time periods, extremely accurate observations are needed to validate model predictions. Direct testing of models will also facilitate model improvement, enabling more reliable long-term forecast performance.

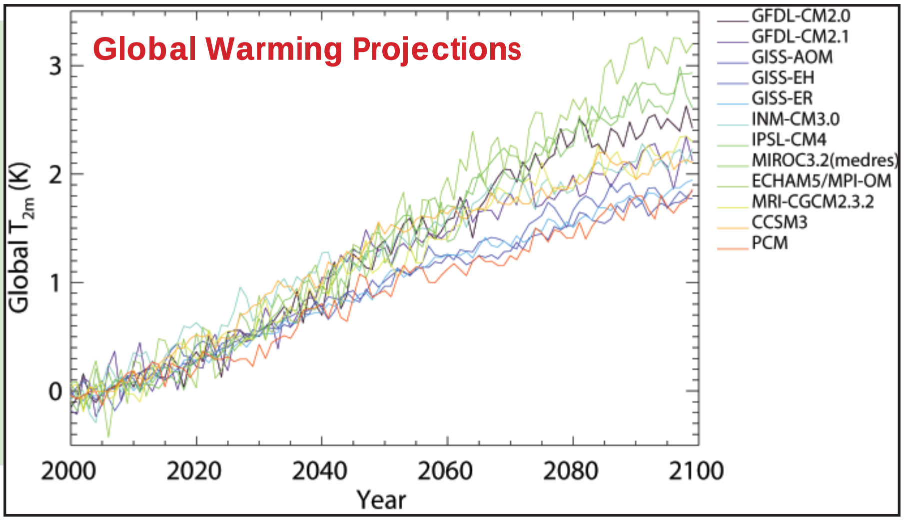

Figure 2 Predicted global surface air temperature trends for twelve climate models subjected to greenhouse gas forcing equivalent to 1% per year carbon dioxide increase. (After Leroy et al., 2006)

What is required is a climate observing system in space consisting of a series of extremely well calibrated instruments that will observe the changing climate with unquestionable accuracy. These observations will be used to provide credible assessments of the rate and extent of climate change, and to develop more rigorous models of the climate system to enable accurate forecasts that can be used by governments worldwide for societal planning.

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3.

Goals and Attributes of a Climate Monitoring System

3.1 Goals

Design of climate observing and monitoring systems must ensure the establishment of global, long-term climate records that are of *high accuracy, tested for systematic errors on-orbit, and tied to irrefutable international standards* maintained in the U.S. by the National Institute of Standards and Technology (NIST).

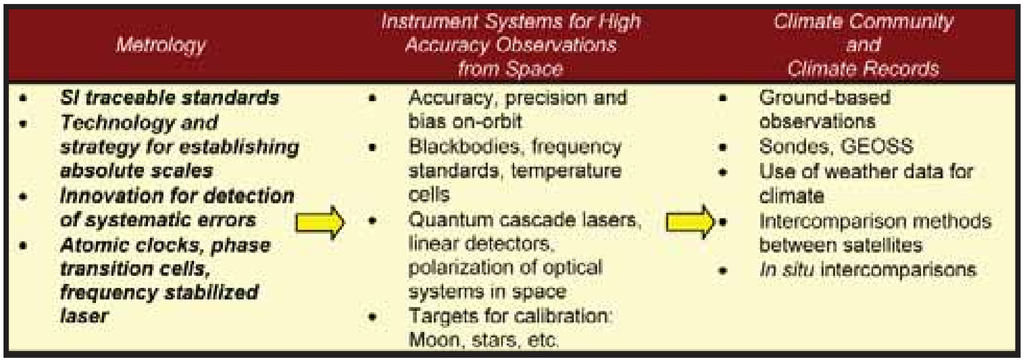
Except for a few exceptions–solar irradiance, earth radiation budget, ozone, and sea level –current long-term climate data records from space-based measurements are derived from instruments designed for short term environmental applications, e.g., weather prediction. While such operational systems have the benefit of continuity of measurement, the instruments do not have the high accuracies needed to measure long term global change. The data records are constructed from a series of limited life satellites. Significant (for climate) systematic differences exist among instruments in the series, and construction of seamless climate records requires accounting for these offsets. These differences can be determined during the time periods of satellite overlap. Fortunately, although not a requirement for the operational satellites, all of the satellites in NOAA's POES series have overlapped one another for varying amounts of time. However, as illustrated by the MSU record (see Section 2), uncertainties in these corrections leads to uncertainties in the climate data record. Unknown instrument drifts during the life of each sensor represents another serious problem. To minimize these problems requires highly accurate, highly stable space instruments. The greater the accuracy, the shorter the time needed to detect a long term climate trend.

These climate requirements for accuracy are neither the objective nor the capability of current systems. Our fundamental responsibility to present and future generations is to:

- Put in place a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards.
- Develop an operational climate forecast that is tested and trusted with a disciplined strategy using state of the art observations in combination with mathematical structures to systematically improve those forecasts to establish credibility.

A key consideration underpinning a national strategy for obtaining climate quality observations from space involves a careful analysis of evolving scientific developments in three important sub-fields: (1) Metrology, the sub-field of physics that addresses measurement accuracy and traceability, as it is practiced at the National Institute of Standards and Technology and in the physics and chemical physics scientific literature; (2) instrument system development, innovative on-orbit calibration technology, orbit selection for climate, etc., for high accuracy observations from space that incorporate Systeme International (SI) traceable standards *on-orbit*; and (3) the Earth Science community that employs climate models, in situ, and remote observations to address the mechanistic coupling of dynamics, radiation and chemistry in the context of climate. These subfields are shown in Table 3 to highlight the distinct contributions that each makes to the development of high accuracy global climate observations from space.

Table 3 Important Sub-Fields Related to High Accuracy Long-Term Climate Records



Metrology	Instrument Systems for High Accuracy Observations from Space	Climate Community and Climate Records
• ***SI traceable standards*** • ***Technology and strategy for establishing absolute scales*** • ***Innovation for detection of systematic errors*** • ***Atomic clocks, phase transition cells, frequency stabilized laser***	• Accuracy, precision and bias on-orbit • Blackbodies, frequency standards, temperature cells • Quantum cascade lasers, linear detectors, polarization of optical systems in space • Targets for calibration: Moon, stars, etc.	• Ground-based observations • Sondes, GEOSS • Use of weather data for climate • Intercomparison methods between satellites • *In situ* intercomparisons

As noted above, when human life is at stake, the fundamentals central to each of the subfields displayed in Table 3 become very important for setting an effective national strategy. Yet in critical instances, these fundamentals are not intrinsic to the nation's climate program, as it is currently constituted.

3.2 Attributes

The key attribute of a climate observing system is:

- High accuracy, verified on orbit, for absolute climate records in perpetuity that are checked against fully independent observations pinned to the International System of Units (SI).

Prior to discussing a strategy for achieving the needed high quality space observations, we define what is meant by accuracy and the associated attributes of measurement quality: precision, bias, and stability.

3.2.1 Accuracy, Precision, Bias, and Stability

Accuracy – Closeness to the truth
Precision – Random error
Bias – Systematic error
Stability – Change of bias with time

Accuracy is a "Measure of how close the result of an experiment comes to the "true" value" (Bevington and Robinson, 1969). It is the measure of the random and non-random or systematic errors that are the offset between an experimental Result (a measured value) and a "True" value for that result. The "True" value constitutes a Standard SI; is the result of physical measurement and analysis; and, is "known to be true" with some uncertainty. A statement of accuracy traced to the International System of Units, abbreviated SI includes the uncertainty that the measure (or Result) is the "True" value. Without an explicit statement that a Result uncertainty is traced to the International System of Units it is possible for the uncertainty to be based upon an arbitrary standard.

Precision, in sharp contrast, is the measure of the random errors of an experimental result without regard to a "true" value, i.e. the uncertainty of the result is or is not traced SI. Experimental results can be quite precise but inaccurate and imprecise yet accurate. Precision is a measure of the random errors and is not a measure of the systematic errors. Increasing the total number of independent results averaged can improve the result precision without reducing the systematic errors. Precision is sometimes referred to as reproducibility or repeatability

Bias is the measure of the non-random or systematic errors of a result. Some arbitrary Reference can be chosen as an invariant to validate a result has some precision. However, an accuracy statement SI is invalid until the uncertainty of the arbitrary Reference can be traced to the International System of Units.

Stability is a measure of the change of bias with time. It is determined relative to a Reference that is arbitrarily chosen or is an absolute SI. It is a term often invoked with respect to long-term records when an SI standard is unavailable. Measuring, often called estimating, the time-dependent, months to years, biases that arise as an operational instrument ages without completing the uncertainty estimate SI ignores the fundamental issue being sought: that the measurement uncertainty is in fact related to a "true" value.

A more comprehensive discussion of these important terms is in Appendix A.

3.2.2 Observational Strategy

Achievement of high accuracy, global climate records from Earth orbit introduces two unique aspects to the metrology of the endeavor. First, the instruments employed on the satellite to obtain the climate observations cannot be recovered such that biases against an SI traceable standard in the laboratory can be established. Second, and as a result, SI traceability on-orbit is required to establish a climate record that is tested and trusted. It must be assumed that the bias, *B*, which develops as a normal aspect of the instrument aging process on-orbit, is time dependent. The unequivocal determination of this time dependence of bias–or stability of the observational record–for any instrument is critical to the strategy of a climate record. The ability to extract long-term trends from climate records depends directly upon the unequivocal determination of the time dependent bias in each of the physically independent observation techniques that are inter-compared to reveal systematic error. The absolute standard must be intrinsic to the design of the instrument and this fact engenders specific strategic choices associated with the design of such an instrument. One conclusion is that the time dependent bias, must be determined by SI traceable standards carried on-board the satellite. That is, the stability of the instrument, which is a measure of the time-rate-of-change of the bias, is a quantity of significance if and only if it can be directly and repeatedly proven against an absolute standard throughout the lifetime of the instrument—as is the case in the laboratory wherein instrument bias is repeatedly measured against an SI absolute scale.

In the absence of SI traceable standards on-orbit, which is basically the case for the current observing system, other approximate methods must be used to determine the stability of the observations. These techniques include the use of external stable calibration targets such as the Moon, stars, Earth reference sites, and aircraft and ground-based observations. Another method to determine the stability of observations, which has been successfully applied to solar irradiance measurements, is to compare the time series of independent measurements. If the time series have a constant offset, then the measurements

If an observation is not initially SI traceable against an absolute scale, it cannot engage in the logic of testing for systematic error. If an observation cannot independently establish its time dependent bias against an SI traceable standard throughout its observing lifetime, it cannot, by the logic of metrology, provide independent evidence of trends in the climate record—it therefore ceases to constitute a climate benchmark.

are stable within some uncertainty. They can then be used to measure *changes* in the variable under observation, but the absolute value uncertainty will include the biases present. The population of solar measurements includes those from each instrument.

Since satellites have finite lifetimes, long-term records must still be constructed from the observations of a series of satellites. Inter-comparisons of satellite observations co-located in time and space, or of overlapping time series, are used to determine, and adjust for, systematic biases between the instruments, thus eliminating jumps in the record. For the current observational system with its relatively large (for climate) systematic differences, such procedures are quantitatively suspect due to the tight accuracies required for the climate data records (e.g., 0.1 C) and the errors associated with these techniques, including difficulties in obtaining precisely simultaneous/collocated observations and overlapping records with the same sampling characteristics. The satellite to satellite intercalibration errors would be considerably reduced, if not eliminated, with benchmark measurements of high accuracy that are SI traceable against absolute standards.

The presence of natural climate variability complicates the problem of detecting trends in the climate system. The effect of measurement accuracy and natural variability on the time required to detect a global warming signal is discussed in the sidebar.

Natural Variability

Detection of long term trends in the climate system is complicated by the presence of natural variability. It is intuitively clear that the larger the natural variability, the longer it will take for a signal to emerge from the time series containing both natural variability and a long term climate trend. The length of time required to detect the signal depends both upon the magnitude of the natural variability and the measurement accuracy. We quantify here this dependence. We then show, with a simple but fairly realistic example, how the length of time needed to detect the expected global warming signal in the presence of the observed natural variability depends on measurement accuracy. For more details see Leroy et al., 2007.

How natural variability influences signal detection can be described by linear regression and its associated error analysis. With a time series of data, for example, annual global mean atmospheric temperature, T, one data point per year (at time t_i) for N years, linear regression gives us a trend m in the temperature time series:

$$m = \left(\sum_{i=1}^{N} (t_i - \bar{t})^2 \right)^{-1} \sum_{i=1}^{N} T_i (t_i - \bar{t})$$

where $\bar{t}$ is the mean time (Williams, 1959; von Storch and Zwiers, 2001). If the standard deviation of the natural variability is σ_v , the measurement uncertainty is σ_m, and both are uncorrelated from year to year, then the squared uncertainty in the determination of the slope is

$$\left\langle (\delta m)^2 \right\rangle = \frac{12(\sigma_v^2 + \sigma_m^2)}{(1\,\mathrm{yr})^2 (N^3 - N)}$$

In order to build confidence in the detection of a trend, one wishes to acquire an estimate of a slope m greater than the uncertainty of its estimate by a factor of S, the signal-to-noise ratio. Notice that it is impossible to distinguish natural inter-annual variability from measurement error, so one adds the two in quadrature.

With estimates of a signal trend, natural variability, and measurement accuracy, it is possible to deduce the amount of time it should take to detect a signal with a predetermined level of confidence. For a trend of 0.2 K decade^{-1} and natural variability of 0.1 K, the table shows the number of years it takes for a signal to emerge with a signal-to-noise ratio of 2 (98% confidence of detection).

Measurement Accuracy	Detection Time
0.00 K	10.7 yrs
0.05 K	11.5 yrs
0.10 K	13.4 yrs
0.20 K	18.2 yrs

Thus, even with a perfect instrument it would take almost 11 years to detect the global warming signal. These detection times would increase further as a result of serial correlation in the temperature time series. But the important points are: 1) detecting expected warming trends in the presence of natural variability takes decades, and 2) reducing the accuracy from 0.1 K to 0.2 K leads to a substantial increase in detection time.

3.2.3 Guiding Principles

These principles from metrology constitute the foundation for the concept of benchmarks as a critically important category of observations that are of fundamental importance to the establishment of a climate record. No climate observation system has been developed in this country, nor does a clear roadmap presently exist to realize this critical national objective. In order to accomplish this goal, it is necessary to establish a set of Guiding Principles for Satellite Climate Observations.

Some Guiding Principles for Satellite Climate Observations

1. Completely independent methods of observing the most critical climate variables from space must be developed, each having accuracies that satisfy the requirements of climate (e.g., 0.1 K for temperature) and that are SI traceable on-orbit to absolute standards.

2. The fundamental requirements of climate must be recognized in the design of instruments that constitute the backbone of the national climate observation array: Optical Designs, Orbits, Calibration, etc.

3. Trust in the accuracy of key long-term climate observations must be built upon: (a) open access to the details of experimental execution; (b) publication in the scientific and technical literature; (c) individual scientific responsibility; and (d) continuity in laboratory, airborne, and satellite analyses that together dissect systematic errors.

4. The experimental design and execution of long-term climate observations must be cost effective, responsive to emerging knowledge, and adaptable to technological innovation.

5. Calibration and associated subsystem development resources must be given high priority and the analysis of accuracy achieved by the observing systems must be systematically critiqued over the period of decades. Fundamental development of calibration facilities at NIST must be supported with ongoing commitment.

6. Primary long-term climate observations must be global in coverage, must provide required accuracies in both horizontal and vertical structure, and must be free of interference from uncontrolled boundary conditions.

7. Climate forecast testing and improvement places specific demands upon the data vector produced by the climate observation and upon the mathematical structure used to couple the observations to the forecast. Thus, selection of the highest priority observations must be done in concert with an understanding of the structure of the forecast model.

A Generalized System-level Approach to Satellite Instrument Calibration

State of the art electro-optical sensors for today's space-based environmental applications require a complete characterization and thorough calibration, especially for climate applications. The generalized system-level approach outlined below encourages early planning and continuity of effort throughout the lifetime of the project (pre- and post-flight) to minimize uncertainty for the intended application. A more detailed discussion can be found in Tansock (2004).

Calibration Philosophy A thorough system-level approach to satellite instrument calibration should address calibration throughout a sensor's lifetime, from the design phase through on-orbit operations, and provide an efficient, cost effective method to perform the calibration. This approach provides a complete calibration, estimates uncertainties in determining various calibration parameters, and minimizes the risk of not meeting measurement requirements.

Complete Calibration A complete sensor calibration provides a thorough understanding of sensor operation and performance. It verifies that the sensor meets the mission instrument requirements, verifies a sensor's readiness for flight, quantifies radiometric and goniometric performance, provides traceability to appropriate standards, and quantifies measurement uncertainties.

A complete and methodical approach to sensor calibration should address all phases including (1) requirements definition, (2) planning during sensor design, (3) subsystem and component measurements, (4) sensor level testing and calibration testing, (5) follow on activities to verify, maintain and update calibration throughout mission life (i.e., ground and on-orbit).

A complete calibration should address each of the five responsivity domains (Wyatt 1978): radiometric, spectral, spatial, temporal, and polarization. In addition, calibration should quantify uncertainty and be traceable to SI standards (ISO, 1992; Pollock, 2003; and Wyatt, 1998).

Good Specifications Improve Calibration
Clear and concise quantitative and verifiable specifications reduce the risk of cost and schedule overruns, having a poorly calibrated sensor and even failure.

Calibration Planning
Calibration planning should start as early as possible. Ground calibration establishes the baseline of sensor performance, but calibration must be maintained with periodic measurements during launch preparations, early on-orbit calibration, and extended on-orbit operations.

Satellite Instrument Validation during On-Orbit Operations
The purpose of validation is to assess performance of satellite instruments by comparison with validating measurements. Apparent differences in results between validating and primary measurement systems are due to mismatches in time and space, differences in vertical and horizontal resolution, limitations of finite accuracy and repeatability, and physical measurement differences (i.e., spectral, sensor, platform, etc.) A validation assessment model can be used to make comparisons more accurate by understanding and accounting for these differences and to better understand the advantages and disadvantages of different validation approaches.

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Infrared Instruments

4.

4.1 Introduction and Overarching Goal

Infrared radiation measurements are a particularly important component of a climate monitoring system in that they are sensitive to critical climate forcing (CO_2, CH_4, N_2O, CFCs, and aerosols) and feedback and response (water vapor, clouds, and temperature) variables. In other words, such measurements, if performed over the entire infrared spectrum, capture the entire magnitude and the details of the anthropogenic greenhouse effect, as well as the details of the Earth's adjustment to this enhanced greenhouse forcing. Current (e.g., Atmospheric Infrared Sounder [AIRS]) and planned (Crosstrack Infrared Sounder [CrIS] and Infrared Atmospheric Sounding Interferometer [IASI]) satellite IR instruments focus on measuring the atmospheric temperature and water vapor profiles and sea surface temperatures needed for weather forecasting. While they can provide some information on climate variations, they have not been designed with long term climate monitoring in mind, and thus do not have the on-board calibration systems and traceability to irrefutable international standards such as those maintained in the US by the National Institute of Standards and Technology (NIST) (Pollock et al., 2000, 2003). However, if calibrated against a benchmark infrared instrument in space, such observations could be transformed to more reliable climate (as well as weather) measurements.

A downward-directed spectrometer in Earth orbit measuring absolute spectrally resolved radiance in the IR with high accuracy (0.1 K/3-σ brightness temperature) is the benchmark instrument that would provide the trusted long term measurements, calibrate the operational IR sensors, and facilitate rigorous testing of climate forecasts. Both the radiative *forcing* of the atmosphere resulting from greenhouse gas emissions and aerosols and the *response* of the atmospheric variables are clearly observable in the spectrally resolved signal of the outgoing radiance. The increase in greenhouse gas concentrations and aerosol loading imply changes in the spectral distribution of outgoing IR radiation. Similarly, large differences among model projections of temperature, water vapor and cloud distributions imply, for each model, different predicted changes in outgoing radiation. The spectrum of IR radiance, if observed accurately and over the full thermal band, carries decisive diagnostic signatures in frequency, spatial distribution, and time. At satellite altitudes, the boundary conditions on radiative processes can be measured without interference.

Overarching Goal

The overarching goal is to realize a state-of-the-art climate observing system by augmenting currently planned infrared (IR) measurement capabilities with an orbiting benchmark infrared mission.

4.2 The Role of Infrared Radiance Observations in Climate Studies

Figure 3 shows the spectrally resolved radiance encompassing the thermal IR emitted from Earth to space observed by a nadir viewing interferometer. Here, different spectral radiances are linked to the atmospheric features they represent. Rotational lines of water dominate emission between 200–600 cm^{-1} and, in combination with the 200–400 cm^{-1} and the 800–1000 cm^{-1} spectral interval, determine the presence of clouds. Spectral features of CO_2, CH_4, N_2O, CFCs, and other well-mixed greenhouse gases clearly reveal climate forcing from the release of these species over time. Atmospheric windows in the water vapor channels allow

IR sensing of the sea and land surfaces to observe the important time/space thermal changes that influence the atmospheric climate system. There is no other single measurement that can yield such a wide range of key climate information. The dynamic range of the individual line strengths of emission from water vapor, carbon dioxide, and ozone is such that temperature, water vapor, and cloud changes in the atmosphere are detectable from specific layers of the atmosphere.

4.3 Current Status and Impediments to Progress

The experimental and technological foundations now exist for obtaining SI traceable spectral IR measurements for climate. A key aspect in the achievement of SI traceability on-orbit is the important role of spectral resolution as discussed in Appendix B. The accuracies attained for current sensors that were designed without the benefits of these advances are not sufficient for meeting the national objectives for climate. For example, current operational IR sensors exhibit discrepancies larger than the stated instrument uncertainties and larger than the accuracies required to resolve global climate change established in the 2002 workshop (Ohring et al., 2005).

A case study investigating the differences between sea surface temperatures obtained from two different sensor types is presented that typifies this problem. In Figure 4, the difference between a global IR sea surface temperature (SST) and one computed from simultaneous passive microwave data from the Advance Microwave Spectral Radiometer (AMSR) is plotted. This difference was corrected for all known bias errors in both AVHRR and AMSR data. There are still large areas of this map of monthly global difference that exceed 0.5 K.

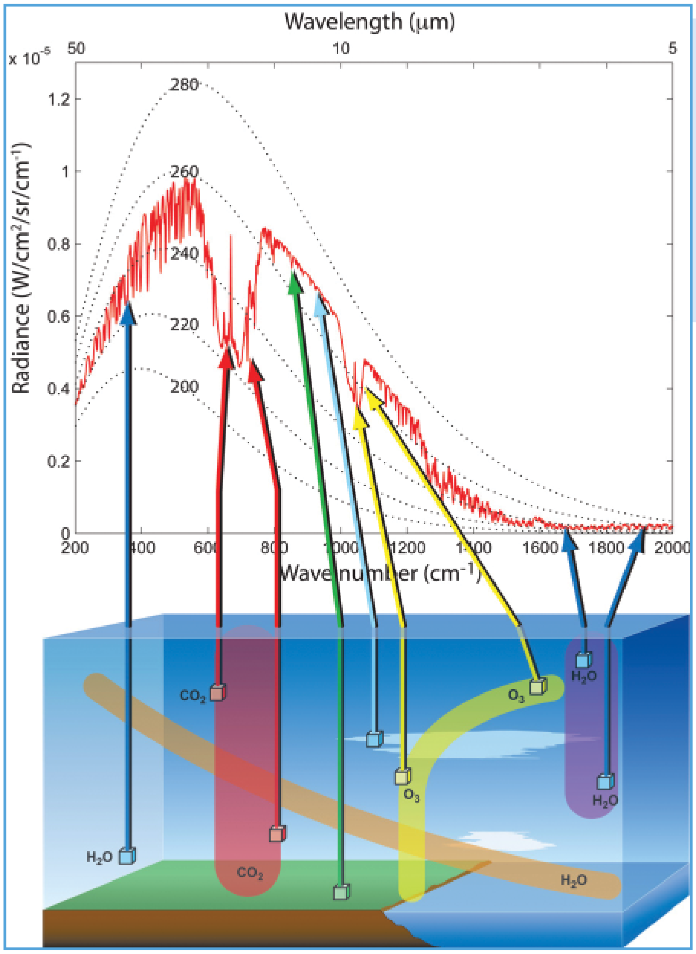
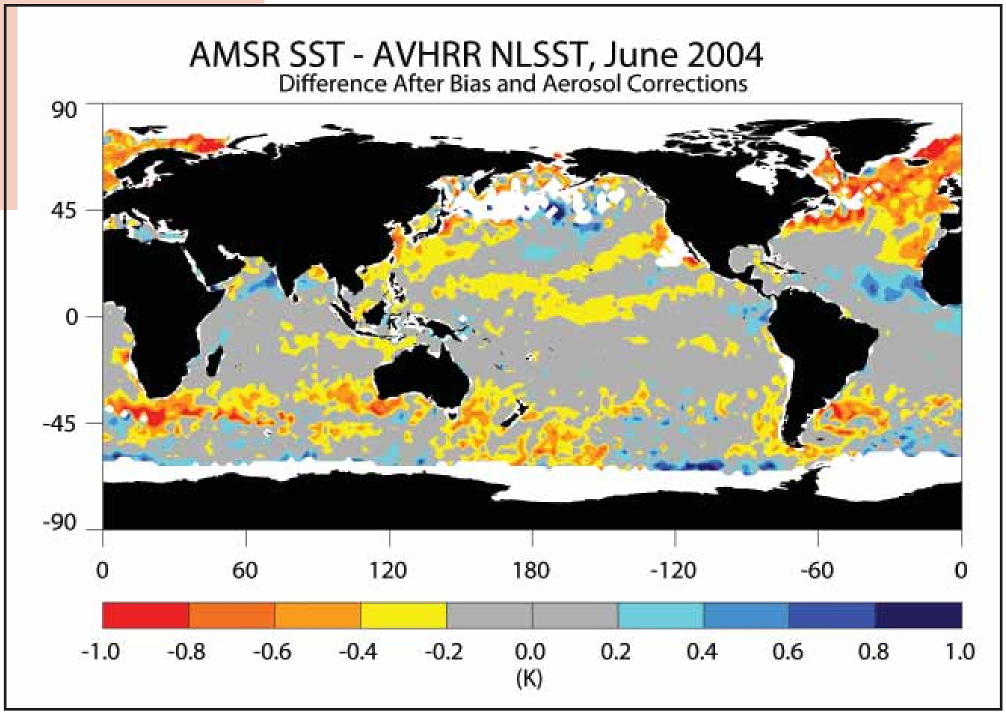


Figure 3 The thermal IR spectrum. Frequency is in wavenumbers (cm^{-1}), radiance in W cm^{-2} sr^{-1} (cm^{-1})$^{-1}$. Water vapor exhibits strong, narrow lines in the frequencies intervals 200–550 and 1100–1500 cm^{-1}. Carbon dioxide absorbs in its ν_2 band in the frequency interval 550–770 cm^{-1}. The area under this curve measures the flux of thermal IR energy radiated to space, thus cooling the Earth system.

Figure 4 SST difference between AMSR and AVHRR for June 2004 (white indicates persistent cloud cover and black is land; Castro et al., 2007).



On-orbit sensors generally degrade over time. Without some type of very stable on-orbit calibration source this "drift" is difficult to detect, let alone compensate for. Therefore, the accuracy and stability of both onboard and external IR calibration sources are extremely important.

In the IR, relatively few external calibration sources can be used. The Moon, with dayside temperatures up to ~390 K, night side below 100 K, and 70–80 K variations across the sunlit surface, presents significant dynamic range issues. Stars are generally too weak and do not have the appropriate temperatures to be effective for IR sensors designed to measure climate variables. In addition, reference sources onboard many spacecraft are not adequate to provide the accuracy needed in the routine measurement of IR temperatures. For example the "pseudo black-body" in the Advanced Very High Resolution Radiometer (AVHRR) does not adequately provide a reference value for IR temperature measurement when compared with the much more precise black bodies flown with the Along Track Scanning Radiometer (ATSR). Added to this problem is the assumption that the backplane used as a reference for the AVHRR is thermally homogeneous, which is frequently not the case.

Some investigators have tried to use Earth surface targets for IR validation, a process termed "vicarious" validation (Los et al., 1994), but there are difficulties with this approach. First, atmospheric attenuation of the IR signal must be corrected for, which leads to uncertainties larger than acceptable for climate measurements. Second, it assumes the ground targets are uniform and stationary, which is not likely. Still, these efforts can be an important way to inter-compare sensor performance on-orbit.

Simultaneous observations at orbital intersections (Cao et al., 2002, Cao et al., 2005) of two or more sensors with similar spectral bands and coverage allow for sensor-to-sensor cross-verification and should be an important element of any calibration/validation program. These observations can be used to quantify sensor-to-sensor variability but will not produce irrefutable traceability to SI standards – a fundamental requirement to understanding climate.

Even the best calibration/validation program will not overcome the lack of continuity when spectral bands and their spectral response are chosen without considering previous satellite missions. Efforts are currently underway to make new sensors consistent with the old, thereby providing a long time series of measurements in the same spectral range. Even using the same nominal spectral bands will result in some differences between bandpass instruments. Examples of these effects are given in Appendix C.

Analysts are struggling to understand why a comparison of simultaneous spatial, spectral and temporal data from a pair of instruments exceeds the stated uncertainty for both instruments. While the pre-and post-launch remote sensor radiometric calibrations are stated as meeting an uncertainty, the uncertainty is in fact not traced to SI as directly as possible, or does not include independent cross-checks. Many IR calibrations are traced to SI through temperature sensors. Numerous examples have been reported in the literature of temperature errors associated with mounting stress or handling stress on platinum resistance thermometers (PRT) temperature sensors that are commonly used in blackbody sources (Carter et al., 2006; Rice et al., 2003; Jarecke et al., 1993, and Horne and Toole, 1980). NIST has made significant advances in both source and detector based IR radiometric standards (Rice et al., 2004; and Eppeldauer et al., 2003). Meeting the climate change requirements requires that all of the available tools be used and inter-compared. Until this situation is remedied by following the most fundamental of scientific protocols and stating uncertainties in SI units, it will not be possible to adequately quantify climate change variables with the certainty required.

Practical considerations dictate that an Earth observing infrared instrument for climate will utilize only source-based scales on-orbit. Thus it becomes further necessary to demonstrate the fidelity of the on-orbit blackbodies to their pre-launch performance at the required level throughout the lifetime of the instrument. This objective requires specialized blackbodies, which are designed to be robust to degradation in the space environment and self-monitoring. Designs for blackbodies and complete Earth observing spectral IR radiometers that meet these objectives have been reported in the peer-reviewed literature but are not currently planned for flight (Dykema and Anderson, 2006).

4.4 The Challenge

Separating Climate Forcing from Climate Response

One of the most critical requirements for any climate observing strategy is the ability to uniquely separate the forcing and response of the climate system. In order to maintain equilibrium of the climate system over time (for a given incident and reflected solar irradiance) the radiative forcing by greenhouse gas emission in combination with the resulting increase in volatile infrared active molecules must be offset by the temperature response of the surface and atmosphere). Thus, if we take long-term climate averages, integrated over the thermal IR as a broad-band instrument would report, forcing and response would cancel. In sharp contrast, an instrument that possesses spectral resolution can uniquely separate and calibrate forcing and response. Also of great importance for climate is the fact that an instrument that possesses spectral resolution—and thus the ability to determine the spectral response function and absolute calibration on-orbit—not only separates forcing and response but also calibrates each component separately against SI traceable standards on-orbit.

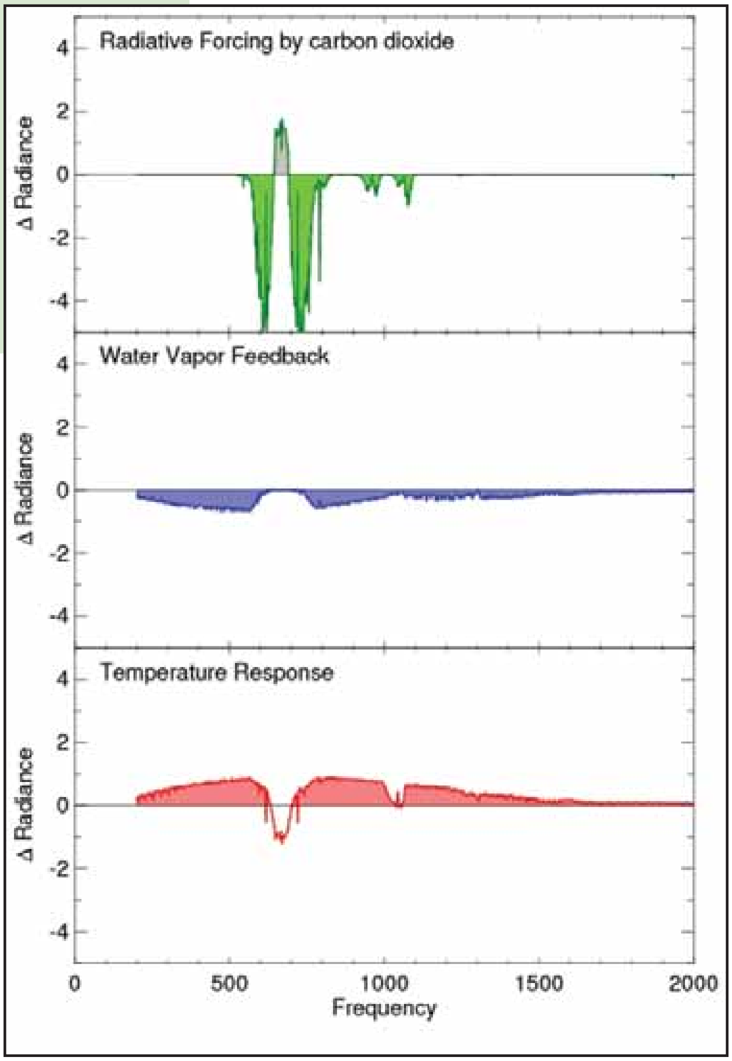


Figure 5 Perturbations to the IR spectrum by the addition of 10 years of carbon dioxide, by the increase in water vapor resulting from a temperature increase, and by the final perturbation to tropospheric temperature. The radiance perturbation units are mW m^{-2} $(cm^{-1})^{-1}$ $(decade)^{-1}$, plotted against frequency in cm^{-1}. Computations done using SRES-A1B forced run of CCSM3 in the Tropics with MODTRAN version 4 used to simulate IR spectra. Clouds were not included.

Expected changes in the IR spectrum due to CO2 increases over a 10-year period are shown in Figure 5. These are very small changes, indeed, in comparison to the baseline spectrum shown in Figure 3. Fractionally, perturbations are < 1% over the ten-year interval. Any instrument used to monitor changes in the IR spectrum must therefore be accurate or stable to about 0.1%.

4.5 Recommendations to Accelerate Progress

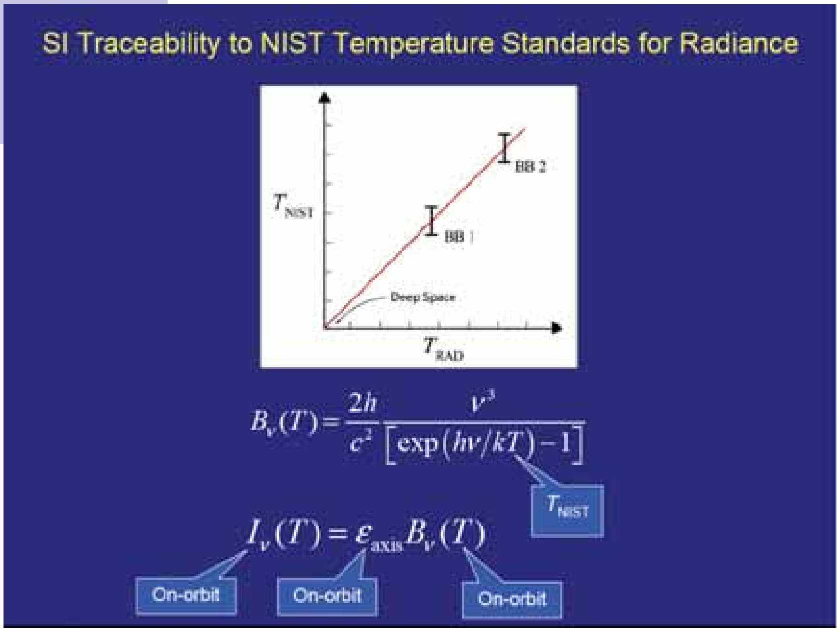
The overall goal is to realize a state-of-the-art climate observing system by augmenting currently planned IR measurement capabilities with higher accuracy spectral measurements. It is expected that a satellite mission will allow this important goal to be achieved. By providing a standard in space for radiometric inter-comparison this addition would leverage the far more extensive spatial sampling provided by the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the Geostationary Operational Environmental Satellite-R (GOES-R) to elevate these planned operational systems to the level of a very capable, dual-purpose system for weather and climate. This approach would avoid imposing the climate change monitoring requirements on systems such as NPOESS and GOES-R, whose highest priority is weather observations. This approach also avoids the mass and power impact of adding a more accurate and stable blackbody to every observing system. In addition to improving the accuracy for all of the current and planned operational systems, this instrument could be used to fill some of the spectral and diurnal sampling gaps.

The major step is to design and fly a mission to augment the planned new operational systems such as NPOESS and GOES-R. That mission must (1) fill in coverage of the far IR portion of the spectrum, (2) make observations that are SI-traceable on-orbit according to the principles laid out in this report, (3) have a signal-to-noise that allows the new system to serve as a standard of comparison for improving the operational system, and (4) incorporate the ***Guiding Principles for Satellite Climate Observations*** of Section 3.2.3. In addition, every effort should be made to incorporate improved absolute accuracy and spectral sampling into our upcoming and future operational sensors. These two basic steps will make the upcoming operational environmental satellite system far more capable for assessing climate change as soon as it gets on orbit and will assure that it continues to grow in capability as a combined weather and climate system. And it is achievable in the early NPOESS Preparatory Platform (NPP) time frame at a very modest cost, a key factor for the current circumstances of our economy.

4.5.1 Approach to Achieving SI Traceability in the IR

Establishing SI traceability on-orbit in the thermal IR is shown diagrammatically in Figure 6. The figure emphasizes four points. First that the radiance scale is built upon a very simple foundation— the Planck function. Second, the absolute temperature scale must be established on-orbit, and accomplished on-orbit by the use of the phase transition temperature of a pure element, such as gallium. While PRTs calibrated against NIST standards in the laboratory would be used, they would be checked independently against the phase transition temperature of one or more elements. Third, the emissivity of the blackbodies used to establish the radiance scale would be determined directly on-orbit in combination with high aspect ratio blackbodies that provide a very large ratio between surface emissivity changes within the cavity and the on-axis emissivity of the cavity that sets the radiance scale. This greatly facilitates the conversion of measured changes in the reflectance characteristics of the interior blackbody surfaces to changes in the on-axis emissivity by suppressing the latter by some two orders of magnitude over the former. Fourth, detector chain linearity can be verified by the use of two independent blackbodies with programmable temperature ranges coupled with deep space view that uniquely sets the intercept. Another approach that can be used to measure detector chain linearity makes use of the small signal linearity technique which is independent of an absolute source and has shown great success for ground calibration measurements (Bird et al., 2003; and Larsen et al., 1997). This approach should also be considered for on-orbit linearity calibration.

Figure 6 Establishing SI traceability on-orbit in the thermal IR.

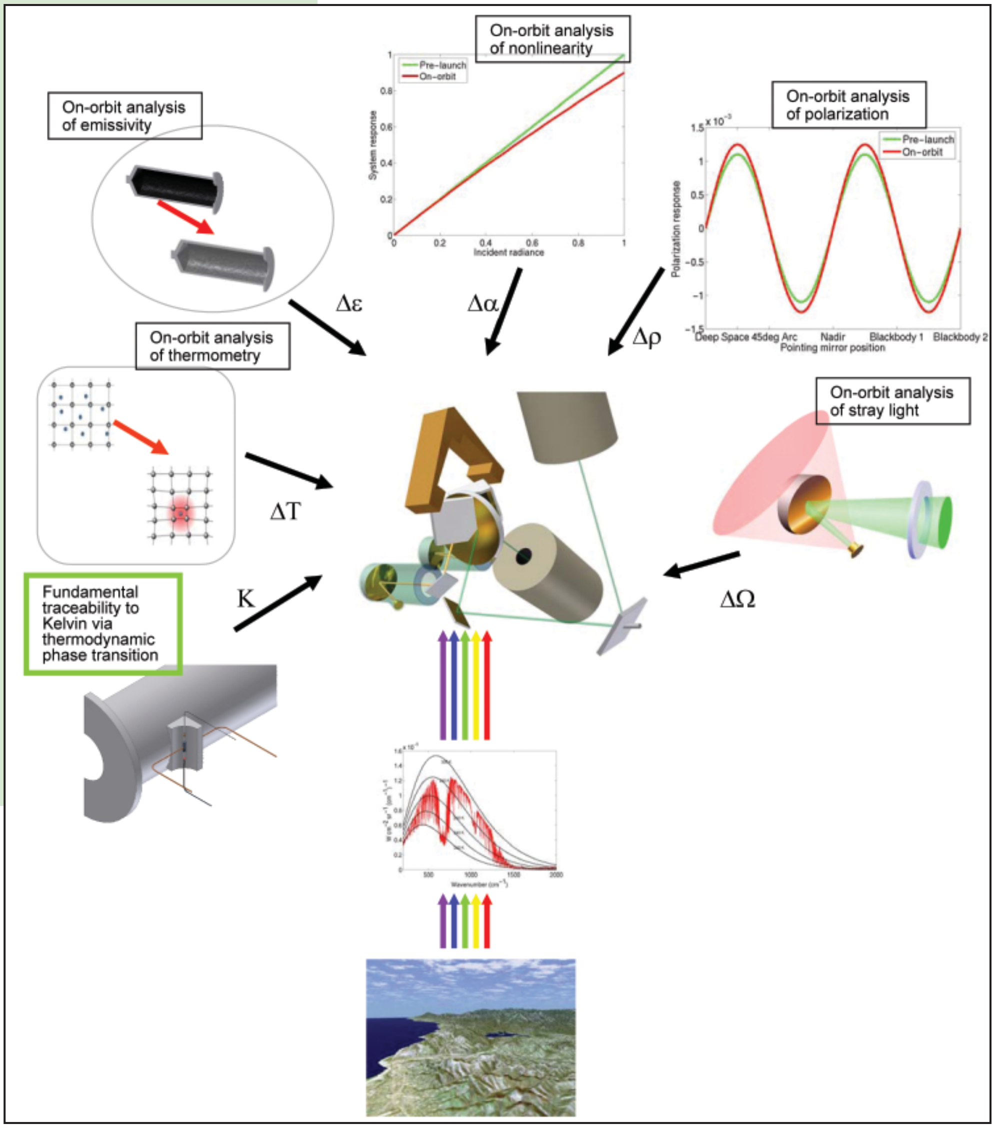


SI Traceability to NIST Temperature Standards for Radiance

$$B_\nu(T) = \frac{2h}{c^2}\frac{\nu^3}{\left[\exp(h\nu/kT)-1\right]}$$

$$I_\nu(T) = \varepsilon_{axis} B_\nu(T)$$

Figure 7 SI traceability is proven on-orbit by checking each significant source of measurement uncertainty throughout the mission lifetime. The fundamental traceability of the on-orbit calibration is established through the fixed-point temperature reference, illustrated by the miniaturized gallium cell at lower left. Moving clockwise, the measurement uncertainty due to blackbody thermometry (DT), blackbody emissivity (De), detector signal chain nonlinearity (Da), the polarization effect (Dr), and stray light (DW) must each be shown to hold below the threshold set by the climate science objectives.



4.5.2 High Level Initiative

The following is the single most important recommendation or top-level initiative from the IR breakout group: Realize satellite measurements that are International Standards (SI) traceable on-orbit and spectrally resolved radiance measurements in the thermal IR that provide climate level accuracy in perpetuity (<0.1 K brightness temperature a 3-σ value).

We recommend that a mechanism to achieve this goal be urgently developed in the next three years. We believe the next major step is to design and fly a benchmark mission that is SI traceable and will provide a cross-calibration reference for existing and future research and operational IR satellite-based instruments. This benchmark mission must (1) employ a new generation of absolute temperature scale on orbit, (2) observe blackbody cavity emissivity directly on orbit, (3) observe instrument polarization directly on orbit, (4) test instrument linearity directly on orbit, and (5) test for stray light on orbit.

Recommended High Level Measurement Specifications for Benchmark System

Radiometric Accuracy:	<0.1 K brightness temperature at scene temperature, 3-σ (including all sources of error except noise)
Spectral Coverage*:	Complete coverage from 5-50 microns (Nyquist sampled)
Spectral Resolution*:	< 1 cm^{-1} Full Width Half Maximum (FWHM)
Spatial Resolution:	Optimized for the dual purpose of regional climate observations and serving as a calibration inter-comparison standard (range of 50-100 km)
Temporal Coverage:	Coverage of the diurnal cycle including semi-diurnal and higher harmonics, selected to minimize climate sampling biases

** Reasonable exceptions might be considered in designing an optimized system*

4.5.3 Additional Recommendations

- Every effort should be made to incorporate improved absolute accuracy and spectral sampling into our upcoming and future operational satellite sensors.
- Climate change measurements place stringent requirements on accuracy, precision, and stability of our observations. To reduce the risk of not meeting these requirements, a calibration plan from beginning to end-of-life (i.e., ground to on-orbit operations) should be developed as early as possible (preferably during instrument design). This must be a collaborative effort between the science team and instrument engineers.
- To promote mission success, in accordance with an approved calibration plan, calibration and validation resources (budget, personnel, schedule, hardware, etc.) should be given high priority and not be the first area to be cut when schedule and budget become tight.
- A supporting Science Team, collaborating with the Principal Investigator (P.I.) or Project Scientist, should be formed, with adequate resources from instrument design through end-of-life. Resources should be sufficient for the Science Team to analyze data from instrument testing, model sensor performance, examine quantitatively the effects of relaxing requirements, etc.
- IR calibrations at the NIST Spectral Irradiance and Radiance Calibration with Uniform Sources (SIRCUS) facility should be further improved in the thermal IR for climate objectives. Climate objectives would also benefit from the development of new fixed point blackbodies operating at temperatures between 200 and 350 K.
- New instrument designs should better utilize detector and source based scales (traceable to NIST) to achieve and maintain SI traceability from pre-launch through and including the operational environment. For example, whenever possible, on-board calibration sources should be based on physical principles (i.e., physical constants, etc.), and required to have radiometric traceability to NIST standards. For this reason, further development of thermal IR on-board calibration sources is needed.
- Careful and sufficiently detailed pre-launch calibration is required to establish the

instrument accuracy and minimize the risk of discovering a problem on-orbit.

- It is recognized that there are many compelling science applications for climate change in the far IR (wavelengths greater than 15 microns). For example, up to 50% Outgoing Longwave Radiation (OLR; surface + atmosphere) is beyond 15.4 microns. Continued further development of instrumentation and calibration of measurements in this spectral region is recommended.

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5.

Ultraviolet, Visible, and Near-Infrared Instruments

5.1 Introduction

Ultraviolet (UV), Visible (VIS), and Near-Infrared (NIR) instruments observe spectral solar radiation that has been reflected or scattered back to space by the Earth's surface, clouds, and atmosphere. These observations are used to measure: snow and ice cover, health and vigor of vegetation, ocean chlorophyll, cloud amounts and thicknesses, atmospheric aerosol amounts, and the total amount and vertical profile of atmospheric ozone and other trace gases. As in the case of the infrared, the reflected solar radiation spectrum provides important information on climate forcings (net solar radiation, ozone, aerosols), and responses and feedbacks (clouds, snow and ice cover, and vegetation).

The workhorse instrument for long term records of VIS and NIR observations has been the Advanced Very High Resolution Radiometer, which NOAA has flown on its polar-orbiting satellites since 1979. Designed for weather imaging applications and not climate monitoring, the AVHRRs, unfortunately, have no on-board calibration systems for their VIS/NIR measurements. Neither does the visible channel on the Imager on NOAA's GOES satellites. Calibration of these instruments depends on the pre-launch laboratory calibration modified by vicarious calibrations against stable desert sites while the instruments are in orbit. More recent VIS/NIR instruments, e.g., NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), do contain on-board calibration devices, and operational instruments planned for NPOESS and GOES-R will include this component. UV instruments, such as NASA's TOMS and NOAA's SBUV series, which were designed specifically to detect small long term ozone trends, have had on-board solar diffusers since 1979 to monitor instrument radiometric stability.

Accuracy and decadal stability requirements for satellite measurements in the reflected solar bands are becoming increasingly stringent for climate and weather applications, requiring even more careful attention to pre-launch and post-launch instrument calibration and validation. The Visible Infrared Imager / Radiometer Suite (VIIRS) presently under development for the polar-orbiting NPOESS platform has a 2 % ($k = 1$ or 1σ) measurement requirement for top-of-the-atmosphere band-integrated radiances measured by its M1 through M11 visible to short-wave infrared moderate resolution spectral bands (Murphy et al., 2004). Geostationary satellites likewise require small measurement uncertainties. The GOES-R Advanced Baseline Imager (ABI) has a measurement requirement of 3 % ($k = 1$ or 1σ) for the visible and short-wave infrared band-integrated radiances (Geostationary Operational Environmental Satellite (GOES), 2004). These challenging measurement requirements must be maintained throughout the operating life of the instrument.

Satellite measurements must be tied to fundamental standards based on the SI International System of Units to ensure comparability of measurements between different satellite sensors and between satellite and non-satellite sensors. The internationalization of environmental monitoring, as illustrated by the Global Earth Observation System of Systems (GEOSS) initiative, is increasing the importance of SI traceability to ensure measurement comparability over generations, independent of the nation performing the measurement. For U.S. satellite programs such traceability is obtained typically through spectral radiance, irradiance, transmittance, and reflectance standards maintained and disseminated by NIST. These programs procure standards either directly from NIST or indirectly through secondary standards laboratories. The standards are used to perform the pre-launch calibration and characterization of the sensor and associated reflectance standards used for later on-board calibration. Validation of the satellite measurements through satellite measurement intercomparison, ground truthing with vicarious targets, and lunar and stellar observations provides an independent assessment of the quality of the calibration and of the stability of the sensor and on-board standards.

5.2 Current Status

5.2.1 Pre-launch calibration

For ultraviolet-to-short-wave infrared instruments operating in the 150 nm to 2500 nm wavelength region, pre-launch calibration and characterization include radiance, irradiance, and reflectance calibration and spectral, spatial, and polarization characterization. The characterization and calibration effort extends to on-board standards such as solar-illuminated Lambertian diffusers required for transferring and maintaining the ground-based calibration to orbit.

Complete pre-launch calibration and characterization of the sensor is critical for resolving on-orbit anomalies. Such completeness is difficult to achieve, with stringent timelines and delays in sensor development often severely constraining the time for calibration. Once launched, the instrument calibration is subject to change due to launch vibration, temperature gradients, contamination, radiation damage, and other unanticipated events. Unfortunately, the evidence for such a change in calibration on orbit is often incomplete. Despite the lack of such evidence, extensive pre-launch calibration and characterization offer the opportunity to recover the pre-launch calibration. For example, a shift in the wavelength scale may be apparent at strong solar or elemental lamp lines, but be uncertain elsewhere in the spectrum. Full pre-launch characterization of the wavelength scale may allow for a complete wavelength recalibration based on a small number of on-orbit reference wavelengths. Sophisticated instrument models continually maintained and updated throughout mission life are important components of any on-orbit recalibration attempt.

5.2.1.1 Radiance Calibration

For the radiance calibration of a sensor, a lamp-based spherical integration source (SIS) is often used as the calibration light source. The SIS provides a source of broadband radiance for illuminating the Earth-view port for satellite sensors such as the NASA EOS Moderate Resolution Imaging Spectroradiometer (MODIS), the planned NPP and NPOESS Visible/Infrared Imager Radiometer Suite (VIIRS), the projected GOES-R Advanced Baseline Imager (ABI), etc. A range of lamp output levels or configurations are required to determine a sensor's non-linearity, dynamic range, signal-to-noise ratio (SNR), and short-term stability.

Alternatively, the lamp illumination source can be replaced by a high-power laser source to provide a narrow bandwidth, wavelength tunable source of radiance for instrument characterization and calibration. We note that a 100 cm diameter, 45.72 cm diameter exit aperture sphere such as the Raytheon/SBRS SIS100 used in the calibration of MODIS and Landsat 7

ETM+ instruments (Butler et al., 2003) can provide radiance levels commensurate with typical on-orbit values in a 20 nm full bandwidth when illuminated by < 1 W of laser power for a sphere surface reflectivity of 0.98. The NIST SIRCUS facility (Brown et al., 2000; Brown et al., 2006) has been developed to take advantage of tunable laser-based radiance standards for the calibration and characterization of remote sensing instruments. SIRCUS has been used to calibrate and characterize the EPIC sensor (Early et al., 2002) for the recently cancelled DISCOVR satellite (National Research Council, 2005), as well as a number of ground-based sensors.

The use of an integrating sphere in the radiance calibration of VIS/NIR instruments requires that the sphere be carefully designed and completely characterized. Lamps internal to the sphere should be appropriately positioned and baffled to eliminate direct viewing by the instrument being calibrated and to ensure that light from the lamps is reflected multiple times before exiting the sphere. The lamps should be current controlled with regulated power supplies and the voltage across each lamp should be monitored and recorded during sphere operation. In addition, the output of the integrating sphere should be monitored using stable multifilter radiometers or scanning spectroradiometers during operation. The radiance output should also be mapped for uniformity over the entire exit aperture in advance of any calibrations.

The effect of stray light also needs to be adequately addressed when using a sphere as a radiance standard, particularly when the sensor is calibrated in the near field. For a well-baffled sensor telescope system, the dominant near-field stray light is radiation reflected, i.e., retroreflected, from the primary telescope mirror back into the sphere where it is summed with the primary radiance coming from the sphere and redirected into the sensor. The magnitude of this stray radiation can be calculated from the measurement geometry and further characterized by varying the sphere-sensor separation. The change in sphere output radiance upon coupling to the sensor, as quantified with a radiometer coupled to a monitor port of the sphere, can be used to quantify the magnitude of retroreflected stray light.

Irradiance standard lamps illuminating diffusely reflecting targets have also been employed in radiance calibrations of UV/VIS/NIR instruments. Typically, a 1000 W quartz tungsten halogen FEL lamp is used as the irradiance source and a pressed and sintered poly-tetrafluoroethylene (PTFE) plaque is used as a highly reflective diffuser, both tied to NIST standards. NIST disseminates FEL lamps and deuterium lamps as standards of spectral irradiance from 200 nm to 2500 nm. NIST also provides measurements of the bidirectional reflectance distribution function (BRDF) of diffuse reflectance standards for use by calibration laboratories in their realization of a spectral radiance scale. A measurement intercomparison in support of the Earth Observing System (EOS) program demonstrated that laboratories providing BRDF measurements for remote sensing programs can obtain results agreeing to within 2% of NIST values (Early et al., 2000). NIST uncertainties are on the order of 0.5% ($k = 2$), dependent on wavelength and geometry.

The use of a lamp-illuminated diffuse target as a source of known radiance for instrument calibration has been extensively documented and validated (Walker et al., 1987a). Intercomparisons between integrating sphere and irradiance-illuminated reflectance radiance standards have generally shown excellent agreement, on the order of 2 % for a recent comparison undertaken for the SIMBIOS program (Meister et al., 2003). Proper lamp mounting, alignment, and baffling, expected irradiance uncertainties, and recommendations for recalibration have been summarized (Walker et al., 1987a). Of critical importance is the correct determination of the lamp-diffuser separation. Also, the lamp must be carefully baffled in accordance with recommendations provided in NIST SP250-20 (Walker et al., 1987a, Walker et al., 1987b) as the lamp-diffuser combination offers more opportunities for sources of stray light relative to integrating sphere radiance standards.

Measurements of the diffuser's bidirectional reflectance distribution function (BRDF) are required at the operating wavelengths of the instrument under calibration. The spatial and angular variability of the lamp-diffuser radiance and how it is coupled by the sensor optics to the detector elements must also be understood. Finally, diffuser plaques should be stored and transported with care to limit surface damage and absorption contamination which can change the reflectivity and induce unexpected fluorescence.

5.2.1.2 Solar Diffuser

The reflectance-based calibration of a satellite sensor requires complete characterization of the bidirectional reflectance distribution function (BRDF) of a sensor's on-board solar diffuser over the range of solar illumination and sensor view angles realized on orbit (see Figure 8). Such a characterization is time-consuming because of the range of operating wavelengths and on-orbit solar illumination angles realized for a typical sensor. MODIS, for instance, has 20 reflective solar bands extending from 412 nm to 2130 nm all dependent on the on-board diffuser for calibration. The reflectance of the MODIS diffuser was characterized pre-launch over azimuth angles from -31° to -15° and elevation angles from 10.5° to 14.5°.

Figure 8 Picture of the MODIS Solar Diffuser from modis.gsfc.nasa.gov/about/soldiff.php

Complete pre-launch characterization of a satellite's on-board solar calibration system also requires measurement of the transmittance of the solar attenuator or screen, if present, that is used to reduce the solar irradiance on the diffuser, so that the resulting radiance levels are commensurate with Earth-view levels. For MODIS, the screen consists of a series of 2 mm diameter by 25 μm thick pinholes at a density of 2.71 cm^{-2}, providing a nominal transmittance of 7.8%. The use of such a screen can give rise to a frame-to-frame variation in the number of transmitted light rays illuminating the detector footprint on the diffuser, where each light ray corresponds to the light transmitted through one of the pinholes of the screen (Xiong et al., 2003a). The effect of such a variation on sensor measurements can be as large as 0.05% if uncorrected (Xiong et al., 2003a).

These diffuser and solar-screen subsystem characterizations are assimilated into a system-level model of the instrument response for comparison against a full system-level test of the solar diffuser. A high-quality stray-light model of the sensor-diffuser-attenuator system is critical for developing a system-level model of the instrument response. Accurate knowledge of the BRDF of the interior surfaces/coatings in the diffuser-sensor housing at the various possible angles of incidence for stray radiation is critical for a successful modeling. Such stray-light modeling should also consider the possibly of Earth-shine illuminating the on-board diffuser during sensor viewing (Mills et al., 2005).

5.2.1.3 Relative Spectral Response

The characterization of the in-band and out-of-band relative spectral responses (RSRs) of a sensor is typically performed pre-launch using the output of lamps spectrally dispersed with a monochromator. By monitoring the output of the monochromator with a calibrated reference detector, the spectral responsivity of the sensor is determined. Alternatively, a tunable laser illuminated integrating sphere source (Brown et al., 2002) shown schematically in Figure 9 could be used to measure the relative spectral response.

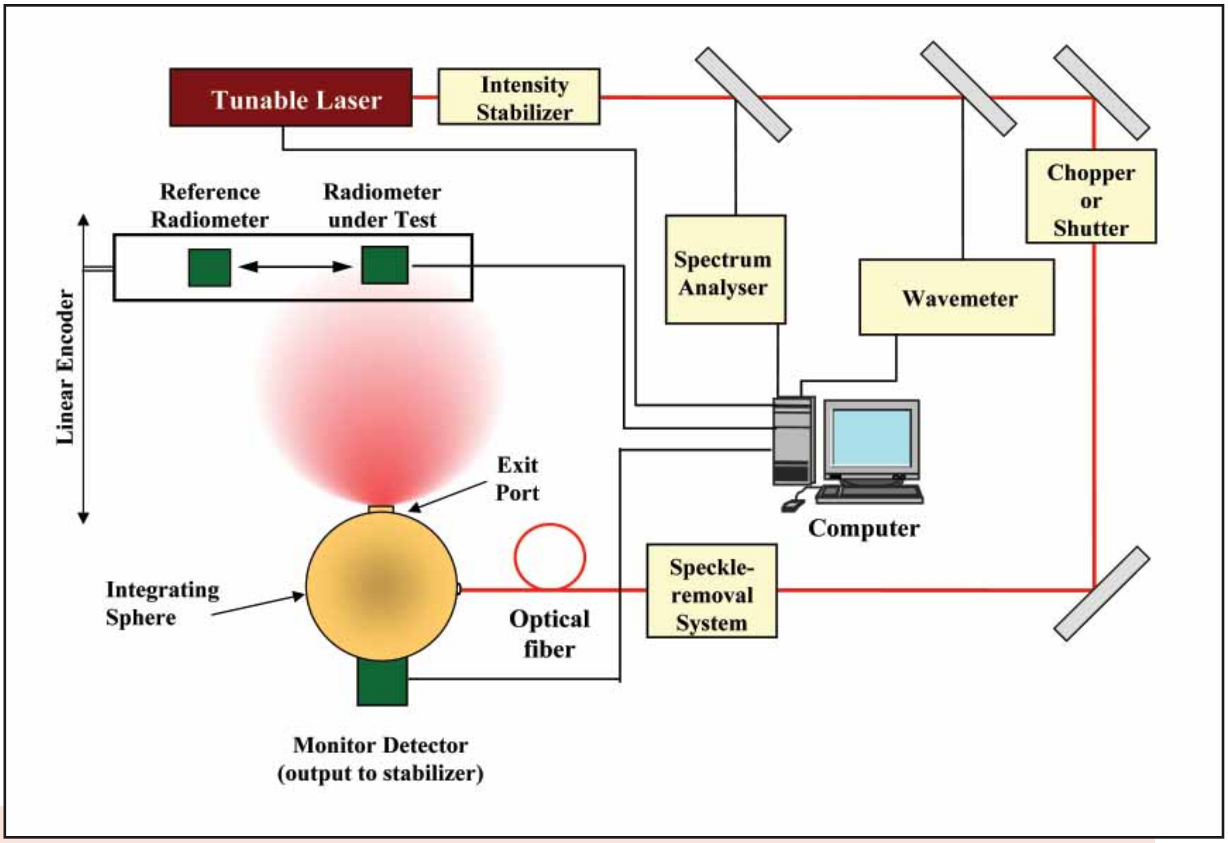

Figure 9 Schematic diagram of the NIST Spectral Irradiance and Radiance Responsivity Calibration using Uniform Sources (SIRCUS) Facility.

Such a laser source provides greater in-band output power, no out-of-band stray light, greater spectral resolution, and higher dynamic range. As laser technology decreases in cost and improves in usability it is expected to replace lamp-monochromator systems for the spectral calibration of sensors.

For many Earth Science applications the relative response between two spectral bands over the same spatial scene is of greatest interest. The ability to accurately determine this ratio is critical for obtaining high quality data products. The possibility of slight variations in spatial footprints between filter bands needs to be considered.

The relative spectral response of filter-based sensors is dominated by the filter transmittance. Filter witness samples should be maintained by sensor programs for later remeasurement when inconsistencies appear in on-orbit measurements. In a retrospective analysis of filters on the NOAA-N´ HIRS/H304 infrared sounder, significant discrepancies were found between original vendor measurements and NIST measurements of filter transmittance peaks (Cao et al., 2004).

5.2.1.4 Polarization

The characterization of the polarization response is needed to ensure that satellite instrument measurements meet science-driven remote sensing specifications. Polarization characterization is particularly significant for scanning imaging radiometers and can be on the order of 1 to 4 % in the visible through near infrared (Barnes et al., 1998; Knight et al., 1999). The polarized response of an instrument must be determined over its complete range of on-orbit viewing angles and for all operating wavelengths. This implies that the spectral response versus scan-angle (RVS) of an instrument's scanning optics must be carefully characterized prior to launch for both *p*- and *s*- polarizations. Various strategies have been developed to reduce the sensitivity of the sensor to polarization, such as the use of a depolarizer on SBUV/2 or direct measurement of the polarization on GOME (Hartmann et al., 2001).

5.2.1.5 Spatial Characterization

Pre-launch spatial or geometric characterization of a satellite sensor is necessary to determine whether that sensor will meet its performance specifications and to determine the geometric characteristics of the sensor and all ancillary data to enable image processing. Key to this activity is the accurate determination of a sensor's field of view over all scan angles, detector fields of view, and band centers. New calibration technology under development based on micromirror arrays, such as pictured in Figure 10, offers the opportunity to recreate the spatial, spectral, and temporal scenes as experienced by a sensor on orbit (Rice et al., 2006). Such technology will provide more realistic characterization and calibration of satellite sensors than possible with present methods.

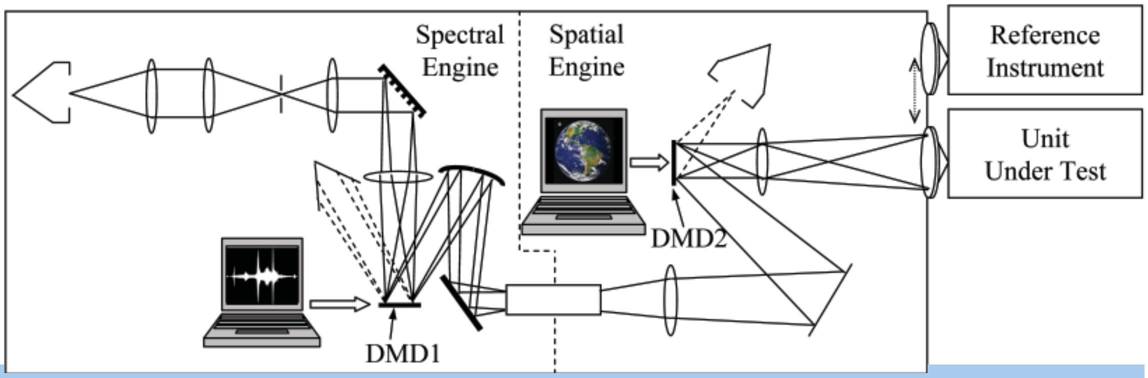

Figure 10 Schematic diagram of the NIST Hyperspectral Image Projector using Digital Micromirror Devices (DMDs) to project artificial spatially, spectrally, and temporally variable scenes for the calibration of various optical sensors.

5.2.1.6 Miscellaneous

In addition to the calibration and characterization discussed above, numerous other measurements are performed to ensure full characterization of the sensor necessary to derive accurate climate products. When possible, system or subsystem characterization and calibration should be compared with component level optical, sensor, and stray light models. Measurements performed include in-and out-of-band stray light, detector linearity, gain factors determination, dark signals/noise level measurements, wavelength calibration, etc.

5.2.2 On-orbit calibration

Even after careful and complete calibration and characterization of instruments in pre-launch testing, changes in instrument performance from pre-launch calibration present significant challenges in providing measurements which meet climate requirements. A variety of hard and soft measurement and analysis tools have been applied to reconcile deviations from expected performance and to monitor the degradation of optical elements and detectors. This subsection provides an overview of some of these methods.

5.2.2.1 Solar Diffuser

Lamps and solar diffusers are used in the on-orbit radiometric calibration of UV/VIS/NIR/SWIR remote sensing instruments. Solar diffusers have the advantage that the color-temperature difference between the source illuminating the on-board diffuser and the source illuminating the Earth scene are eliminated since in both cases the source is the Sun. Solar diffusers have the disadvantage in requiring an extensive pre-launch characterization of the BRDF as a function of illumination angle for each of the sensor spectral bands. Moreover, these measurements alone are insufficient for providing sensor calibration over the lifetime of the mission since the diffuser reflectance continually changes on orbit, including possibly its angular dependence. The challenge in using solar diffusers is to accurately track this reflectance degradation over the full mission lifetime. Moreover, changes in the diffuser reflectance properties must be separated from changes in the performance of other instrument components. Two approaches have been successfully implemented to monitor on-orbit changes in the diffuser reflectance and separate such changes from decreases in instrument throughput and sensitivity. These approaches are based on solar diffuser stability monitors or on multiple diffusers with varying Sun exposure times.

One solar diffuser stability monitor, successfully implemented on the SBUV/2, uses an on-board Hg Lamp to measure the reflectance of the diffuser by comparing the measured intensity of the lamp output with the intensity of the lamp output reflected from the diffuser (Goodrum et al., 2000). The ratio of these two measurements gives the diffuser reflectance. Since the diffuser is monitored with a Hg lamp, one must transform the changes in reflectivity measured at the wavelengths of the lamp emission lines into estimates of changes in reflectivity at the operating wavelengths of the sensor.

Complicating the use of a lamp to monitor drift in the diffuser reflectance is that changes in the spatial distribution of the lamp footprint on the diffuser over time will lead to an apparent change in reflectivity of the diffuser. For the SBUV/2, reversing the lamp current polarity between measurements and averaging the results reduces the magnitude of this spatial distribution change. We note that for some instruments the computed diffuser reflectivity for the two polarity states differs by as much as 1%.

Alternatively, the Sun can be used as the source for monitoring the change in reflectance of the diffuser. On MODIS, for example, an integrating sphere with a view port views the Sun, a dark background, and the solar diffuser (MODIS, 2006). The integrating sphere ensures uniform illumination of the 9 filtered detectors within it by the Sun and diffuser. To effectively transfer the pre-launch diffuser calibration to on-orbit, it is critical that the diffuser reflectivity be measured early on-orbit to provide an initial baseline prior to degradation by the Sun or contamination by volatiles from satellite surfaces. Diffuser degradation can be severe, particularly at shorter wavelengths towards the UV. As an example, over 1000 days the diffuser reflectance changed from 1.0 to 0.92 at 412 nm for Terra MODIS (Xiong et al., 2003b).

A second approach for addressing diffuser drift is to use multiple diffusers. Such an approach has been implemented on the Total Ozone Mapping Spectrometer (TOMS) (McPeters et al, 1998). With two diffusers, regular frequent measurements are made with one diffuser (termed the working diffuser) while less frequent measurements are made with a second diffuser (termed the reference diffuser), perhaps only once or twice a year. The hope is that the reference diffuser which experiences significantly reduced solar exposure will see little change between uses, thus providing a monitor of the degradation trend in the working diffuser.

If we assume that the diffuser reflectivity degradation is due to polymerization of contaminants present at the start of the mission or to changes in the diffuser material itself, then analysis of the time dependence of the reflectivity will allow the reflectivity to be tracked as a function of exposure level. Accelerated deployment (changing the frequency of solar measurements) can be used to try to separate instrument throughput degradation from diffuser changes by varying the relative time scales of the two effects. Complications arise from wavelength-dependent and angle-dependent changes and sensitivity of the irradiance measurements to subareas of the diffuser. Soft calibration methods using Earth targets to estimate diffuser changes are discussed below.

Given the complexity of diffuser changes and the angle dependence of the BRDF, it is advisable to have repeatable solar viewing angles from year-to-year. To achieve such repeatability requires stable orbits. Checks of the consistency of the BRDF can be made from analysis of sequences of solar measurements extending over a range of angles. It is also important to avoid stray light contamination of the diffuser measurements, such as from Earthshine discussed above (Mills et al., 2005).

5.2.2.2 On-Board Lamps

In addition to tracking diffuser degradation, on-board lamps have been used to monitor optical and detector behavior including wavelength calibration changes, detector linearity, and array nonuniformity. Spectral lines in lamps offer easy verification of the wavelength scale (Coldewey-Egbers et al., 2006), similar to the use of solar Fraunhofer lines (Caspar and Chance, 1997; Remund et al., 2004). White light sources monitored by photodiodes have been used for flat fielding array detectors (Sakuma and Ono, 1993), while monochromatic sources, such as light-emitting diodes (LEDs), have been used to directly illuminate detectors for flat fielding and linearity checks (Remund et al., 2004). The latter requires a stable source as the variation in signal strength with change in integration time is used rather then the variation with change in light intensity. The lack of availability of on-board light sources with sufficient short and long-term stability remains a problem.

For lamp-based, on-orbit calibration systems, the goal is to transfer a lamp's radiometric scale from pre-launch to on-orbit and to maintain or monitor that scale over the course of the mission. This is difficult because of the need to compensate for thermal and gravitational effects on the lamp intensity. Also, the color temperature of lamps does not closely match that of the Sun. FEL lamps, for example, have a color temperature near 2850 K, approximately half that of the Sun, for which the color temperature is 5800 K. In addition, the irradiance of FEL lamps varies with orientation. Such lamps are generally calibrated in a vertical orientation; when used in a horizontal orientation irradiance output changes significantly, by as much as 12 % at 280 nm (Early and Thompson, 1996). The effect is due to gravity, which induces a circulation pattern within the lamp envelope with the hottest gas rising to the top.

5.2.2.3 Extraterrestrial Targets

Extraterrestrial calibration sources (Moon, Sun, and various stars) have been successfully used to monitor satellite instrument stability and degradation from the ultraviolet through the shortwave infrared.

Moon. The Moon, in particular, has attracted significant interest as a reference standard for tracking instrument degradation, with a number of satellite instruments able to view its surface, including SeaWiFS (Barnes et al., 2004), Terra and Aqua MODIS (Xiong et al, 2003b), and the Advanced Land Imager (ALI) on EO-1 (Mendenhall et al., 2005). The reflectivity of the Moon's surface is exceptionally stable (Kieffer, 1997), and a model has been developed based on extensive Robotic Lunar Observatory (ROLO) (For an extensive description of ROLO and an associated bibliography see: http://www.moon-cal.org/index.php) observations to specify the relative irradiance as a function of phase and libration angle to approximately 1% (Kieffer and Stone, 2005), sufficient for many climate applications. Absolute accuracy is estimated to be better than 10%, limited in large part by uncertainties in modeling the atmospheric column contribution to the ROLO measurements. A proposal has been made (Lorentz, 2006) to improve the absolute accuracy of the lunar irradiance by quantitative spectral measurements at higher altitude, i.e., balloon and mountaintop, where the atmospheric extinction is less. Independent of the absolute accuracy, long term observations of the Moon by satellite have the capability to characterize and correct instrument sensor drifts with precision better than 0.1%/year, as demonstrated by SeaWiFS (Barnes et al., 2004). The long-term stability of the Moon and its potential as an absolute radiometric standard has led to recommendations (National Research Council, 2000; Ohring et al., 2004; and Guenther et al., 1997) that satellite sensors routinely view the Moon. For most sensors in low-Earth orbit, such viewing will require maneuvering of the spacecraft. We note that the VIIRS sensor (Murphy et al., 2004) of the NPOESS Preparatory Project (NPP) and the ABI sensor for GOES-R will be able to view the Moon, NPP-VIIRS through a space-view port (Patt et al., 2005). Currently there are no plans to maneuver the NPOESS spacecraft to view the Moon.

Sun. Aside from its application as an irradiance standard for illumination of on-board diffusers, the Sun also provides other assessments of instrument performance. As mentioned previously, the known wavelengths of the solar Fraunhofer lines can provide a check on the wavelength calibration of the sensor (Caspar and Chance, 1997). Furthermore, the use of a high resolution reference solar spectrum in combination with solar measurements provides on-orbit information on the spectral resolution and related instrument function of the sensor. Solar observations are also used to compute a Solar Index, such as the Mg II index, to provide a measure of solar activity variation. To compute the index, the ratio of the irradiance at the absorption line center to the average irradiance at the two wings of the line is calculated. Such an approach provides a measure of solar variability in the UV that is relatively insensitive to changes in instrument response (SBUV, 2006).

Stars. A number of stars have been radiometrically calibrated, allowing their use for the on-orbit characterization and calibration of satellite sensors. For accurate absolute sensor calibrations, it is preferable that the values for the absolute stellar irradiances be determined from top-of-the-atmosphere measurements in order to eliminate uncertainties in the atmospheric extinction correction. Such measurements have been performed for the star Vega using the STSI instrument (Bohlin and Gilliland, 2004), for example. For assessing sensor stability, stellar targets must be radiometrically stable, but the irradiances need not be known absolutely. However, the utility of star measurements is limited since their irradiance is several orders of magnitude less than Earth-viewing instruments are designed to measure, and their light is nearly collimated compared to typical Earth scenes viewed by the satellite sensors.

Despite their limited utility there have been a number of applications of stars to the calibration and characterization of satellite sensors. Bowen (2002) has attempted to use previously cataloged stellar radiometric data in combination with new IKONOS satellite measurements of the same stars to perform a radiometric calibration of IKONOS, with the goal being to reduce the cost of performing ground validation measurements and of installing on-board calibration sources for commercial remote sensing applications. To assess instrument stability, Bremer and colleagues (Bremer et al., 1998) have used a retrospective analysis of star measurements by the GOES 8 and 9 Imager and Sounder and found sensor throughput losses of 3.8 % to 9.6 % per year.

The Moon as a Calibration Source

The Moon is accessible as a calibration target to all satellites, regardless of orbit. It is a spatially extended source that can utilize the full optical train of an Earth-viewing instrument; its brightness is similar to that of clear land at solar reflectance wavelengths, 350 to 2500 nm. The primary challenges to using the Moon are its non-uniform distribution of albedo, and the variation in its brightness due to illumination and view geometry (primarily the lunar phase) and a complex surface reflectance function. However, the Moon's diffuse reflectance is considered to be radiometrically stable to better than one part in 10^8 per year (inferred from studies of impact cratering and the space environment; such a stability metric cannot be measured directly) (Kieffer, 1997). Thus it is possible to predict the geometric brightness variations with high precision and accuracy.

Comparison of on-orbit observations against a lunar standard, whether over time or between instruments, requires a photometric model for the Moon that accommodates unrestricted geometry. A successful model and technique for lunar calibration developed at the U.S. Geological Survey works with the spatially disk-integrated irradiance. This model explicitly accounts for the effects of phase, the spatial variegation of the lunar surface, the changes in the hemisphere of the Moon presented to an observer (the lunar librations), and the strong backscatter enhancement at low phase angles (the "opposition effect"). The basis for the model is a dataset of ground-based radiometric measurements of the Moon spanning several years, covering a sufficient portion of the 18.6-year libration cycle, although libration coverage is limited to visibility from Flagstaff, AZ.

Spacecraft instrument teams utilize the USGS lunar calibration system through a largely formalized set of data exchanges. Because the Moon is used as an irradiance source, the spacecraft observations must capture the entire lunar disk, typically oversampled. Distances from the Moon to the Sun and the instrument are corrected to standard 1 AU and 384,400 km (the mean Earth-Moon distance) based on an ephemeris and the spacecraft location at the time of the observation. Correction for oversampling can be done a priori by the instrument team, or from measurement of the down-track size of the Moon in the spacecraft image. Model results are interpolated to the instrument wavelength bands along a smooth lunar reflectance curve.

The capability of the lunar model for predicting in-band variations in the lunar irradiance with geometry is ~1% relative over the full range of the phase and libration variables. With a time series of lunar measurements collected by an instrument, comparison against the irradiance model can produce sensor response trending with sub-percent per year precision; this has been demonstrated for SeaWiFS (Barnes et al., 2004).

The level of precision attained by the current lunar irradiance model and comparison techniques supports spacecraft instrument stability monitoring that meets the requirement for climate data production. To achieve this benchmark, routine observations of the Moon by spacecraft instruments are essential. Thus, regular lunar views are recommended as part of spacecraft operations for calibration. Restriction of phase angles to a narrow range is not a requirement (restriction of libration angles is not practical). Use of the Moon as a calibration source may be the only means of achieving climate-level instrument stability at solar reflectance wavelengths.

Space View. Most instruments are designed to take measurements of non-sunlit portions of the Earth, with an entrance aperture closed, or of deep space through a space-view port, in order to measure the instrument's response to zero radiance. Such measurements provide estimates of dark current, detector noise levels, and offsets. When performing such measurements, care must be taken to avoid portions of the orbit passing through the South Atlantic Anomaly (SAA), as noise levels and dark counts can increase from the high charged-particle density in this region. Masked and over-clocked regions of the detectors also provide information on dark signals and noise levels. Measurements of detector regions outside the image FOV can be used to check stray and scattered light models.

5.2.2.4 Reference Sites

A number of well-characterized Earth-based reference sites are available for validating instrument performance and for tracking the long-term stability of sensors. Such sites or targets include deserts, ice caps, deep convective clouds, and open oceans. Specific examples include the Libyan Desert used to track the stability of AVHRR (Rao and Chen, 1995), and Railroad Valley (Scott et al., 1996) and Lunar Lake (Thome et al., 1998) used in the reflectance-based validation of MODIS. For ocean color measurements, the Marine Optical Buoy (MOBY) (Clark et al., 2001) stationed off the coast of Hawaii is available, and has been used by MODIS and SeaWiFS. Terrestrial reference sites should be periodically reexamined to ensure their stability and that they are appropriately characterized. Characterization should include seasonal variation and changes due to weathering. Transferring a ground reflectance measurement to a satellite sensor is complicated by the intervening atmosphere, which is prone to change from short-term and long-term disturbances induced by weather, volcanoes, forest fires, and air pollution, and by the need to understand the site reflectance as seen by the satellite sensor for the various solar zenith and azimuth angles of viewing. Instrumented sites typically perform solar extinction measurements with calibrated solar radiometers to determine the atmospheric column above the site. Characterizing the atmosphere remains a significant source of uncertainty for the reflectance-based technique.

5.2.2.5 Relative Measurements

Relative measurement techniques have been developed to minimize the need for performing absolute radiance measurements on orbit. Satellite experiments based on occultation use this strategy, including the Halogen Occultation Experiment (HALOE) (Russell et al., 1993), Stratospheric Aerosol and Gas Experiment II (SAGE II) (SAGE II, 2006), and the Global Ozone Monitoring by Occultation of Stars (GOMOS) (Bertaux et al., 1991). These limb-viewing instruments use extraterrestrial sources such as the Sun, Moon, or stars as light sources for viewing through various atmospheric layers. The atmospheric measurements are normalized by a zero atmosphere measurement, eliminating the need for an absolute radiometric calibration. The retrieved atmospheric variables can be used for validating other space-based products. Due to orbital constraints the method suffers from infrequent data collections and limited spatial sampling when the Sun is used as the source, and direct ground measurements are not possible. Also, the spatial resolution within the atmosphere is poor due to the long tangent path lengths.

5.2.2.6 Calibration Instruments in Orbit

One approach to address on-orbit changes in instrument calibration and performance from the pre-launch values is to tie or pin satellite sensors to one or more well calibrated and characterized standard sensors. The Global Space-Based Inter-Calibration System (GSICS) organized by the World Meteorological Organization (WMO) (Hinsman, 2005) recommends benchmark measurements by well calibrated satellite sensors for calibration of other satellite instruments. The success of the Global Earth Observation System of Systems (GEOSS) is dependent on the successful intercalibration of satellite measurements.

An example of such a facility for UV measurements is the Shuttle SBUV (SSBUV) (Frederick et al., 1991; and Hilsenrath et al., 1993) flown aboard the space shuttle. The SSBUV shuttle flights underflew the Solar Backscatter Ultraviolet (SBUV/2) instruments on NOAA-9 and NOAA-11, as well as other sensors, allowing simultaneous measurements to verify their calibration. Being a space shuttle-based instrument, the SSBUV was retrievable and thus could be calibrated before and after deployment.

5.3 Impediments to Progress

Achieving on-orbit measurements of the climate system of sufficient accuracy for climate change monitoring continues to be challenging at both the technical and program level.

Technical issues include the following:

- Lack of quantitative understanding of the physical mechanisms for on-orbit changes in optical component behavior, such as degradation of solar diffuser reflectance and deterioration in mirror reflectance.
- Inability to provide simultaneously realistic and robust pre-launch tests of sensor spectral, spatial, and temporal performance.
- Poor understanding of the optical properties and spatial distribution of atmospheric aerosols and other variable components necessary for tying ground-based measurements to satellite measurements.
- Inability to accurately estimate the on-orbit measurement uncertainty based on pre-launch data.
- Lack of availability of "standard" satellite measurements to validate on-orbit performance of satellite sensors.
- Inadequate accuracy in the absolute irradiance of the Moon necessary for absolute sensor calibration.

In principle, program issues should be more easily addressable; however, solutions are challenged by the increased cost of satellite programs relative to available funding. Program related issues include the following:

- Continued cost overruns and development delays in satellite programs that lead to reductions in calibration resources and time.
- Inability to accurately estimate satellite sensor costs so as to limit such cost overruns, which ultimately impact calibration.
- Absence of continuity in critical sensor calibration and characterization expertise as satellite programs are completed and new contract awards go to different instrument satellite vendors.
- Lack of clarity in sensor performance specifications, impacting the ability to assess whether performance requirements are being met.
- New satellite program paradigms that limit opportunities for on-orbit overlap between sequential satellites.
- Challenge of requiring that satellite sensors meet operational (weather) and research (climate) requirements simultaneously, with the consequence that climate sensors are considered expendable when budgets are stressed, as in the case of NPOESS.

Some of the recommendations below help address the impediments outlined above.

5.4 Recommendations to Accelerate Progress

5.4.1 High Level Initiative

In support of the new paradigm for long term climate observations from space, we recommend that a hyperspectral benchmark mission be flown to measure the Earth's reflectance spectrum from the UV to the NIR. Such an instrument would provide accurate and stable long term environmental measurements in its own right, and also serve as a space-based calibration facility for calibrating other satellite UV, VIS, and NIR instruments. This dedicated benchmark mission would have the ability to view and measure the Moon, have additional redundant calibration and validation capabilities and infrastructure to include multiple solar diffusers and on-board lamps, and have operational infrastructure to support ground-based measurements, including reference sites and special field campaigns. The spectral and spatial resolution should be sufficient for valid intercomparisons at the resolution of the majority of satellites of interest and the radiometric accuracy must be close to 0.5%. Ideally, a series of such sensors would be deployed to allow continued long-term overlapping measurements of the Earth necessary to ensure long-term calibration/validation of other satellite sensors and to develop its own highly accurate climate record.

5.4.2 Additional Recommendations

To improve the application of UV/VIS/NIR/SWIR satellite instrument data for climate research the recommendations below are presented. Some of these recommendations have been made before (Guenther et al., 1997; and Ohring et al., 2004).

1. The accuracy and stability of calibration and characterization sources and equipment operating in the UV/VIS/NIR/SWIR must be thoroughly validated before being used in the pre-launch calibration of satellite instruments. Clear and specific requirements on this calibration and characterization equipment should be derived directly from the satellite instrument calibration specifications and clearly articulated prior to any work. The validation process must include all optical and mechanical aspects of the equipment. The validation of the calibration equipment should be at a level at least equivalent to that imposed on flight instrumentation. Lastly, a strong commitment on the part of project management in terms of time and resources to accomplish this important validation must be obtained.

2. The response of the satellite sensor in the UV/VIS/NIR/SWIR must be measured in enough operational and environmental configurations (e.g., different instrument temperatures, focal plane temperatures, electronics temperatures, and operational voltages) to ensure that the short- and long-term performance of the sensor is adequately understood.

3. Multiple measurement methodologies must be encouraged and nurtured from the pre-launch calibration and characterization through the on-orbit operation of satellite instruments. Agreement between measurements made by different instruments or methodologies establishes strong confidence in the accuracy and quality of those measurements. This multiple approach validates the retrieval algorithms and calibration assumptions, and identifies biases, non-linearities, and uncertainties.

4. A commitment must be made to permit the reanalysis of pre-launch and on-orbit UV/VIS/NIR/SWIR calibration data and the rederivation or reprocessing of satellite instrument data if necessary. Such an effort would be facilitated by requiring satellite programs to retain and archive witness samples of filters, apertures, coatings, etc. for later testing to address potential anomalies.

5. Complete structural, optical, thermal, and radiometric numerical models of satellite sensors should be required early in the instrument development program and continually updated based on information from the pre-launch and on-orbit calibration and characterization.

6. Additional work is needed on the pre-launch quantitative characterization of the response of a satellite instrument to high contrast scenes. This process would properly account for near-field and far-field effects that can contaminate the signal measured by an instrument within its field of view.

7. With the recent successes related to the use of the Moon and other extraterrestrial sources for on-orbit calibration, the recommendation is made that all spacecraft be designed with the ability to maneuver to view these sources, and that flight operations plans include regular observations. Additionally, an effort must be made to improve the accuracy of absolute radiometry of the Moon to allow its use for assessment of sensor measurement uncertainty.

8. Overlap between successive satellite instruments and the intercomparison of their measurements in near real-time is essential to any satellite climate remote sensing program. A minimum of 6 months on-orbit operational overlap is needed to establish the necessary radiometric and geometric ties between instruments.

9. New scene-generating technology should be nurtured to allow the realistic pre-launch calibration and characterization of satellite sensors by furnishing spatial, spectrally, and temporally variable scenes that mimic those viewed on orbit.

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Microwave Instruments

6.

6.1 Introduction

Satellite microwave observations of the atmosphere, land, and oceans provide critically pertinent information to better predict and understand the changes in weather and climate, and are now a major component of the global environmental observing system. These versatile instruments provide information on atmospheric and sea surface temperatures, sea ice and snow cover, cloud properties, precipitation rates, atmospheric water vapor, and ocean surface winds. Over the past two decades, microwave observations have improved numerical weather predictions and contributed to long term climate monitoring. The former is due to better satellite instruments, and improvements in NWP models and data assimilation techniques, while the latter is attributed to the stability and improved intercalibration of instruments such as the microwave sounding unit (MSU).

In the weather arena, the Advanced Microwave Sounding Unit (AMSU) on board the series of NOAA POES satellites has been a major factor in significantly increasing the accuracy of global medium-range forecasts to the point where current five-day forecast accuracies are about the same as three-day forecast accuracies were ten years ago.

For climate studies, the nine MSUs on board the early NOAA satellites have provided a unique 26 year time series of the global tropospheric temperature as well as its trend (Vinnikov et al., 2006; Christy et al., 2003; and Mears, 2005). Differences in instrument calibration are accounted for by inter-calibrating the MSU instruments using overlapping orbital data (see, e.g., Grody et al., 2004). In order to extend the temperature and trend analysis to longer time periods it is necessary to continue the MSU time series using AMSU data. In addition to the NOAA microwave instruments, the Special Sensor Microwave Imager (SSM/I) onboard the Defense Meteorological Satellite Program (DMSP) satellites have observed the Earth's atmosphere for nearly two decades, beginning in 1987. The SSM/I measurements provide vital information on the atmospheric hydrological cycle over the world's oceans. Just as the MSU and AMSU instruments are important for monitoring temperature trends, the SSM/I and its follow-on SSMIS instruments are critical for measuring climatic changes in the hydrological parameters.

6.2 Current Status

Calibration refers to the process of quantitatively determining a sensor's response to known controlled signal inputs. Pre-launch laboratory calibration establishes a sensor's characteristic response function. The pre-launch calibration algorithm can then be carried into the post-launch era by requiring only straightforward coefficient updates after a satellite is on orbit. However, the need for new post-launch calibration algorithms becomes evident when unforeseen behavior or an uncharacteristic sensor response is identified through detailed scientific analysis of the on-orbit sensor data. Post-launch effects leading to abnormal measurements may come from outgassing, space environment, variation in filter transmittance and spectral response, slow deterioration of the electronic or optical system, or even mechanical malfunction following the intense rigors of launch. In such situations the new post-launch calibration algorithms must make use of calibration data from onboard sources, ground truth data, and inter-sensor comparisons so that the measurements are consistent over time.

6.2.1 Pre-launch Calibration

Microwave calibration consists of evaluating the sensor in a thermal vacuum (T/V) chamber using three calibration targets: (1) a cold calibration target that is cooled with liquid Nitrogen to about 80 K, (2) a variable temperature target from about 80 K to 330 K placed in the scene Field of View, and (3) the sensor's on-orbit warm calibration load. The radiometer's two point calibration is determined from the warm and cold targets within the T/V chamber. It is tested at a variety of "scene temperatures" that are simulated by changing the temperature of the variable temperature target.

A combination of model-based and empirical corrections to the two-point instrument calibration is necessary in order to take into account the uncertainties from the antenna spill-over energy emanating from the spacecraft, cross-polarization, and antenna side lobes beyond the earth's horizon, etc. It is difficult to claim that the on-orbit calibration achieves better than 1 K residual calibration accuracy. Corrections based on pre-launch laboratory data have been found to be in error when applied to the on-orbit sensor calibration. Accordingly, new corrections based on on-orbit measurements can be applied to improve sensor calibration.

6.2.2 On-board Calibration Devices

Microwave instruments use either a cross-track or conical scanning antenna system depending on the application. For example, a cross-track scanner provides a large swath width but with a variable field of view (i.e., resolution), while a conical scanner provides a nearly constant field of view with a somewhat smaller swath width. A conical scanner also provides separate polarization measurements, which is very important for deriving sea surface temperature and wind speed, for example. However, while cross-track instruments such as MSU and AMSU view Earth and the two calibration targets using the same antenna, conically scanning sensors such as the SSM/I and SSMIS use a different antenna configuration for viewing cold space, which can introduce additional sources of calibration error.

For conically scanning instruments the antenna and calibration subsystem typically consists of a main reflector for viewing earth and a stationary warm load, while a sub-reflector is used for viewing cold space. During each scan of the main reflector, the radiation from Earth, the warm load and sub-reflector is focused to feedhorns, which in turn transfer the microwave radiation to a receiver subsystem for filtering, amplification, detection and integration. Periodic calibration of the Earth measurements is obtained using an equation that incorporates the warm load and cold space measurements, taken at the end of each scan line.

6.2.3 Earth-Based Reference Sites

Vicarious techniques generally involve the use of stable external targets for testing and improving the calibration of a satellite instrument. These target areas generally consist of homogeneous land and ocean surfaces whose surface and atmospheric features are well known. At NOAA, the angular distributions of the observed brightness temperatures from AMSU over the Libyan Desert and Amazon are used to evaluate instrument performance. The measurements of the NOAA-16 and NOAA-18 AMSUs are compared in Figure 11 (Mo, 2007). The

establishment of a land calibration target is an important addition to the few tools available to date for calibration and validation of space-borne microwave instruments.

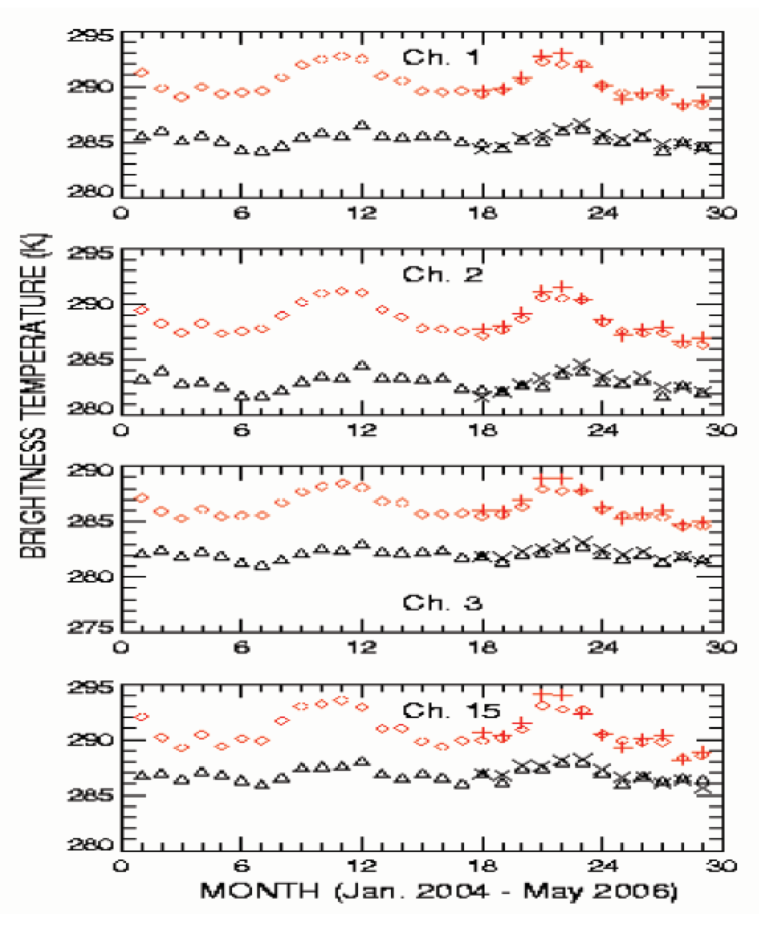


Figure 11 Monthly averaged AMSU-A brightness temperatures over Amazon rain forest from NOAA-16 and NOAA-18 (Ch 1, 2, 3, 15 = 23.8, 31.4, 50.3, 89 GHz). The NOAA-16 data are from January 2004 through May 2006 whereas those of NOAA 18 are from June 2005 through May 2006. Red symbols: Ascending orbits, Black symbols: Descending orbits. NOAA-16: Diamonds and triangles, NOAA-18: Pluses and crosses.

6.2.4 NWP Model Simulations

The major NWP centers compare model-simulated and observed radiances on a daily basis for those satellite data that are assimilated in the models. Although the NWP model and its associated radiative transfer system have their own biases, the model calculations can be used as a reference to determine instrumental anomalies, the bias of one instrument relative to another or the stability of an instrument over time. For example, the observed radiances of the first Special Sensor Microwave Imager and Sounder on board the DMSP F-16 satellite display several on-orbit performance anomalies. These anomalies were found from the difference between global NWP simulated and observed brightness temperatures (Figure 12; Yan and Weng, 2006). The anomaly pattern depends strongly on geolocation and season and is utilized to guide the development of algorithms for removal of the anomalies.

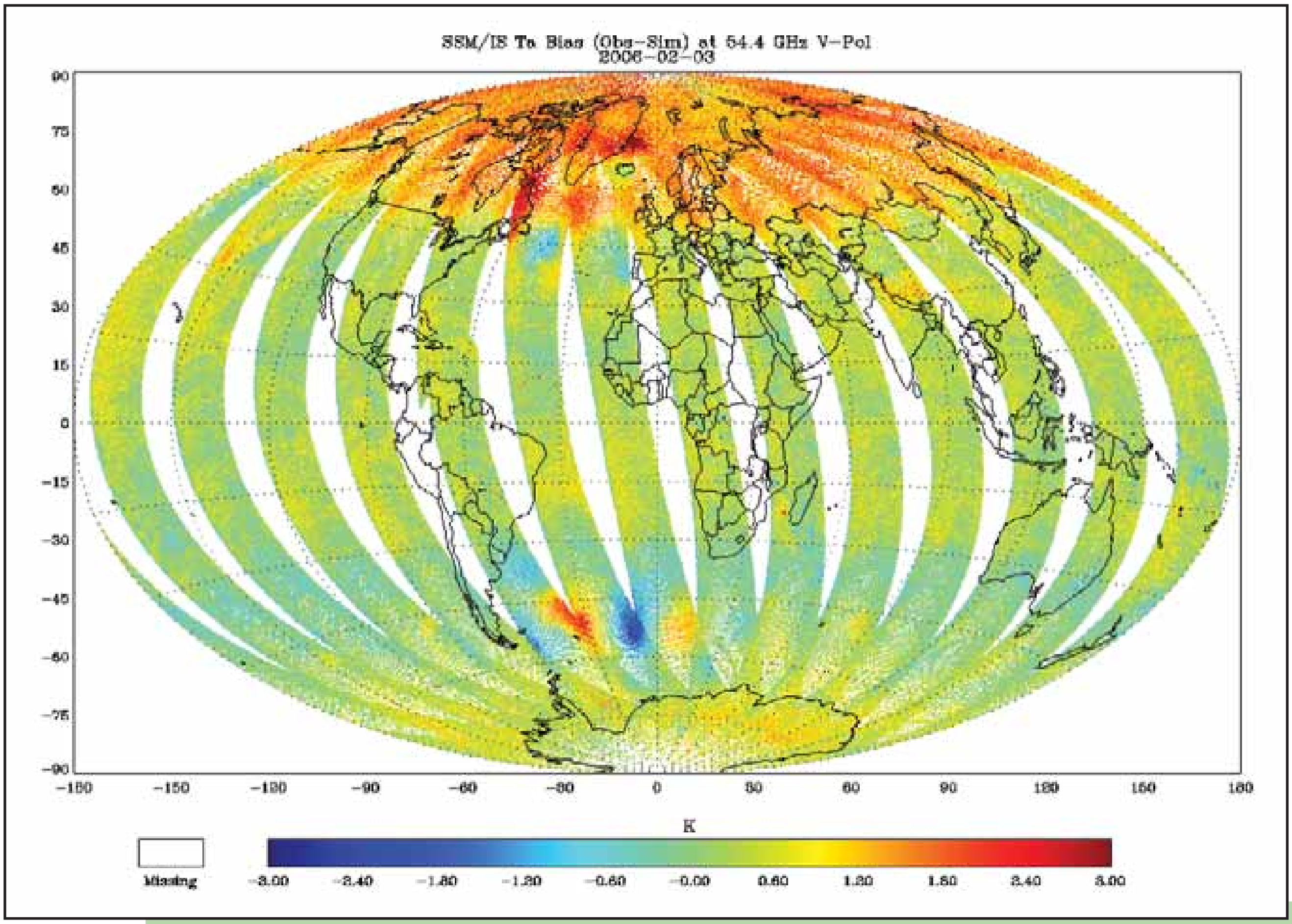


Figure 12 Special Sensor Microwave Imager Sounder (SSMIS) observations compared to modeled background data illustrating bias and residual errors.

6.2.5 Benchmark Measurements

To extend the time period of observation it is necessary to use a series of satellite instruments (e.g., MSUs), which are inter-calibrated against one another to establish a common calibration point of reference (Grody et al., 2004). Intercalibration has proven to be very effective, but in general requires that the measurements from each satellite instrument be adjusted for their different times of observation as well as orbital drift using a procedure such as that described by Vinnikov et al., 2004. As an alternative approach, simultaneous observations can be sought at high latitudes where the satellite orbits overlap in time so that the different satellites observe the same area at the same time (Zou et al., 2006; Cao et al. (2004).

Such relative calibration may be adequate for climatic trend analysis (i.e., a constant offset in the time series does not affect trends) as long as there are no gaps in the series of satellite instruments used to establish the long term record. Highly accurate observations would insure a stable record even in the presence of data gaps and would also be required for monitoring the magnitude of geophysical parameters. To provide absolute calibration, one of the sensors has to be calibrated with very accurate onboard calibration traceable to an SI standard.

6.3 Impediments to Progress

For climate studies, calibration stability must be accomplished over decadal periods. For microwave observations of atmospheric temperature trends, instrument accuracies of 0.5 K and decadal stabilities of 0.04 K must be maintained: for sea surface temperature, the corresponding numbers are lower—0.03 K and 0.01 K (Ohring et al., 2004)—due to reduced microwave sensitivity resulting from low microwave ocean emissivities and wind roughening effects. The impediments to decadal scale climate monitoring are long term instrument changes, such as the degradation of the targets used to calibrate microwave radiometers. In contrast, degradation of the system noise equivalent temperature (NEΔT) only increases the random error of the measurements, without introducing any bias in the instrument's calibration. The random error component can be reduced by temporal averaging of the data, whereas the bias can only be accounted for by intercalibration or through the use of the Earth-based reference sites discussed previously.

After establishing the accuracy and stability values, it is still necessary to interpret the values supplied for the calibration goals. This task requires establishing a timeframe and reference for their application. The 0.03 K accuracy goal may require the microwave brightness temperature accuracy to be tied to a NIST standard Platinum Resistance Thermometer (PRT). Establishing a direct error budget relating standard microwave radiance to a NIST-calibrated PRT appears to be extremely difficult for microwave sensors due to the errors associated with radiometric measurement of the warm calibration load and uniqueness of each radiometer's RF characteristics and its coupling to the calibration target. Perhaps a more useful interpretation of the 0.03 K accuracy goal for the immediate future is to maintain residual systematic calibration errors to be less than 0.03 K. This allows the systematic bias in the sensor brightness temperature to be stable with respect to some defined truth to within 0.03 K. The calibration error budget will determine requirements on many aspects of the system including NEΔT, non-linearity correction, and image processing (sampling), etc, after the biases are removed. Parameters of the system can be varied for specific applications.

To meet the calibration stability goal, for example, a 200 K scene measured by a microwave radiometer as 200.5 K at its Beginning of Life (BOL) would have to be measured as 200.5±0.01 K at its End of Life (EOL). Calibration stability is established by controlling changes in the instrument state or characteristics over the sensor's lifetime. Microwave radiometers such as the MSU offer an extremely stable basis for comparing long term records as initially described by Spencer and Christy (2000) and more recently by Vinnikov et al. (2006), Christy et al. (2003), and Mears and Wentz (2005). The primary driver of differences on this timeframe of years, assuming that ambient conditions are indeed identical for the two measurements, is aging of the calibration targets and the electronic components (which is seldom considered in microwave radiometry).

Impediments to improved calibration include all aspects of the tools (see Tables 3 and 4) used to establish calibration and specifically: pre- and post-launch sensor characterization and calibration target quality and characterization. Fundamental problems remain in the following areas:

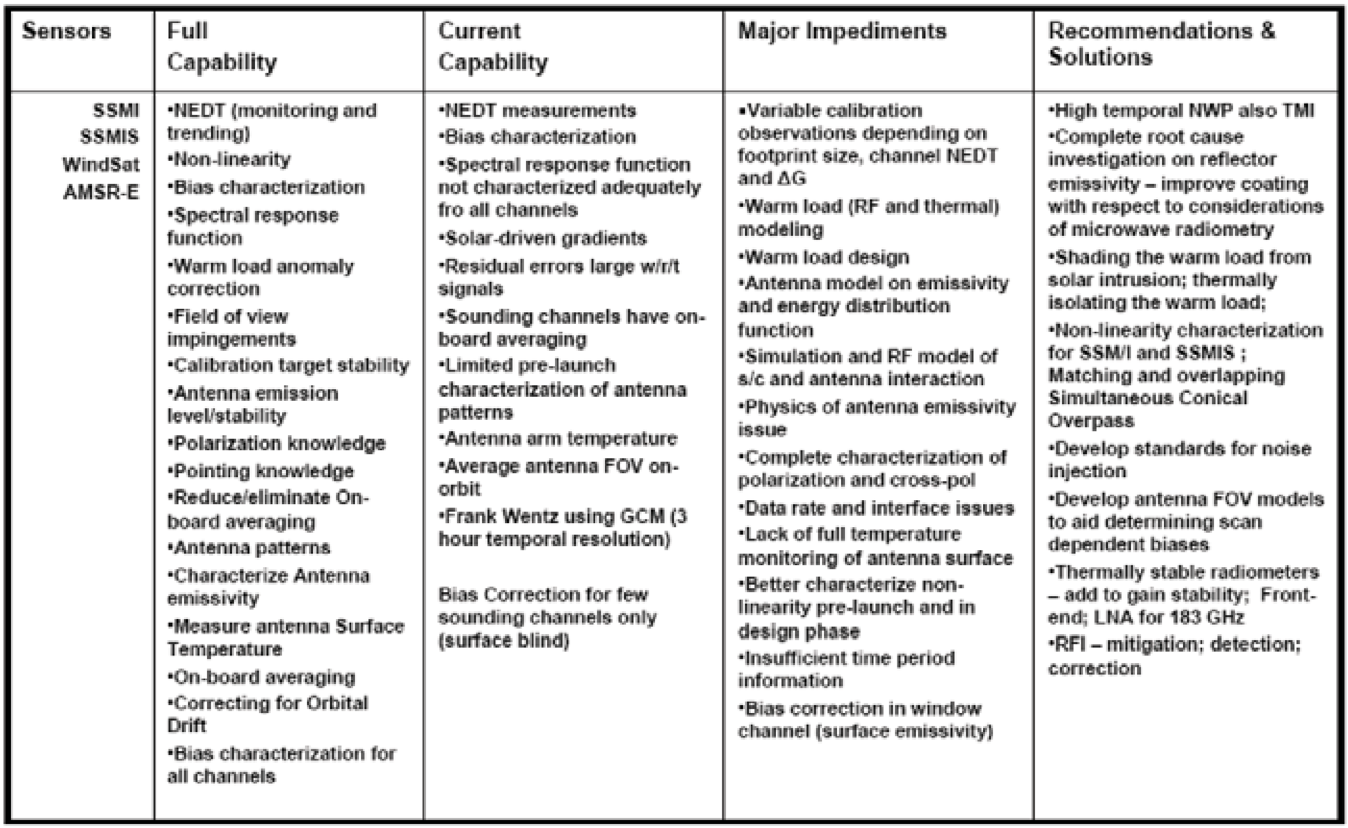
- Difficulty to correct for satellite orbit drift in trend analysis
- Calibration uncertainty from instrument non-linearity
- Anomalous emission from unknown targets
- Warm load instability and solar and stray slight contamination
- Difficulty to characterize the Radio Frequency Interference

- Pre-launch characterization, antenna patterns, brightness temperature standard, and well characterized target

The orbital drift of the early National Oceanic and Atmospheric Administration (NOAA) -7, -9, -11, -14 series of satellites is noticeably large and results in a significant diurnal effect on the microwave instrument measurements (Figure 13). For example, NOAA-11 initially observed the Earth around 13:30 local time (LT) in 1989, but by the end of 1994 its overpass time had shifted to 17:00 LT. The orbital drift leads to measurements at different local times during a satellite's lifetime, thereby introducing a temporal inconsistency in the climate data record. More recent NOAA POES satellites have much reduced orbital drifts.

The Defense Meteorological Satellites Program (DMSP) has launched a series of spacecraft to investigate the Earth's environment from an altitude of ~800 km. They were all put into Sun-synchronous near-polar orbits (inclination ~ 99 degrees). The SSM/I on the F8 satellite, launched in 1987, had a negligible drift during its five year life span, but other DMSP satellites have had larger drifts.

Table 4 Calibration Assessment of Conical Microwave Scanners



Sensors	Full Capability	Current Capability	Major Impediments	Recommendations & Solutions
SSMI SSMIS WindSat AMSR-E	•NEDT (monitoring and trending) •Non-linearity •Bias characterization •Spectral response function •Warm load anomaly correction •Field of view impingements •Calibration target stability •Antenna emission level/stability •Polarization knowledge •Pointing knowledge •Reduce/eliminate On-board averaging •Antenna patterns •Characterize Antenna emissivity •Measure antenna Surface Temperature •On-board averaging •Correcting for Orbital Drift •Bias characterization for all channels	•NEDT measurements •Bias characterization •Spectral response function not characterized adequately fro all channels •Solar-driven gradients •Residual errors large w/r/t signals •Sounding channels have on-board averaging •Limited pre-launch characterization of antenna patterns •Antenna arm temperature •Average antenna FOV on-orbit •Frank Wentz using GCM (3 hour temporal resolution) Bias Correction for few sounding channels only (surface blind)	•Variable calibration observations depending on footprint size, channel NEDT and ΔG •Warm load (RF and thermal) modeling •Warm load design •Antenna model on emissivity and energy distribution function •Simulation and RF model of s/c and antenna interaction •Physics of antenna emissivity issue •Complete characterization of polarization and cross-pol •Data rate and interface issues •Lack of full temperature monitoring of antenna surface •Better characterize non-linearity pre-launch and in design phase •Insufficient time period information •Bias correction in window channel (surface emissivity)	•High temporal NWP also TMI •Complete root cause investigation on reflector emissivity – improve coating with respect to considerations of microwave radiometry •Shading the warm load from solar intrusion; thermally isolating the warm load; •Non-linearity characterization for SSM/I and SSMIS ; Matching and overlapping Simultaneous Conical Overpass •Develop standards for noise injection •Develop antenna FOV models to aid determining scan dependent biases •Thermally stable radiometers – add to gain stability; Front-end; LNA for 183 GHz •RFI – mitigation; detection; correction

Table 5 Calibration Assessment of Cross-track Microwave Sensors

Sensors	Full Capability	Current Capability	Major Impediments	Recommendations & Solutions
AMSU MHS MSU ATMS	•NEDT (monitoring and trending) •Non-linearity •Bias characterization (asymmetry) •Calibration target stability (pre-launch •Polarization knowledge (asymmetry-related) •Correcting for Orbital Drift •Bias characterization for all channels •Footprint matching for noise reduction •Radiometric equivalence of pre-launch cal targets	•NEDT measurements •Limits to non-linearity characterization (Pre-launch) •Bias characterization limited to few channels just over ocean •Homogeneity of WL target •Measurements need to be incorporated •Frank Wentz using GCM (3 hour temporal resolution) •Bias Correction for few sounding channels only (surface blind) •Simple average •Confuse scan asymmetry with differences in emissivity	•Better characterize non-linearity pre-launch and in design phase •Incomplete characterization of polarization and cross-pol •Insufficient time period information •Bias correction in window channel (surface emissivity) •Lack of detailed antenna pattern (2 cuts are not enough) •Instrument characterized without detailed understanding of its surrounding s/c structure •Frequency stability	•High temporal NWP also TMI •More antenna pattern cuts and better understanding of antenna characteristics •Improved surface emissivity model to improve bias estimates in window channels. •Measure cross scan asymmetry in pre-launch characterization – support this with detailed instrument simulation (DGS) – help to attribute errors •Non-linearity measurements (post launch refinement) SNO matched pairs (only done for MSU to date) •'Better emissivity measurements of the warm load. Warm load characterization

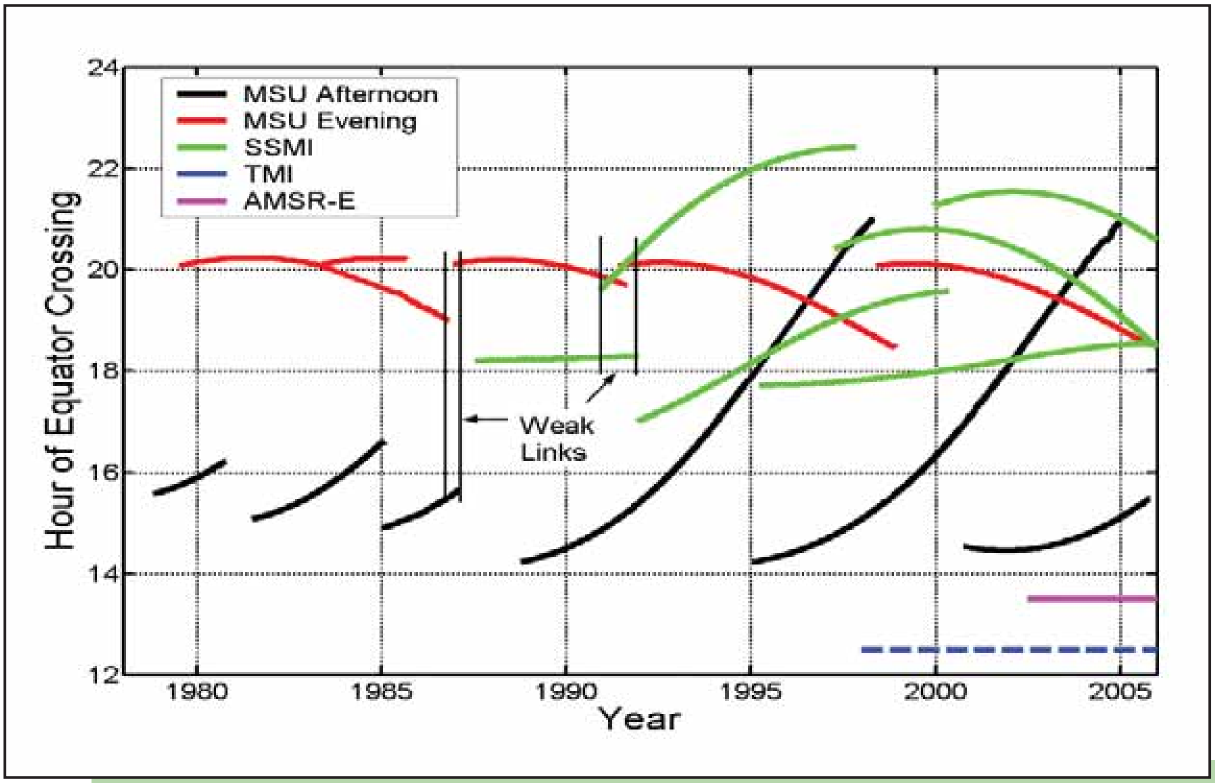


Figure 13 Orbit drifts for satellites with microwave instruments (Wentz, 2006).

Pre-launch characterization of the sensor's non-linearity involves accurate end to end calibration testing in order to determine its repeatability as well as the effects of instrument ambient temperature and scene temperature on the non-linearity characteristics. To determine the actual sources of nonlinearity, it is important to trace the effects on a component level, e.g., the detector stage and trans-impedance amplifier. In general, uncertainty in the knowledge of the non-linearity characteristic leads to the introduction of residual errors if a mathematical correction is applied. The problem is mitigated by more complete characterization, and reduction, during the design phase, of the instrument's departure from an ideal square-law characteristic. A post launch approach should also be sought to account for errors in the instrument's nonlinearity parameters. An example of such an approach for the MSU instruments is given in Grody et al., 2004.

The calibration and validation activities for satellite microwave radiometry systems have also shown that the impact of solar illumination of the warm calibration load for conical scanning radiometers was not limited to a single design (e.g., both SSMIS and WindSat are affected). The problem needs to be addressed for all conical radiometer designs by paying special attention to the warm load design. Practical steps in warm load design are to improve the effectiveness of the warm load enclosure or shroud to prevent direct illumination of the warm load tines to sunlight, and/or providing thermal insulation that is transparent to radio frequencies (warm load cover of Styrofoam or similar material as was done for the MSUs).

Radio Frequency Interference (RFI) or contamination of measured brightness temperature (T_B) by anthropogenic emissions has resulted in major impacts on the utility of the 6-GHz band for passive microwave remote sensing. This band has no allocation protecting passive measurements from interference by active anthropogenic sources. Other frequency bands, although protected, are still subject to strong adjacent-band signals or possible interference from services sharing the band, such as in the band segment of 10.6–10.68 GHz. Regardless, use of the spectrum is increasing and with it, the probability of significant impacts to data utility from RFI. Accordingly, effective RFI detection and mitigation is paramount to ensure continued operation, particularly for environmental parameters that are effectively monitored using lower frequencies (6- and 10-GHz) such as soil moisture and sea surface temperature.

It is not an uncommon experience (post-launch) to find that critical aspects of a microwave sensor were either not covered adequately in the sensor characterization, or not monitored adequately on-orbit. The SSMIS provides excellent lessons learned with its increased reflector emission (need better on-orbit monitoring of reflector) and antenna pattern measurements (impact of field of view biases at the edge of scan). It is not uncommon for antenna range testing and calibration testing and verification to be constrained by imposed limits of program level-of-effort (LOE) or schedule. Typically, characterization data are used to their fullest in the cal/val and post-launch evaluation period. Sensor cal/val teams often need additional information, which is often unavailable, in order to adequately address the needs of algorithm development, reduce the impact of anomalies, or apply corrections for biases that were not understood.

6.4 Recommendations to Accelerate Progress

6.4.1 High Level Initiative

NASA is exploring a new calibration system for its Global Precipitation Measurement (GPM) Microwave Imager (GMI). The new system will address a number of issues such as non-linearity removal and warm load mitigation. Noise diodes will probably be deployed to mitigate the instability of warm loads. The GMI must be well calibrated in order to serve as the unifier for constellation members in global precipitation.

NIST is studying a methodology and procedure for establishing a standard measured radiance from a microwave calibration target through development of a measurement error budget, standard design warm load, and standard measuring technique (Randa et al., 2004).

6.4.2 Additional recommendations

1. *Use hourly NWP outputs to define the diurnal variation of brightness temperatures:* A major issue in the analyses of atmospheric temperature trends based on MSU observations has been the need to correct for the effect of diurnal temperature variations because the NOAA satellites undergo orbital drift. NWP models have hourly outputs and these can be used to calculate brightness temperatures from which a climatology of the diurnal variation of brightness temperatures for each channel can be derived. However, some channels are difficult to simulate due to lack of needed parameters in the forward model calculation, especially those channels that are affected by precipitation or sensitive to surface properties.

2. *Characterize and/or determine and remove the non-linearity factor:* Use sensor models that include the effects of instrument nonlinearities as well as the errors in the warm load and cold space calibration target measurements to determine inter-satellite biases and non-linearity factors, as was done for the MSU instruments (Grody et al., 2004). Use NWP models to identify the biases resulting from other unanticipated error sources, as was done for the SSMIS instrument (Yan and Weng, 2006). Recently, Zou et al. (2006) used a simultaneous nadir overpass (SNO) matchup dataset generated by Cao et al. (2004) to inter-calibrate the NOAA satellites and showed that uncertainties in intersatellite biases—largely due to uncertainties in the non-linearity factor—can be reduced substantially compared to previous studies. These bias-reduced satellite observations result in more accurate climate trend results. SNO matched pairs should be used to refine the post-launch non-linear factor in the two-point calibration algorithm.

3. *Improve determination of reflector emissivity and temperature through better antenna technology:* Calibration anomalies of the SSMIS are well illustrated in Figure 12, showing the SSMIS residual bias over a period of three orbits. For SSMIS, the reflector emission can be addressed by improved sensor and antenna characterization (modeling) and better instrumentation on orbit (more PRTs on the antenna). Currently, the uncertainty in the temperature of the SSMIS reflector is the most significant impediment to improving the utility of the SSMIS and reducing its on-orbit calibration anomalies.

4. *Apply Fast Fourier Transform and other filters to remove the jumps in warm counts and PRT time series:* Algorithms should be developed to detect anomalies that may occur due to solar illumination of the warm load and any other impacts to the sensor calibration that may result in residual calibration errors in the sensor scene data. Algorithm and software design to reduce such calibration errors will require robust analysis of radiometer gain variation over various length periods (orbit, day, month, season etc). Processing and trending of instrument gain to improve sensitivity to calibration anomalies yields significant improvements to the quality of radiometer data in cases similar to the SSMIS warm load contamination.

5. Correct for radio frequency interference: Microwave radiometers are subject to radio frequency interference, largely from anthropogenic sources. Improvements in digital processing with the availability of Field Programmable Gate Arrays (FPGAs) allow significant capability to be incorporated into space-based radiometers such as RFI detection and mitigation, and digital polarization correlation. RFI detection algorithms should be tuned to or otherwise optimized for the RF environment and the sensor channels. Research on RFI mitigation theory and techniques should continue to provide more effective RFI detection, mitigation and correction to achieve uncontaminated measurements.

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Broadband Instruments

7.

Broadband instruments relevant for climate change studies are those which measure spectrally integrated radiative power incident on or emitted from the Earth. The incoming radiation is from the Sun and is centered in the visible with large contributions in the near infrared. The outgoing radiation from the Earth is either scattered incident sunlight or thermal blackbody emission characteristic of the region from which it is emitted. This radiation shows large variations spatially across the Earth's surface as well as through the Earth's atmosphere, and has spectral components including both the reflected sunlight and the mid-infrared thermal emission. Nominally the net broadband outgoing radiation carries the same energy as the total incident radiation, except for a small ocean heating. Measuring this Earth radiation energy balance is limited by instrument accuracy for both incoming and outgoing broadband measurements.

7.1 Incoming Broadband Radiation (Total Solar Irradiance)

The Incoming Broadband Radiation usually referred to as the total solar irradiance (TSI), is the Sun's radiative input to the Earth. It represents the broadband radiative energy incident at the top of the Earth's atmosphere and is the dominant driver or radiative forcing of terrestrial climate. Prior to the industrial age, natural influences including solar variability were the dominant causes of climate change, with striking examples being the correlations between the 70-year period of low solar activity known as the Maunder Minimum in the late 1600's and Europe's Little Ice Age, as well as the increased solar activity that corresponded with the Medieval Warm Period (Crowley, 2000). Natural solar influences on climate continue today, although they are increasingly difficult to discriminate from human-caused influences.

7.2 Total Solar Irradiance: Current Capabilities and Climate Data Record Requirements

The Sun's broadband radiative input to the Earth's atmosphere varies by 0.1 % over a solar cycle and by approximately 0.2 % on shorter (days to weeks) time scales. Climate change may depend on yet smaller changes over greater periods of time, making the required measurements of solar variability extremely difficult. To detect small but long-term changes in TSI, instruments require either:

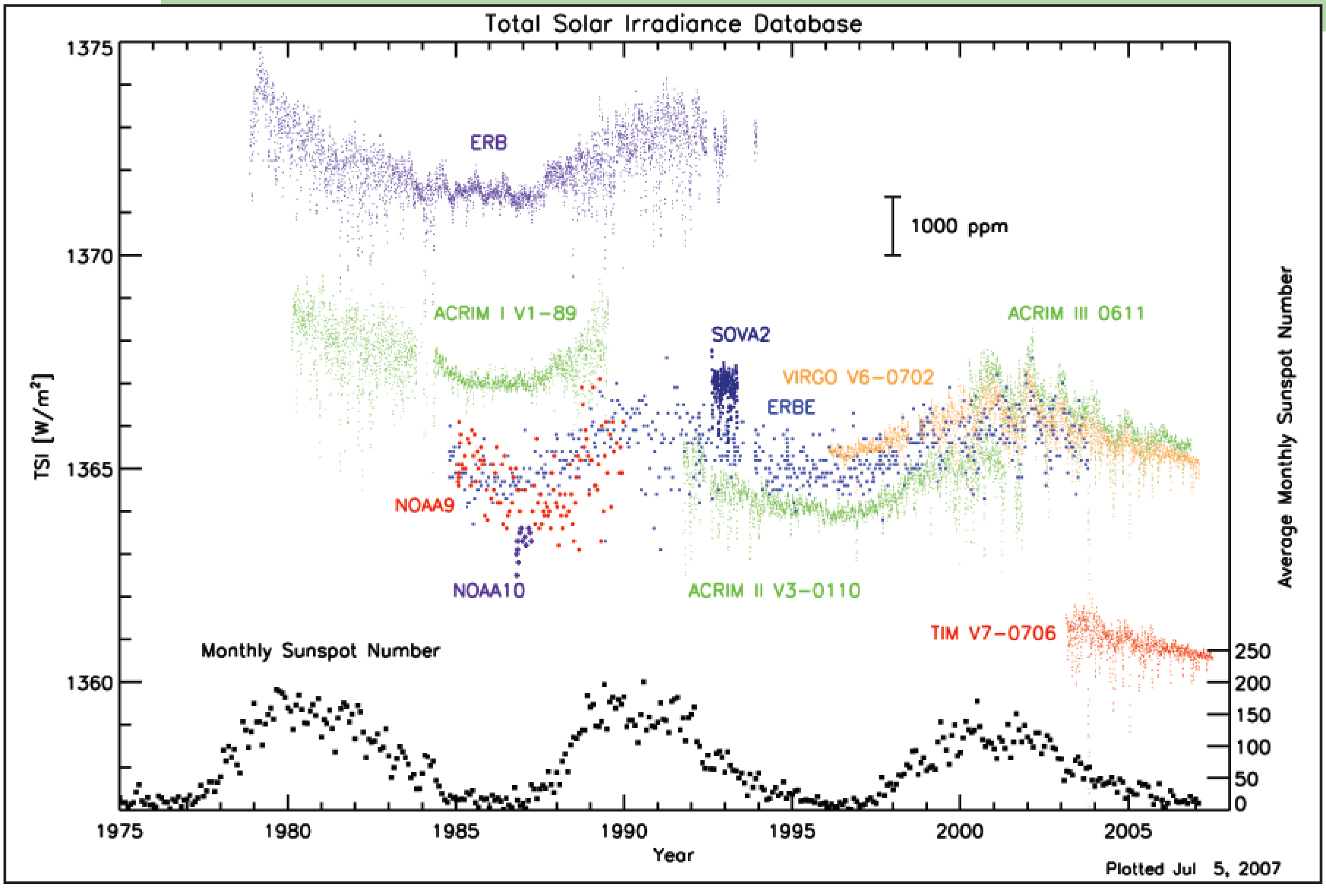
1. **Uncertainties of <0.01 % in accuracy**—This level of accuracy on an absolute scale, with measurements spanning decades to centuries, helps mitigate potential gaps in the data record and maintain a link to the existing TSI record.

2. **Uncertainties of <0.001 %/year in long-term repeatability and continual, overlapping measurements**—Overlapping measurements with stable instruments able to correct for on-orbit sensitivity degradation can determine relative changes in solar irradiance. The simpler of the two approaches, this method is susceptible to loss of data continuity.

The latter has been achieved; the former has not, with reported accuracies ranging from 0.035 % to 0.5 % (Kopp et al., 2005). Relying on instrument stability and data continuity has risk, as the existing TSI data record—currently almost 30 years long and the beginning of a record that will likely become centuries long—is susceptible to a break in measurement continuity. A discontinuity in these measurements would make connection to future TSI records at the accuracies needed to detect small solar variability extremely difficult or impossible. The longer—and thus more valuable—the data record, the more critical is continuity and the more important is measurement accuracy.

The existing 28-year TSI record is the result of several overlapping TSI instruments on different missions (see Figure 14). This data record currently relies on instrument stability and continuity, whereby successive instruments are linked to the existing TSI data record despite offsets between instruments on an absolute scale. The TSI record clearly shows the Sun's variability over the 11-year solar cycle and on shorter time scales. The accuracy of the measurements and the length of the TSI data record are insufficient currently to definitively indicate multi-decadal variations in the solar irradiance; with current instrument sensitivities and levels of solar variability, this will require a longer record.

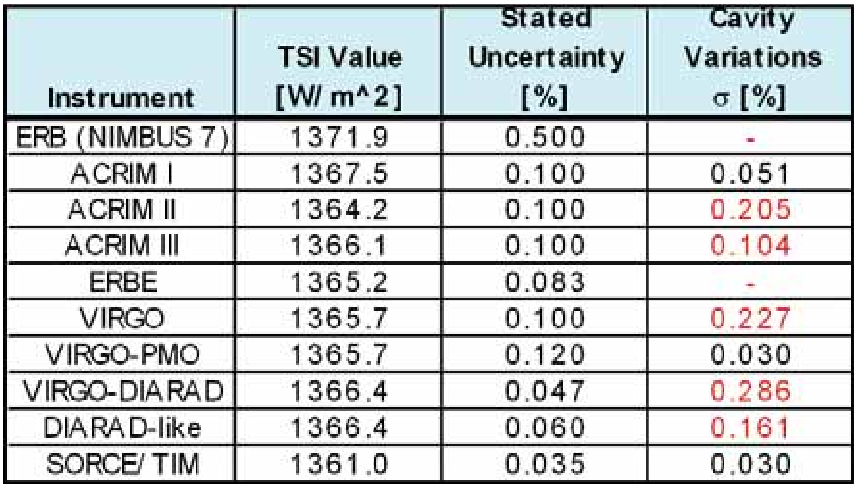
Figure 14 The 28-year Total Solar Irradiance record comes from several overlapping instruments. Offsets are due to inconsistent absolute accuracies, although each instrument precisely monitors short-term TSI changes. None of these instruments is calibrated end-to-end for irradiance at the desired absolute accuracy levels, as no such facility currently exists. The error bar shown indicates 0.1 % variation. (Kopp, 2007)



The risk of relying on data continuity for a climate data record expected to last centuries is high. Mitigating this risk requires a greater emphasis on absolute accuracy; thus the causes of the offsets between the instruments in Figure 14 are worth understanding.

The 'TSI Accuracy Workshop' was hosted by NIST and NASA in July 2005 to discuss the absolute accuracies, stabilities, and potential future calibration improvements of the TSI instruments. Representatives of the most recent seven TSI instruments presented the details of their instrument's design, calibrations, and stated uncertainties. All current instruments are calibrated at the component level, as no end-to-end calibration facility exists to measure irradiances at solar power levels to the desired accuracies. Many stated instrument uncertainties were found to contradict the relatively large internal instrument variations among the multiple channels in the instrument (see Table 6). Such internal instrument variations establish a lower limit to an instrument's actual uncertainty; this suggests one of the primary outcomes of the workshop, that many current TSI instrument uncertainties are underestimated.

Table 6 Comparison of TSI instrument stated uncertainty with variations between internal cavities. Red indicates instruments whose internal cavity-to-cavity variations exceed the stated instrument uncertainty. A dash indicates the instrument lacks multiple cavities.



Instrument	TSI Value [W/ m^2]	Stated Uncertainty [%]	Cavity Variations σ [%]
ERB (NIMBUS 7)	1371.9	0.500	-
ACRIM I	1367.5	0.100	0.051
ACRIM II	1364.2	0.100	0.205
ACRIM III	1366.1	0.100	0.104
ERBE	1365.2	0.083	-
VIRGO	1365.7	0.100	0.227
VIRGO-PMO	1365.7	0.120	0.030
VIRGO-DIARAD	1366.4	0.047	0.286
DIARAD-like	1366.4	0.060	0.161
SORCE/ TIM	1361.0	0.035	0.030

Causes of the differences in TSI instrument absolute values shown in Figure 14 were discussed. The most likely causes for such large variations are: the applied power in the flight TIM instrument is very different from that of ground-based units; or unaccounted- for scatter and diffraction from the front of the instruments [other than the TIM, which has a different optical layout (Kopp and Lawrence, 2005)] will systematically and erroneously increase their measured TSI values. NIST presented calculations of diffraction corrections that should be applied to each instrument, and pointed out a correction should be applied to the three ACRIM instruments to lower their reported values by 0.13 %, and that a smaller correction should be applied to the ERBE instrument to lower its TSI value. Unaccounted for scatter in all the instruments could systematically lower their reported values still more.

7.3 Total Solar Irradiance: Impediments to Progress

All space-borne TSI instruments rely on component level calibrations; no end-to-end calibration facility exists with the needed 0.01 % absolute accuracy level for measuring irradiance at solar power levels. No laboratory solar-type light source exists with radiant output known to this level. No ground-based method of inter-comparing instruments exists at the desired accuracy level: currently inter-comparisons are done viewing the Sun through the Earth's atmosphere (which has significant off-axis circumsolar scatter) and are often done operating in air, whereas the thermal conditions of the TSI instruments are best understood when operating, as designed, in vacuum. Additionally, such inter-comparisons mainly indicate *relative* differences between instruments, but do not indicate which is correct on an *absolute scale*.

The current TSI record relies on continuity of measurements with overlap between successive TSI instruments. With NPOESS having recently descoped its TSI instrument, there are no future U.S. plans beyond the upcoming Glory mission (Mishchenko et al., 2007) for maintaining this important climate data record. Until absolute accuracy at the 0.01 % level is achieved with a direct link to the existing nearly 30-year data record, any gap in TSI measurements risks loss of connectivity with this established data record.

7.4 Total Solar Irradiance: Recommendations to Accelerate Progress

Good instrument stability combined with data continuity is critical until improved absolute accuracy requirements are achieved. Since the current method of determining potential long-term variations in total solar irradiance relies on continuity and instrument overlap, instrument stability, or *long-term repeatability*, is needed. Having multiple redundant sensors with different frequencies of sun measurements allows for on-orbit correction of sensitivity degradation with solar exposure and has proven successful on the several TSI instruments employing this method. Offsets between the multiple channels within an instrument also offer a lower bound to the stated uncertainty in *absolute accuracy* that could be claimed by that instrument.

There is currently good rationale for flying instruments of different designs simultaneously. These instruments likely respond differently to solar exposure and age, so systematic changes affecting measurement sensitivity may be easier to diagnose from instruments of different type. This approach, useful for determining *relative* changes in TSI, has been successfully applied on the SOHO/VIRGO as well as in the construction of TSI composites (Fröhlich, 2005).

Improved absolute accuracies are needed to reduce the risk of a potential data gap in the long-term TSI record. NASA, NIST, and the TSI community are taking several steps to improve the absolute accuracies of TSI instruments via new calibration facilities:

1. **Radiant Power Calibration:** NIST has proposed a comparison between ground-based units of each of the currently flying TSI instruments and a reference trapped diode to validate the radiant power measurement accuracy of the instruments. This will be done with the TSI instrument operating in vacuum and with an input light source of appropriate power to simulate solar viewing conditions. This test is not a full irradiance test, which includes many additional and subtle optical and thermal effects from having an aperture in the beam, but it will validate each instrument's ability to measure radiant power correctly. This radiant power calibration, using a similar method to that developed by the National Physical Laboratory and World Radiation Center (Romero et al., 1996), has been completed at NIST on a ground-based TIM instrument; calibrations of other TSI instruments are pending.

2. **Scatter and Diffraction Measurement**: NIST proposes measuring the effects of scatter or diffraction off the front of the instruments, as these effects, if uncorrected, systematically and erroneously increase the reported TSI values.

3. **Irradiance Calibration**: NASA and the University of Colorado/Laboratory for Atmospheric and Space Physics are building the 'TSI Radiometer Facility' under the Glory program. This facility is intended to perform end-to-end *irradiance* calibrations at solar power levels by comparing a TSI instrument under test and in vacuum to a reference cryogenic radiometer (Kopp, 2007). This will become a permanent facility providing improved calibration accuracy for current and future TSI instruments.

Proposed satellite missions could provide on-orbit calibrations of some benefit to the TSI record (Fox et al., 2003). While TSI alone may not justify a separate, dedicated calibration mission, such a mission could benefit the absolute accuracy of TSI measurements by establishing a link to the existing record.

The designs of future TSI instruments are intended to have greatly improved absolute accuracies to establish and maintain a link to the current 28-year Solar Irradiance Environmental Data Record. *Until such improvements in absolute accuracy are achieved, data continuity of this solar irradiance climate record is critical, and it is of particular concern that there are currently no future plans for TSI instruments after the Glory mission*.

7.5 Outgoing Broadband Radiation

The majority of climate change uncertainties (IPCC, 2001) are driven by changes in the Earth's outgoing broadband radiation. Once the incoming solar radiation is known (section 7.1), the fraction of that solar energy reflected back to space, called Earth's broadband albedo, determines the amount of radiation absorbed by the Earth. This solar absorption in turn regulates the amount of cooling of the Earth system by infrared broadband radiation emitted to space. More than 99.7 % of the solar radiation that is reflected back to space is between wavelengths of 0.3 and 3.5 μm. More than 99.5 % of the thermal infrared radiation from the Earth is emitted to space between wavelengths of 3.5 and 100 μm, with most of the rest beyond 100 μm. As a result, the most direct measures of the Earth's energy balance observe these "broadband" spectral regions commonly referred to as shortwave or SW radiative flux, and longwave or LW radiative flux. The fluxes are referenced at the TOA (Top of the Atmosphere) which for climate purposes has been shown to be best approximated by the Earth's average solar photon capture diameter, a level on average about 20 km above the surface (Loeb et al., 2002). The magnitude of these TOA fluxes for global mean are ~ 340 Wm^{-2} for solar insolation, 100 Wm^{-2} for reflected SW radiation, and 240 Wm^{-2} for emitted LW radiation. Global climate change can be driven by changes in any of these fluxes, or by changes in the internal spatial distribution of the properties that affect radiative flux.

Climate change driven by changes in the Earth's albedo, for example, range from aerosol direct and indirect radiative forcing, vegetation and snow/ice albedo feedback, and cloud feedback. These include many of the largest current uncertainties in future climate change (IPCC, 2001, 2007). The thermal infrared fluxes primarily involve greenhouse gas radiative forcing, water vapor feedback, and cloud feedback. Note that if Earth's albedo is constant (no aerosol, snow, ice, vegetation, or cloud changes) and if there are no infrared cloud feedbacks, then in this very limited case, the global average outgoing thermal infrared flux is unchanged, even though its spatial distribution may change. Given the complexity of the climate system, however, it is expected that both global mean fluxes as well as regional distributions will change. This is also what current climate models predict (IPCC, 2001).

7.6 Outgoing Broadband Radiation: Current Capabilities and Climate Data Record Requirements

Recent studies highlight the issues involved in observing and interpreting the broadband radiative energy balance of the Earth's climate system. Wielicki et al. (2002) used broadband active cavity data from the ERBS mission to infer unexpectedly large decadal and interannual variability of 2 to 3 Wm^{-2} in tropical mean TOA SW reflected and LW emitted radiative fluxes. A later re-analysis of the ERBS data to account for small changes in satellite altitude and improved analysis of SW filter dome changes, greatly reduced the LW flux changes, left the SW flux changes essentially unchanged, and increased the magnitude of tropical mean Net flux changes (Wong et al., 2006). The Wong et al. (2006) paper also showed that the interannual variation of 60S to 60N average of ERBS net radiation (87 % of Earth area) agreed with recent ocean heat storage data to within the estimated spatial sampling noise of the ocean data, about 0.4 Wm^{-2} (1σ). The variability in global net reached about 1.5 Wm^{-2} in the satellite data, and 2 Wm^{-2} in the ocean heat storage data. Given the global average reflected SW flux of ~ 100 Wm^{-2}, and emitted LW flux of ~ 240 Wm^{-2}, the range of changes seen in the 1980s and 1990s satellite data were of order 1 % for LW, 2 % for SW, and 0.5 % for Net flux.

The difficulty in documenting climate variability and change lies in the calibration stability requirements. Estimates of anthropogenic total radiative forcing in the next few decades are 0.6 Wm^{-2} per decade (IPCC, 2001). A 25 % cloud feedback would change cloud net radiative forcing by 25 % of the anthropogenic radiative forcing, or 0.15 Wm^{-2} per decade. The global average shortwave (SW) or solar reflected cloud radiative forcing by clouds is ~50 Wm^{-2}, so that the observation requirements for global broadband radiation budget to directly observe such a cloud feedback is approximately 0.15/50 = 0.3 % per decade in SW broadband calibration stability (Ohring et al., 2005). Similarly, the global average longwave (LW) thermal infrared cloud radiative forcing is ~30 Wm^{-2}, so that 0.15/30 = 0.5 % per decade in LW broadband calibration stability is required. Note that consistent with this view, climate model studies have shown a roughly linear relationship between cloud feedback and changes in broadband net cloud radiative forcing (Soden and Held, 2006).

The most critical of these components is SW reflected flux, since it has been shown that low clouds dominate the uncertainty in cloud feedback in current climate models (Bony and Dufrense, 2005). Low clouds have a large effect on SW radiation and small LW effect. Achieving this stability per decade in calibration is extremely difficult and has only recently been demonstrated for the first time by the ERBS and CERES broadband radiation budget instruments (Wong et al., 2006; Loeb et al., 2006). As in the case of solar irradiance observations, absolute accuracy alone cannot currently reach this accuracy and overlapping continuous broadband observations are required (Ohring et al., 2005). Achieving highly accurate satellite calibration for solar reflected energy is much more difficult than for thermal infrared, where blackbodies can be used. But even for thermal infrared—with the most accurate broadband radiation budget data of the past (ERBE) at 1 % accuracy, and current (CERES) at 0.5 % accuracy—the expected differences with non-overlapped data can reach 1.5 % of the mean LW flux or 240*0.015 = 3.6 Wm^{-2}.

Figure 15 Satellite record of tropical mean (20°S to 20°N latitude) anomalies in broadband thermal emitted LW flux. Anomalies are referenced to the ERBS scanner baseline period of 1985 through 1989.

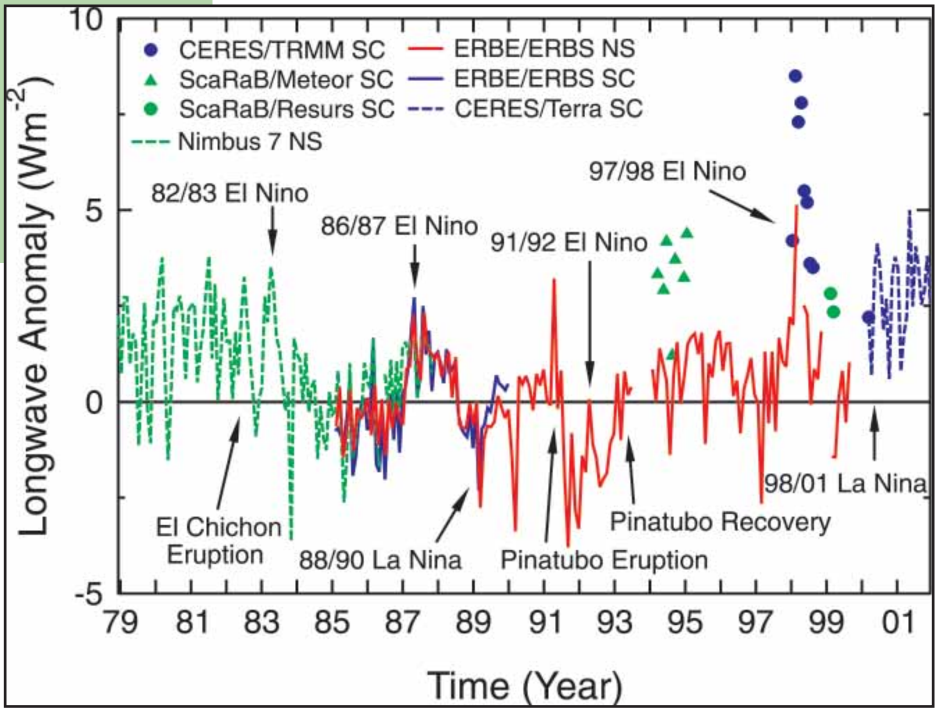


Figure 15 shows the variability of absolute calibration of broadband LW flux radiation budget data sets currently available for the 1980s and 1990s, and confirms the critical need for overlapping observations. Recall that a 25 % cloud feedback and therefore 25 % change in climate sensitivity will be signaled by a 0.15 Wm^{-2} per decade change in global cloud radiative effect. Even if the global signal is dominated only by changes in tropical mean (almost half of the Earth area), the signal in the tropics would still only be 0.3 Wm^{-2} per decade. *We conclude that continuous overlapping broadband radiation budget data are critical to determination of cloud feedback and therefore climate sensitivity over the next 2 decades*.

The largest uncertainty in anthropogenic radiative forcing remains the effect of aerosols on clouds. In this case, simultaneous high accuracy observations of aerosol properties, cloud properties, and broadband radiative fluxes are essential from a physical process and climate monitoring perspective. **In all cases, the most effective use of broadband data occurs when a broadband instrument is flown in combination with a high quality imager like MODIS or VIIRS, or at least with an AVHRR class instrument for aerosol and cloud property determination in the broadband fields of view**. The imager is also required to obtain the accuracy needed for radiance to flux conversion (Loeb et al., 2003).

The merged MODIS and CERES data products have recently provided the first interannual variations of cloud properties and Earth's albedo at climate accuracy (Loeb et al., 2006). The results are shown in Figure 16 and demonstrate that changes are driven by the tropics, and that cloud fraction drives the changes as opposed to variations in cloud optical depth or cloud particle size.

These results also allow the first estimation of the amount of time needed to detect a climate change signal in low cloud feedback (where SW flux dominates the cloud effect) above the level of natural variability shown in Figure 16. The length of record needed to detect change is shown in Figure 17 and suggests that 15 years of global observations are required to constrain cloud feedback to ±50 % with 90 % confidence above natural variability, and that 23 years are needed to constrain cloud feedback to ±25 % uncertainty (Loeb et al. 2007). Note that while Figure 16 suggests that the signal from tropical cloudiness changes are larger than global, the variability is also larger, and Figure 17 shows that the time needed to detect change is similar for tropical and global means.

For independent confirmation of calibration stability, comparisons were made over Tropical Ocean for interannual anomalies and trends in SeaWiFS lunar determined stability in visible narrowbands with the CERES broadband SW fluxes shown in Figure 16 (Loeb et al., 2007b). The two agreed for monthly tropical anomalies to within 0.3 %, and for decadal trends to 0.2 % per decade, within the Ohring et al. (2005) requirement for TOA SW flux. Unfortunately, this simple use of narrowband visible data to infer broadband climate change is only well suited to Tropical Ocean during this time period. Narrowband to broadband conversion is much more complex over land, desert, snow and ice, and comparisons for global ocean, land, or global mean showed 1 to 3 Wm^{-2} discrepancies in the narrowband (plus radiative transfer) estimates of broadband radiation. When less well calibrated ISCCP visible channel results are used with radiative transfer to estimate broadband flux anomalies, the global mean monthly differences reach +/- 3 Wm^{-2}, with decadal trend estimates different by a factor of 10 from the broadband data ((Loeb et al., 2007b). The better calibrated MODIS imager data yield anomalies consistent with the CERES broadband data to within +/- 1.5 Wm^{-2} for interannual anomalies, but narrowband-broadband issues remain at a level too high for climate change detection, especially for land surfaces.

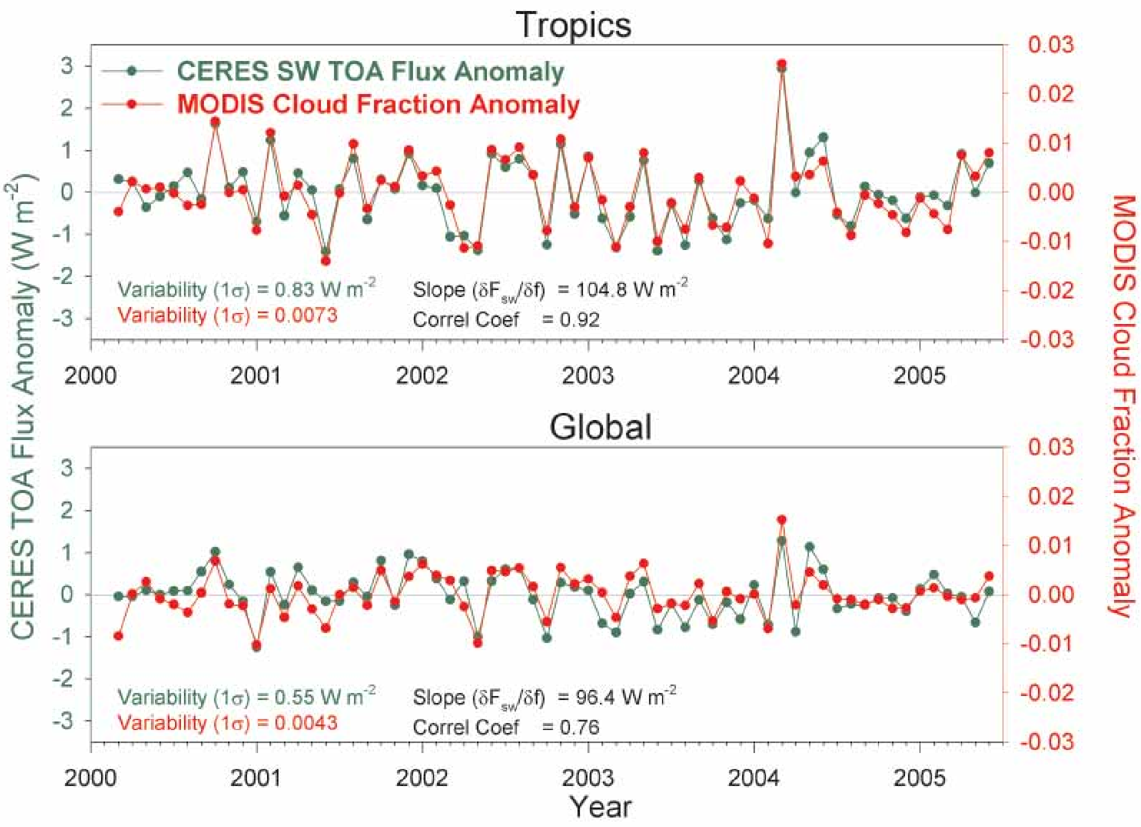
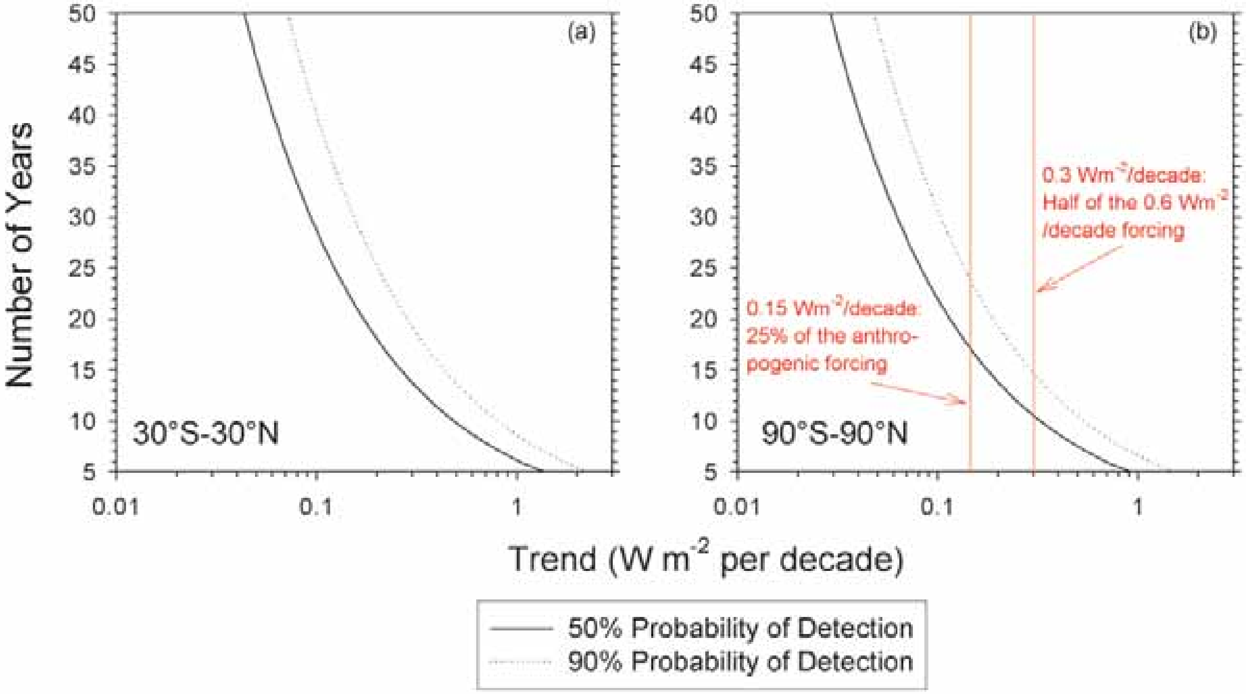


Figure 16 Monthly deseasonalized anomalies in tropical and global mean reflected CERES SW flux (proportional to albedo) and matched MODIS determined cloud fraction.

CERES instruments continue to operate with full capability on Terra (2 instruments) and

Aqua (1 instrument). Their design life is 5 years, while spacecraft design life is 6 years. One of the Aqua instruments has lost its SW channel but retains its Total and window radiation channels. NASA originally planned to build additional CERES copies and to launch a series of three spacecraft separated by 5 years in both morning (Terra) and afternoon (PM) orbits. When NPOESS decided to build and fly copies of CERES on their afternoon satellites (originally planned for 2009), NASA cancelled future radiation budget sensor builds. One NASA CERES instrument remains to be flown (CERES FM-5). Given the need to combine radiation budget data with observations of aerosol and cloud properties, the next opportunity to fly CERES FM-5 is on the NPP mission for launch in late 2009 to mid-2010. The current plan is to wait until NPOESS C1 in 2013/2014, which makes a critical gap far too likely.



Given climate variability, 15 to 20 years is required to first detect climate trends at cloud feedback level with 90% confidence

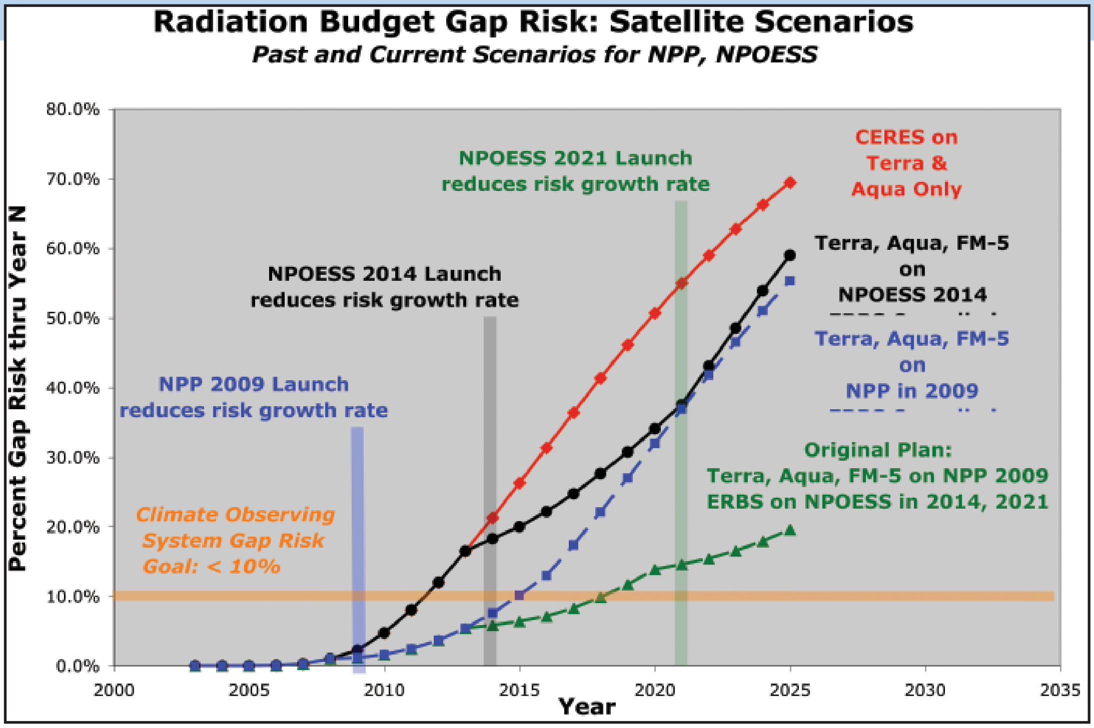
Figure 17 Number of years to detect a given trend in SW TOA flux anomaly with 50 % and 90 % probability for (a) 30°S-30°N and (b) 90°S-90°N. Adapted from Loeb et al. (2007).

A statistical gap risk analysis has been performed using standard engineering failure rates per year based on design life of spacecraft and instruments. Ohring et al. (2005) set a climate data record gap risk of 10 % or less. Figure 18 shows the gap risk for CERES on Terra and Aqua as a function of future launch scenarios. For only Terra and Aqua (red curve) the gap risk exceeds the 10 % goal by 2011. Placing the last copy of CERES (FM-5) on the NPP mission for 2009 launch (blue curve) reduces the risk by a factor of 3 through 2015. Note that a problem in assessing the statistical risk of a gap is that the engineering studies done to date have not considered lifetimes beyond the normal design goals of 1 to 7 years. They assume constant failure rates per year up to this point. For the study in Figure 18, these failure rates per year were doubled after 7 years to allow for the much larger uncertainty for longer lifetimes, and issues such as spacecraft battery life. Further engineering studies are needed to better assess failure rates beyond 7 year lifetimes.

We recommend that the CERES FM-5 instrument be flown on NPP to reduce gap risk, and a strategy be developed to assure continuity following NPP for 2015 and beyond. Because the NPOESS program cancelled its future broadband radiation sensor ERBS (a CERES follow on sensor) as part of its Nunn-McCurdy budget reduction, we also recommend that NASA or NOAA continue an overlapped record of broadband radiation budget past the CERES FM-5 instrument. Finally, we recommend that formal gap risk studies be performed for all major climate observables, not just broadband radiation.

Because gap risk can only increase in time from any starting point, the question arises: how would any satellite based climate observing system ever hold gap risks to the desired 10 % level over 100 year climate record? An analysis similar to that in Figure 18 was performed to answer this question. The study assumed 7-yr lifetime designs for both spacecraft and instrument, the same as that for NPOESS operational instruments. If the climate record begins with the launch of 2 such spacecraft, and launches an additional spacecraft/instrument every 3 years, then the gap risk takes roughly 100 years to grow to 10 %. The gap risk of such a climate observing system approaches a constant 1 % per decade. Clearly none of our current systems are designed this way. It suggests that the concept of a climate calibration system in orbit may be essential to efficient design of long term climate data records, and that this calibration system should be designed with sufficient overlap to reduce calibration satellite gap risks to 1 % per decade until absolute accuracies can be proven at a level sufficient to allow gaps that do not seriously degrade the climate records.

Figure 18 Radiation budget data gap risk for different satellite scenarios. Assumes one CERES instrument on Aqua, and two on Terra.



7.6.1 Pre-launch Calibration

Current state of the art in broadband radiation pre-launch calibration is the CERES vacuum calibration facility originally built for ERBE and improved for the CERES mission (Lee et al., 1998). Many of the calibration recommendations in the other sections of this document were used: calibration in vacuum, calibration against deep blackbody cavity (emissivity of 0.999952) using SI temperature standards, calibration of linearity to 0.1 % from blackbody temperatures across the entire range of 200 K to 320 K. A cryogenically cooled active cavity radiometer was calibrated against the same blackbody and then used to calibrate the spectral output of an integrating sphere for the CERES SW channel full spectral response and calibration. For SW broadband spectral response, 13 wavelength regions were calibrated between 0.3 and 2 μm wavelengths using output of the active cavity calibrated integrating sphere. The vacuum chamber calibration system included cryogenically cooled zero radiance level sources to simulate deep space offsets, as well as sources to determine the radiometer spatial response function or point spread function. The instrument calibration included full spectral characterization of all optics across the entire broadband spectrum from 0.2 to 100 μm (Lee et al., 1998).

Calibration error budget predicted a 1-sigma absolute accuracy of 1 % for broadband SW radiance and 0.5 % for broadband LW radiance. Instrument theoretical models were used to predict thermal and radiometric behavior of the final instrument and were verified against characterization and calibration data. Absolute calibration of the instruments is entirely from ground characterization and vacuum calibration. Three onboard calibration sources are used to monitor any changes in instrument gain from ground to orbit, and while in orbit. These three onboard sources included: a) shortwave source lamps capable of three output levels and determined to be stable to 0.3 % over the equivalent mission life use in calibration tests, b) blackbody with variable temperature levels, and c) mirror attenuator mosaic (MAM) to allow using diffused sunlight as a source in orbit. The MAM was only designed to monitor SW channel stability once in orbit, with the lamp used to monitor change from ground to orbit. The TOTAL and Window channel gains are monitored for change using the blackbody. All channels view deep space twice per scan and these views are used to constantly set instrument zero radiance. **We recommend such partially redundant on-board calibrations to improve knowledge of instrument stability. Improvements are needed in broadband MAM or diffuser designs to meet the new climate stability requirements**.

Both TRMM and Terra missions found spacecraft pitch-over maneuvers to allow scanning of deep space and the Moon to be highly beneficial for calibration verification and instrument characterization. **We recommend that future climate missions allow for regular deep space maneuvers to support climate calibration of zero radiance levels as well as lunar calibrations (e.g., SeaWiFS) or characterization of other radiometric components. This is rarely done with meteorological satellites but only requires a small portion of one orbit to accomplish**.

7.6.2 In Orbit Calibration

Broadband radiation is an 8-dimensional sampling problem that requires accurate handling of latitude, longitude, height, time, solar zenith, viewing azimuth, viewing zenith, and wavelength. The three angular dimensions are especially challenging to sample as the anisotropy of earth's broadband radiation varies by a factor of 2 to 5 with these angles, while 1 % time averaged accuracies are the goal. CERES flew two instruments on Terra and Aqua to solve this challenge: one instrument for normal crosstrack "image" coverage of the Earth each day, and one instrument to scan the entire hemisphere of radiation (but with poor spatial coverage) each 250 km along the groundtrack. The full hemisphere data is merged with simultaneous determination of surface and cloud properties in each CERES field of view using the high spatial and spectral resolution MODIS data. Then using 2 years of this merged full hemisphere scan data for each spacecraft orbit, relationships between radiance and flux are derived as a function of surface type, cloud properties, and atmospheric state. These enable a factor of 2 to 5 improvement over the ERBE TOA fluxes. Once the angular distribution models (ADMs) are observed for a given orbit, then future missions only require flying a single cross-track instrument (e.g. NPP or NPOESS in 1030 am or 130 pm orbits). The existence of two CERES instruments on Terra and Aqua missions allowed a range of independent in-orbit calibration checks not normally possible in space.

Using the onboard lamps and blackbodies, ground to in-orbit gain changes for the CERES on TRMM and Terra were within 0.5 %. The changes were all to increase and not to decrease instrument sensitivity. These results were consistent with ground calibration in vacuum that demonstrated an initial rapid increase of detector sensitivity when placed in the vacuum calibration chamber, slowing after a week to much smaller increases. It was determined that a 2 week vacuum calibration time would be sufficient to restrict further increases in orbit to less than 0.5 %. The explanation for this increase is that the bolometers are covered with a "blackening" paint layer to enhance broadband absorptivity across the spectrum: any small air pockets under this paint layer will outgas in vacuum and increase contact of the absorbing paint layer with the thermally sensitive detector. As a result, a small increase in gain is found. In future calibrations of this type, we recommend further work on improving methods to blacken broadband detectors to reduce the amount of increased gain over time in vacuum.

The largest changes on orbit seen by CERES all occurred in the Aqua FM3 and FM4 SW radiance channels, and all appear to be the result of unanticipated pre-launch and in-orbit optics contamination. The Aqua FM4 SW channel increased in sensitivity by 2 %, seen by the onboard lamp. When corrected against the lamp, the SW radiance agrees in orbit crossing studies with the Terra SW channels. The Aqua FM3 instrument SW channel, however, showed a drop in response of almost 8 % in orbit. The lamp only showed a 4 % change. This is the only CERES channel of the 5 instruments (15 channels) that required calibration against another CERES instrument or channel, in this case against the Aqua FM4 SW channel. Once adjusted its performance as a function of scene type (spectral coloration) or change over time has been similar to the other channels and instruments. An unusual film appeared on the inside of the FM3 MAM cover following spacecraft vacuum testing. The film indicated the potential for some internal contaminant released inside the FM3 instrument, but an investigation at the time concluded that the MAM door had acted as a cold trap during thermal vacuum and that the rest of the instrument (warm) was unlikely to be affected. FM3 showed no such film, nor was it seen on any of the other instruments during inspections. The FM3 SW channel change remains a mystery, and is a cautionary note on the inability to test or clean many instrument optical surfaces just before launch. Had FM3 launched as a single instrument on a spacecraft, its SW channel would have had to be inter-calibrated with a previous broadband SW channel already in orbit. **We recommend that more careful attention be paid to potential contamination of optical surfaces for climate instruments during ground testing, as well as improving the technologies for measuring and correcting any potential contamination**.

A second but smaller contamination issue for SW sensors was found in-orbit with all of the Terra and Aqua instruments (Matthews et al., 2005). No effects were found in the thermal infrared. This in-orbit contamination was found to occur only when the instruments were operating in the CERES Rotating Azimuth Plane (RAP) scan mode used to collect the hemispheric anisotropy data. The contamination was not found during normal crossstrack scanning. Studies with the CERES SW sensors, when not performing crosstrack scans, found that contamination was not spectrally flat, but was stronger for spectrally blue scenes, such as clear ocean (larger reflectance at low wavelengths), than for white scenes (e.g., clouds), or spectrally red scenes (e.g., desert) (Matthews et al., 2005). A study of the literature showed that many instruments in orbit (MODIS diffuser, GOME spectrometer) have had optical systems lose sensitivity starting at 0.5 μm wavelength and increasing exponentially toward 0.3 μm. Figure 19 shows the spectral response of contaminants on optics studied by the Long Duration Exposure Facility (LDEF), which was launched by the space shuttle, spent almost 6 years in orbit for exposure, and then was returned for analysis by the Shuttle. The contaminants were found to be dominated by layers of silicates with thicknesses less than 20 nm. The hypothesis was that these were out-gassed spacecraft contaminants and required UV exposure to polymerize into a solid absorbing layer. No effects were found at wavelengths greater than 0.5 μm, but strong transmittance loss occurred on optics in the UV. Figure 19 shows the spectral response change of the GOME instrument with wavelength and time, showing a similar spectral response. The MODIS diffuser reflectivity has also shown this type of behavior in orbit. For broadband SW radiance, the total effect for the CERES scanners over the first 5 years on orbit averaged 1 to 2 %. Corrections were derived by ratioing time varying changes in the Rotating Azimuth Plane (RAP) instrument on each spacecraft to its partner crosstrack instrument on the same spacecraft. No other changes were made. The stability of the instruments in crosstrack mode was verified by stowing one of the instruments for 2 months while the other instrument continued in crosstrack scan mode. Because both instruments are on the same spacecraft scanning crosstrack before and after the stow period, changes of even a few hundredths of a percent can be seen. An improved resolution of this problem in CERES Edition 3 data products will include an explicit spectral correction using the shape of LDEF, but adjusting the magnitude to agree with the crosstrack/RAP changing ratio. In this case, because the shape of the spectral response change is relatively simple, it is expected that this adjustment will correctly handle a wide range of spectral scene types. The all-sky SW flux results would remain unchanged, but strongly colored individual scene types such as clear ocean might

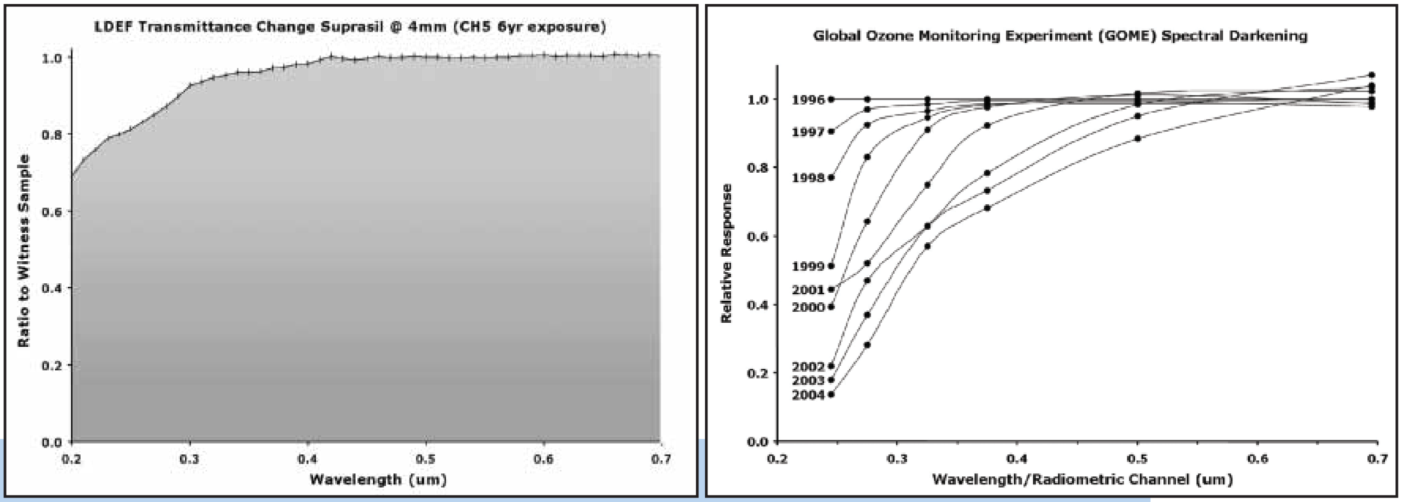


Figure 19 Changes over time: (a) Long Duration Exposure Facility transmission of optics caused by in-orbit contamination layers and (b) GOME.

change by up to 0.5 % over time. Starting in early 2005, the CERES instruments on both Terra and Aqua were restricted to crosstrack scanning to avoid future contamination increases. The same strategy would be used for flight of the CERES FM-5 instrument on NPP or NPOESS. Since the angular distribution models for the 1:30 pm sunsynchronous NPP and NPOESS orbits have already been developed by the Aqua instruments, there is no further need for use of the RAP mode on a continuous basis. **We recommend that flight of the CERES FM-5 instrument use only the crosstrack scan mode to avoid in-orbit contamination of the SW channel optics. We also recommend that future calibration observatories in space be designed to explicitly account for expected in-orbit contamination, even if its level is small. Finally, future broadband instruments should examine the potential for 0.3 to 0.5 μm sources such as small nonlinear optics lasers to explicitly monitor throughput below 0.5 μm. This issue appears to exist for all instruments measuring solar radiation with wavelengths below 0.5 μm and should be accounted for in calibration system design**.

7.6.3 Earth-based Reference Sites

An advantage of broadband detectors is the ability to perform independent checks of the consistency of calibration across the entire solar and infrared spectrum. The ERBE and CERES Total channels observe all radiation from 0.3 to 100 μm, SW channels from 0.3 to 3.5 μm, with daytime LW radiance determined as Total minus SW. One way to check the accuracy of this daytime LW radiance, along with the consistency of the SW channel and SW spectral portion of the Total channel is to use the coldest extensive tropical deep convective clouds as targets (Hu et al., 2004). These cloud systems are selected as overcast clouds with cloud radiating temperature colder than 205 K. These clouds are very high albedo (~ 0.7), giving them typical SW reflected flux of ~700 Wm^{-2}, but because of their cold temperature, a LW emitted flux of only 100 Wm^{-2}. This represents a very difficult test of the Total minus SW estimation of LW flux: the desired LW flux is a small residual of two fluxes an order of magnitude larger. CERES has found these Earth scenes to be the most stable and repeatable of all scenes we have examined: including clear ocean, Antarctica, and the deserts. The clouds are the most Lambertian optically thick targets on the Earth. They are so thick that the results are independent of whether the clouds are over land or ocean, and despite vertical velocities in the land systems being much larger than the ocean counterparts. We have also found that the albedo of these deep convective systems shows little dependence on season or time of day. As a result, they have been found to be one of the most useful Earth-based targets for solar reflectance based calibration studies. **We recommend that the use of deep convective clouds as a visible channel stability target be extended to narrowband visible imagers in an attempt to improve the past record of AVHRR and geostationary imager satellite data back to 1983 (e.g., ISCCP)**. The GEWEX Radiative Flux Assessment is currently examining this approach.

7.6.4 Extraterrestrial Calibration Sources

The Sun has been used with MAM diffusers on ERBE and CERES missions with limited success (see section 7.6.1). The moon has also been systematically scanned with the CERES instruments, primarily to use it as a point source to verify the in-orbit point spread function. Note that the moon diameter is about ¼ of the CERES field of view diameter at nadir. As a result the moon is not a very useful stability source for the CERES SW channel.

7.7 Outgoing Broadband Radiation: Impediments to Progress

The technical impediments have been discussed in the previous sections, along with recommended actions. But there is a wide range of organizational, programmatic, and structural challenges that seriously limit progress. Several of these key impediments are listed below:

- Climate data records require both a research culture (to achieve the accuracy) and an operational culture (long time records). No U.S. agency currently combines these attributes with a climate data record focus.
- Resources at both NOAA and NASA are extremely limited to address the breadth and complexity of the climate problem.
- More rigorous methods of using climate models to determine climate observing system requirements are needed. Without this we are limited to offering very long shopping lists of required near perfect data, everywhere, all the time.
- Current short-term procurement mechanisms are ill-suited to long term high accuracy observations. Calibration expertise (hardware, software, and staff) are needed not only before launch, but continually after launch to reach climate calibration accuracy and rigor. Post launch studies to investigate in-orbit calibration anomalies are difficult to fund. The same is true of maintaining a set of controlled witness samples of key calibration materials: mirrors, filters, diffusers, etc.

7.8 Outgoing Broadband Radiation: Recommendations to Accelerate Progress

7.8.1 High level initiatives

- Eliminate the high risk of a radiation budget climate data record gap by moving the final CERES instrument copy to NPP for launch in 2009/2010 instead of NPOESS C1 in 2013/2014. The current CERES instruments on Terra are already over their 5-year design life, and the remaining fully functional Aqua CERES instrument will exceed its design life by June, 2007. Build follow on broadband instruments to launch on NPOESS or to fly in formation with the NPOESS imager.

- Fly a spectral and broadband calibration observatory in orbit. This should be a transfer radiometer capable of calibrating both narrowband and broadband instruments across the full solar and infrared spectrum from 0.3 to 100µm wavelength. The goal should be to meet the Ohring et al. (2005) stability requirements with SI traceable absolute accuracy sufficient to overcome gaps in the observatory instrument record itself. The threshold or minimum capability should be overlapping climate observatory records with stability of calibration that meets the Ohring et al. (2005) requirements. The calibration observatory must be capable of obtaining sufficient matching in time/space/viewing angle and number of independent samples to calibrate all low earth orbit and geostationary solar and thermal infrared instruments used to derive the climate variables in the Ohring et al. (2005) report at the stability and accuracy requirements in that report with 95 % confidence at least once every 3 months. This time window is chosen to capture variations in instrument calibration sufficiently rapidly to distinguish between rapid instrument changes and slow long- term drift. If such a climate observatory is successful, it would eliminate the current major problem of calibration across data gaps for climate records.

7.8.2 Cross-cutting additional recommendations

- Independent observations and independent analysis of observations should become two additional Climate Observing Principles. This is the only way to assure sufficiently high confidence in surprising results. Almost all data analysis code for satellites is complex and will contain errors: it's only a matter of how many and how serious. Independent analysis allows them to be discovered because two independent teams will make different coding errors. It also allows many algorithm errors to be discovered. The classic example is the MSU satellite temperature record.

- Climate data records from satellites require continuous high quality validation. This requires constant vigilance by a Climate Data Science Team as indicated in the CCSP strategic plan (chapter 12). Operational quality control will not be of sufficient accuracy nor of deep enough scientific understanding to find and resolve problems in long term climate records. This approach has been used in NASA Earth Observing System data sets and needs broader application, including extension to NOAA.

- Reprocessing of climate data records is critical to resolving and correcting time-varying artifacts in calibration, auxiliary input data sets, exception handling, and gap filling. Algorithms and input sources must remain constant during any single reprocessing. Once climate data records reach validated status, have public distribution, and have been used in peer reviewed research papers, they (or a sufficient subset of them) must be maintained in a climate archive to allow quantification of differences over time in different data set versions, and replication if necessary of earlier published results.

- Allowable gap risks need to be defined for climate data records. For example: the gap risk should be less than X % over the next Y years. These are key to prioritization in climate system design and implementation. Gap risk engineering risk analysis should be done for all climate variables. Further engineering work is needed to define instrument and spacecraft failure rates after nominal mission life but good models exist for shorter time periods based on design lifetime and past mission experiences.

- The NASA to NOAA transition of many observations remains a major risk to the climate observing system. The many recent problems with NPOESS for climate observations of solar irradiance, broadband radiation, winds, altimetry, along with continued VIIRS and CrIS technical challenges clearly demonstrate the seriousness of the problem. The nation needs a climate observing system that can put the required critical priority on calibration and overlapping observations.

- Prioritization of climate observations is critical to success. Current climate requirements are done in the "shopping list" mode. We need better methods for prioritizing observation requirements by variable, time/space sampling, and calibration. All three drive resource requirements. Using climate models to perform Climate Observing System Simulation Experiments or OSSEs is one possibility; another is broad canvassing of the climate science community.

- Better consistency is required for quantifying calibration accuracy metrics. For example: accuracy may be quoted as 1 %. But is the confidence in this accuracy 1-σ or 2-σ? Most accuracy estimates are one sigma because there are only a few independent methods of quantifying each error source that goes into an absolute accuracy bound. The “sigma” bound that is used must be stated along with the accuracy.

- Improved characterization of in-orbit contamination of optical surfaces is needed. From the Long Duration Exposure Facility (LDEF) analysis, and instrument experience, this appears to be primarily an issue of transmission or reflectance reduction below 0.5μm wavelength, with the effects increasing toward shorter wavelengths. Future calibration designs should explicitly assume some degradation will occur and be able to account for it.

- Assure that in-orbit calibrations are performed through the entire optical train. For lunar calibration this typically means a satellite pitch-over maneuver similar to those performed routinely by SeaWiFS, or occasionally by TRMM and Terra missions. The same pitch-over maneuver should be used to verify instrument zero radiance levels against deep space in an earth scanning mode of operation.

- Accurate determination of instrument field of view point spread functions will be needed to support accurate intercalibration with in-orbit calibration observatory instruments.

7.8.3 Specific broadband outgoing flux additional recommendations

- CERES instruments were calibrated against SI standard temperatures using deep-well blackbodies for the thermal infrared. This standard was then transferred using a cryogenically cooled active cavity radiometer to a shortwave spectral integrating sphere source that in turn calibrated the CERES SW channel. This method should be compared against the new NIST solar spectral sources that did not exist when the CERES instruments were built. The mirror in the active cavity radiometer should have its spectral response verified using new optics industry and NIST techniques. This would help in confirming the absolute accuracy of the CERES broadband SW channel, currently estimated at 1 % (1σ).

- Improved methods for using solar monitoring of broadband SW channel and SW part of the Total channel should be developed that fully meet the Ohring et al. (2005) broadband stability requirements.

- The GERB geostationary radiation budget instruments on Meteosat have used 1-D arrays of 256 thermistor bolometers. Improvements in spectral blackening coatings of these bolometers are needed, as GERB found the methods used on early arrays to be variable from detector to detector.

- The GEWEX Radiative Flux Assessment activity is underway examining the accuracy of broadband TOA radiation estimates from direct broadband radiation data (ERBE/CERES) as well as narrowband plus radiative transfer theory (e.g., ISCCP). Loeb et al. (2007b) show that the current ISCCP-based estimates sometimes agree but often disagree with the more accurate broadband data. But because length of record is critical for observing cloud feedbacks in the climate system (Leob et al., 2007b), new methods to improve the time varying calibration of the AVHRR and geostationary narrowband data should be pursued. Possibilities for visible channel calibration include the simultaneous nadir overpass method, use of the coldest deep convective clouds, views of the moon, or intercalibration against ERBS SW nonscanner medium or wide field of view. All three methods should be examined. Viewing angle dependencies of cloud properties will also need to be examined.

- Further studies of the space/time matching error of satellite estimated surface radiative fluxes against surface radiometers are needed. These errors are a strong function of the space and time scale of the comparison, and are much larger for SW surface fluxes than for LW fluxes. This understanding is critical for evaluating the significance of issues like "global dimming" of solar insolation at the surface. A recent satellite subsampling study at the surface sites showed large differences between true global averages and these subsampled surface locations (Hinkelman et al., 2006). These studies should include quantifying how representative the surface sites are for radiative fluxes averaged over nearby lat/long grid scales of 0.25, 0.5, 1, and 2.5 degrees for current and future satellite-based climate data sets.

- The international Global Baseline Surface Radiation Network (GBSRN) continues to be a critical component with high accuracy SW and LW surface fluxes. Further research is needed to quantify the stability of these radiometers over annual to decadal time scales for climate change studies. A recent intercomparison of CERES estimated downward SW surface flux averaged over 20 BSRN sites over the globe for 12-month running means showed remarkable consistency of 0.3 Wm^{-2} (1σ) for interannual variations of up to 10 Wm^{-2} over a 5-year period. More extensive open ocean surface radiation data is needed, however, to augment current data only at island surface sites which are biased relative to open ocean, especially for surface heating (LW) and boundary layer cloud (SW and LW). Open ocean solutions could include either GBSRN quality reference buoys or ship board observations. All major ocean climate regions should be regularly sampled.

- Because there is a gap between the end of the ERB nonscanner radiation budget data set (Nov 1984 through Sept 1999) and the beginning of the CERES data set (March 2000), efforts should be made to cross this transition and place CERES/GERB/ERBE/ScaRaB on the same radiometric scale for climate studies. First, an attempt should be made to develop analysis algorithms to correct the ERBS nonscanner data for the 15 degree tilt to nadir of the instrument that occurred after October 1999. This would allow analysis of the ERBS 1999 through 2005 data and overlap of ERBS and CERES broadband records. For SW fluxes, an independent approach is to utilize the SeaWiFS data analogously to the methods of Loeb et al. (2007). The SeaWiFS data should also be used to verify stability of the visible channel deep convective cloud albedo. This could be done for 1997 through 2007, and used to verify the ability of the deep convective cloud method to improve the ISCCP visible channel calibration for AVHRR and geostationary satellites back to 1983.

- As shown in Wong et al. (2006) the global net broadband radiation and global ocean heat storage should be consistent to within about 0.1 Wm^{-2}. Spatial sampling limitations of 1992 through 2002 ocean heat storage data (satellite altimeter plus in-situ) limited this accuracy to 0.4 Wm^{-2} (1σ). The radiation and ocean heat storage data sets agreed at that level during this period. In 2003 to 2005, however, large changes of about 1.7 Wm^{-2} (cooling) were found in ocean heat storage data that are not supported by either altimeter sea level change, CERES net radiation data, or the GRACE ice sheet mass data. As the new ARGO global temperature/salinity record has just recently reached full global ocean coverage, this represents a new opportunity to independently verify the ability to monitor interannual variations in global net radiative flux. It will be important for the ocean and radiation research communities to collaborate, and understand the accuracy of each data set to enable a clear understanding of interannual variations and decadal change in global net radiation.

- Except for broadband instruments such as CERES or ERBE, no instruments currently observe the far infrared (beyond 15µm wavelength) that includes half of the Earth's infrared radiation to space, and almost all of the water vapor greenhouse effect. There are currently no high resolution spectral measurements in this key 15 to 100µm spectral range. This capability has recently been demonstrated for an interferometer in a high altitude balloon flight (Mlynczak et al., 2006) and should have serious consideration for spaceborne flight, at least as part of a climate calibration system. All that currently exists for this key spectral region are broadband radiances and radiative transfer theory.

Chapter 7 Authors

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8.

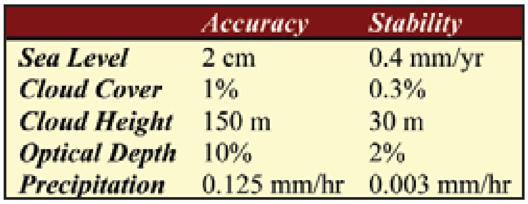
Active Instruments

8.1 Introduction

Active instruments offer advantages over passive remote sensing techniques in measuring some climate variables, particularly those involving elevation or altitude. Active instruments operate by sending out pulses of light or microwave energy and measuring the time-varying signal scattered back to the instrument as the pulse passes through the atmosphere to the Earth's surface. Because of the high accuracy and stability possible with timing measurements, active range measurements can be highly accurate and extremely stable.

As part of the ASIC^3 workshop, a session on active instruments was convened to discuss the use of active instruments to acquire benchmark measurements necessary for understanding climate change. Climate parameters which were considered are listed in Table 7 along with requirements on measurement stability and accuracy. The measurement requirements for sea level height correspond to the performance of the TOPEX/Poseidon and JASON satellites, which have observed global mean sea level to be rising at a rate of 3 mm/year over the 1992-2005 time period. The cloud measurement requirements were identified by the previous Satellite Calibration workshop (Ohring et al., 2004)

Table 7 Climate Parameter Measurement Requirements



	Accuracy	*Stability*
Sea Level	2 cm	0.4 mm/yr
Cloud Cover	1%	0.3%
Cloud Height	150 m	30 m
Optical Depth	10%	2%
Precipitation	0.125 mm/hr	0.003 mm/hr

8.2 Current Status and Impediments to Progress

8.2.1 Satellite Radar Altimetry

Global sea level rise is a combined response to changes in ocean volume (caused by temperature changes) and changes in mass (primarily from the melting of continental ice). Long-term direct measurements of global sea level provide large-scale constraints on possible increases in the temperature and mass of the ocean and are necessary to assess the realism of model estimates (Miller and Douglas, 2004). Ultimately, measurements of sea level trends provide important constraints on global scale energy flows between the atmosphere, the cryosphere, and the ocean.

Tide gauge measurements allow the determination of sea level rise during the 20th century, but the existing tide gauge network is sparse and there are questions of whether the sparse network measurements are representative of the mean global sea level, which is highly variable relative to the magnitude of the long-term trend. There are also questions of whether or not measurements from individual stations are biased due to local effects.

Satellite radar altimetry is used to measure the surface topography or height of the sea surface associated with a broad range of ocean phenomena, from meso-scale eddies (~100 km), to basin scale gyres, to global sea level rise, the last being the most challenging in terms of calibration requirements. Altimeter observations made over the past 14 years show global mean sea level rising at a rate of 2.97 +/-0.4 mm/yr, roughly 50% faster than the 20th century rate determined from long, 50-to-100 year tide gauge records. It is unclear whether this higher value reflects a change in the long-term trend or evidence of decadal variability. A map of the satellite-derived trends (Figure 20) shows large regional variations, with the highest rates in the southern hemisphere where only a handful of tide gauges are located. To monitor these trends and improve the model predictions of sea level rise over the coming decades, it is essential that the Jason series of high accuracy, high precision altimeters be continued with well-calibrated, overlapping missions beyond the launch of Jason-2 (2008).

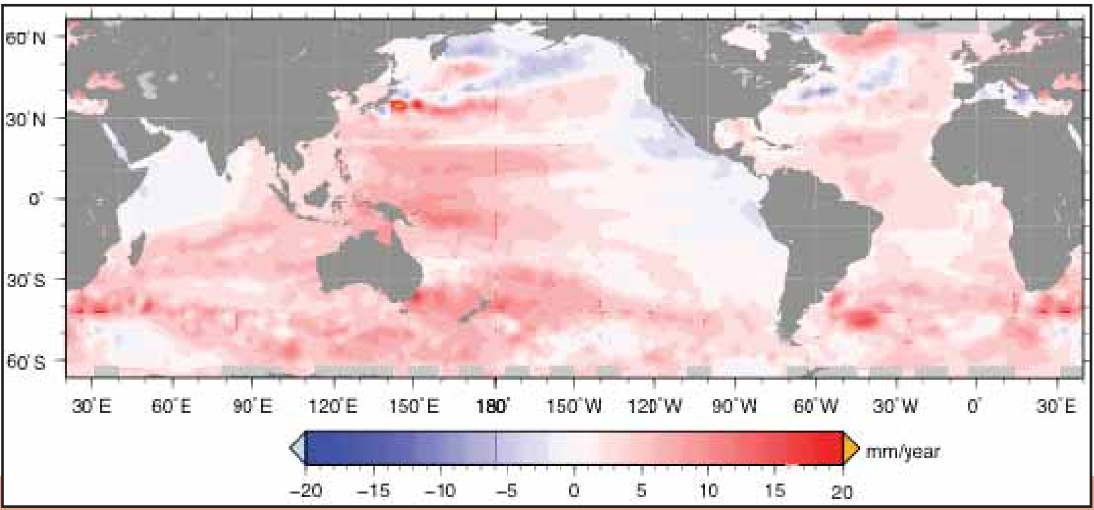


Figure 20 Global sea level trends, 1993 to 2006, from TOPEX and Jason-1 satellite radar altimetry (Casey et al., 2006).

The calibration issue is complicated by the fact that satellite radar altimetry relies on a combination of several different types of measurements to derive sea surface height. The altimeter measures the distance between the satellite and the sea surface by measuring the time of flight of the radar pulse. To determine sea height, one needs to subtract this distance from the satellite orbit height measured with respect to the mass center of the earth by GPS, laser ranging, or some other tracking system. The altimeter measurement also needs to be corrected for various path length delays due, for example, to atmospheric water vapor and the free electron content of the ionosphere.

The altimeter and supporting instruments are subjected to pre-launch and on-board calibrations; however, in practice these procedures only provide baseline error estimates for each mission. Experience with seven separate altimeter missions over the past two decades has shown that post-launch ground calibrations, based on tide gauge observations, provide the only way of insuring that altimeter height estimates are not contaminated by instrumental biases and drifts.

There are at present several dedicated absolute calibration sites and approximately 80 relative calibration sites, consisting of tide gauges deployed and supported as part of the Global Sea Level Observing System (GLOSS) program. The absolute sites are geodetically controlled with GPS and VLBI measurements, making it possible to determine altimeter biases with respect to a terrestrial reference frame at a limited number of locations. For example, the NASA/NOAA Harvest oil platform site off Santa Barbara shows the TOPEX altimeter biased by <10 mm and the Jason-1 altimeter by 97.4+/-7.4 mm.

The relative calibration sites lack the precise geodetic control of the absolute sites, making them unsuitable for determining altimeter biases, however they provide very useful estimates of altimeter drift (Mitchum, 2000). By differencing simultaneous tide gauge and altimeter measurements and then averaging these differences over 80 locations for each satellite repeat period, it is possible to determine altimeter drifts to within +/-0.4 mm/yr, i.e. significantly below the observed rate of sea level rise.

Both the bias and drift calibration procedures have limitations that may make it difficult to monitor for accelerations in the rate of sea level rise. Regarding the bias calibration, there is some evidence that the bias errors of some altimeters are geographically correlated, hence measuring the bias in only a few locations may not be sufficient for determining the global mean bias of an instrument. This could present a serious problem in the future, if there is a gap between altimeter missions. Preliminary studies show that a gap of any length could introduce an additional drift error of more 0.5 mm/yr, due to bias uncertainties. Regarding the drift calibration procedure, roughly half of the present error (+/-0.4 mm/yr) is probably due to uncorrected vertical land motions at the GLOSS tide gauge sites (Mitchum, pers. comm.). GPS receivers are being installed at some GLOSS sites to determine these motions; however the results have not yet been incorporated into the drift calculations on a routine basis.

8.2.2 Satellite Lidar

Uncertainties in cloud feedbacks—how clouds will change in response to changes in atmospheric concentrations of greenhouse gases—are a major contributor to uncertainties in predictions of climate change. Models disagree on the response of cloud radiative forcing to increases in greenhouse gases. Variations between models in the partitioning of the net radiative forcing between shortwave and longwave effects are large, indicating large differences in the representation of cloud feedback processes. Better cloud measurements are required to test and improve the abilities of models to reproduce the physics of cloud-radiation-climate feedbacks, but the changes in cloud properties which must be monitored are small. For example, simple calculations suggest that changes in global cloud amount of just one or two percent, if they occur as a response to climate change, could either double or halve the sensitivity of the climate to changes in atmospheric CO_2. Measurement stability on decadal scales is required to observe these trends. Measurement requirements for key cloud parameters are listed in Table 7.

To date, three lidar instruments have flown in Earth orbit to observe the atmosphere: LITE, which flew on the Space Shuttle for two weeks in September 1994 (Winker et al., 1996); GLAS, on the ICESat satellite, is primarily a laser altimeter but has acquired useful atmospheric profile data during intermittent campaigns conducted to monitor ice sheet thickness since 2003 (Spinhirne et al., 2005); and CALIOP on the CALIPSO satellite, launched in April 2006 (Winker et al., 2004) which is currently planned for a three-year mission. Initial CALIPSO data were released in December 2006. These first-generation satellite lidars are relatively simple instruments which send out pulses of laser light and then measure the light which is elastically scattered from aerosols, clouds, and the molecular atmosphere back to the satellite. However, even these simple backscatter lidars can detect clouds with high sensitivity and make direct measurements of cloud height. For optically thin clouds, the cloud thickness and optical depth can also be directly measured. These observations complement passive sensors by providing accurate optical depth measurements of optically thin clouds, where passive retrievals do not perform well. More sophisticated lidars could also measure aerosol extinction and optical depth directly.

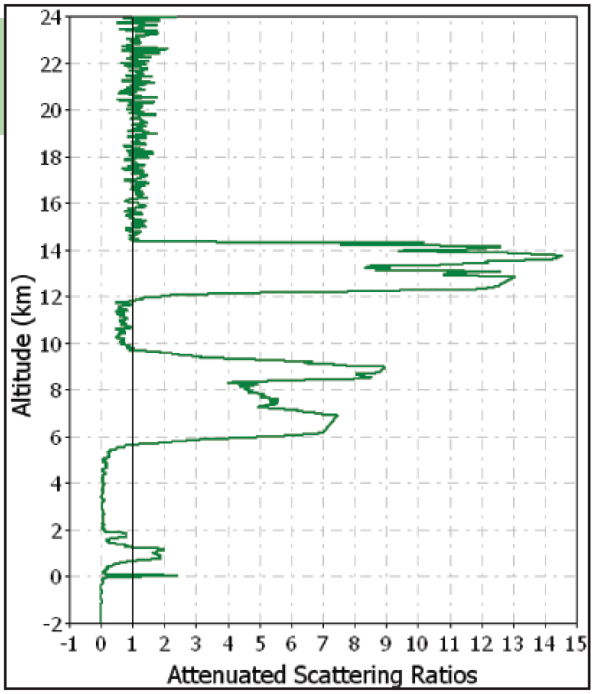


Figure 21 A profile of 532 nm attenuated scattering ratio acquired by LITE.

Figure 21 shows a vertical profile derived from the 532 nm channel of the LITE instrument. The range-normalized 532 nm backscatter signal has been divided by the signal which would have been acquired in a cloud- and aerosol-free atmosphere (computed using temperature and pressure profiles from a gridded analysis product), and then normalized to unity at high altitudes where the atmosphere is known to be clean. The resulting quantity is referred to as attenuated scattering ratio. As can be seen in Figure 21, clouds are readily identified where the attenuated scattering ratio rises above the clear-air baseline value (Winker and Vaughan, 1994; Singh et al., 2005). The height of the clouds is accurately derived from time-of-flight measurements. The accuracy and stability requirements for cloud height measurements (Table 7) are easily met by current lidar technology. Further, because the altitude of the satellite and the cloud altitudes can both be referenced to sea level via the pulse time of flight, the long term stability of the measurement is very high. Due to attenuation of the laser pulse within clouds, the attenuated scattering ratio drops below unity in clear air regions located below cloud layers, which provides a direct measurement of cloud optical depth (Young, 1995). The linearity, dynamic range, and transient response of the lidar receiver are typically characterized extensively on the ground, but radiometric calibration can be performed more accurately on orbit using the molecular normalization technique. However, because cloud height and optical depth measurements rely primarily on timing or on relative measurements of signal strength, the effect of radiometric calibration errors is small.

As shown in Figure 22, a single atmospheric column may contain both cloud and aerosol layers; thus aerosols and clouds must be identified and discriminated. Clouds can often be identified by their stronger backscatter signals; however, there is a region of overlapping backscatter strength between strongly scattering aerosol layers and weakly scattering clouds. In these cases, multiple wavelengths are required to discriminate small aerosol particles from larger cloud particles. CALIOP uses a cloud-aerosol discrimination technique based on ratios of the 532 nm and 1064 nm backscatter signals, as well as the signal magnitudes, which allows improved discrimination based on differences in the size of aerosol and cloud particles (Liu et al., 2004). The molecular normalization technique used to calibrate the 532 nm channel cannot be used on the 1064 nm channel, however, because of the much weaker molecular scatter at that wavelength. Therefore, other means of vicarious calibration are being explored to determine the most reliable calibration technique for the 1064 nm channel. These approaches include comparing the two-wavelength backscatter signals from targets that are nominally spectrally uniform—such as the ocean surface and cirrus particles—and comparisons against calibrated airborne lidars flown underneath CALIPSO.

CALIOP presents several new capabilities for measuring cloud properties in addition to those described above. CALIOP transmits linearly-polarized laser pulses and the 532 nm receiver channel is polarization sensitive. The backscatter return from spherical cloud droplets retains the incident polarization, while returns from ice crystals are depolarized. Thus, analysis of depolarization signals provides unambiguous, vertically-resolved identification of cloud ice-water phase. This unique information is important in determining cloud radiative effects and can also be used to evaluate ice-water phase algorithms used by passive satellite sensors. With the ability to detect multiple cloud layers in a column, CALIOP offers the opportunity to go beyond the traditional definition of 'cloud cover' with observations of cloud multi-layering. The definition of 'cloud height' can also be explored by studying the relation between the effective cloud height sensed by passive instruments and the true vertical profile of cloud observed by CALIOP.

One challenge in using satellite lidar to monitor clouds globally is the sparse sampling provided. However, even nadir-viewing measurements of cloud cover (as an example) can provide climate-quality accuracies on sufficiently large space and time scales. Initial sampling studies indicate that climate monitoring accuracies can be achieved by even nadir-viewing lidar on seasonal-zonal scales (Winker, 2005).

CALIPSO presents the first opportunity to demonstrate that high quality cloud climate data records, with stability and accuracy meeting climate monitoring requirements, can be produced from satellite lidar observations. These measurements could then become benchmarks, contributing to a record of long-term trends and providing a set of accurate measurements against which to test measurements from passive sensors. For future satellite lidar missions, consideration needs to be given to lidar design requirements implied by the need to construct a long-term climate record. Issues such as wavelength, vertical resolution, orbit, and sampling need to be considered. Future missions providing inconsistent data and products would represent a major impediment to the construction of a long-term benchmark time series.

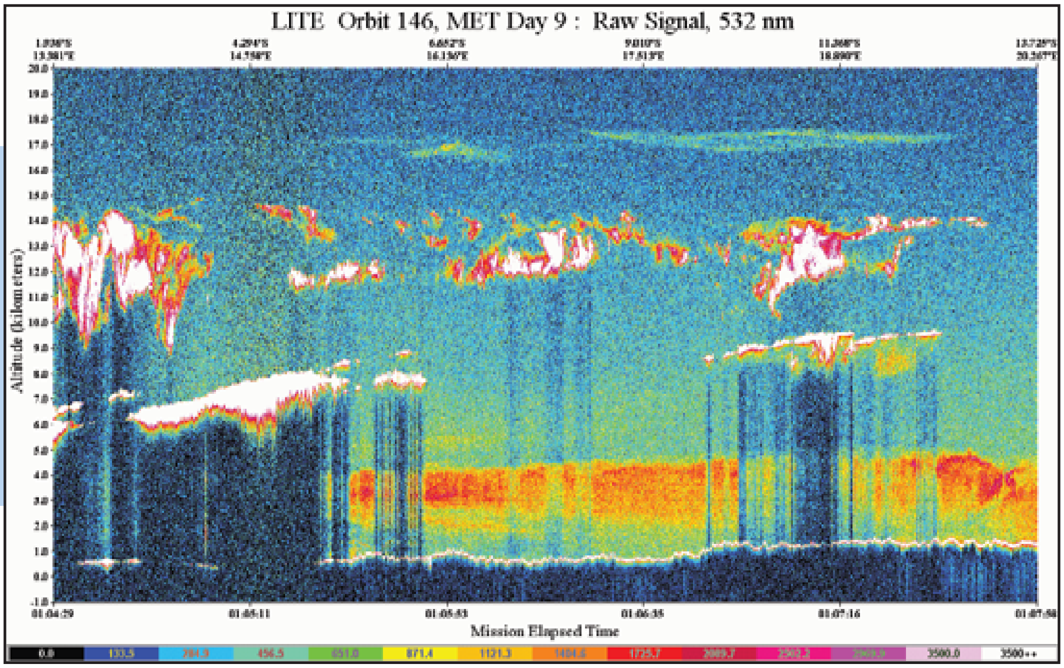


Figure 22 532 nm attenuated backscatter data acquired by LITE over southern Africa showing dense aerosol in the mixed layer (reddish) and multiple cloud layers (white).

8.2.3 Satellite-borne Precipitation Radar

According to the IPCC report (IPCC, 2001), “increasing global mean surface temperature is very likely to lead to changes in precipitation and atmospheric moisture because of changes in atmospheric circulation, a more active hydrologic cycle, and increases in the water-holding capacity throughout the atmosphere.” Consequently, global warming is likely to result in increased total rainfall over the globe. To detect such an increase, an accurate and reliable monitoring system for precipitation is necessary. Accurate monitoring of precipitation from the ground, unfortunately, is very difficult. There are virtually no rain gauges over ocean, and even over land the distribution of rain gauges is very non-uniform. Developed countries have dense rain gauge networks whereas developing countries and unpopulated regions have very sparse rain monitoring sites. Even with such a limited number of sparse data, the IPCC report is able to state “Precipitation has very likely increased during the 20th century by 5 to 10% over most mid- and high latitudes of the Northern Hemisphere continents, but in contrast, rainfall has likely decreased by 3% on average over much of the subtropical land areas.” To monitor global rainfall, especially over ocean, satellite-borne sensors are critical. Historically, passive sensors have been used. However, passive sensors give only indirect estimates of actual surface rain. For example, infrared retrieval uses a rather unreliable statistical relationship between the cloud-top temperature and the surface rain rate to estimate the latter from the measurement of the former. Microwave radiometers sense the microwave emission from rain drops so that the estimates are more direct than the infrared retrievals. However, the microwave sensors view only the integrated rain amount along the column and therefore require an assumed vertical profile of precipitation to convert the integrated liquid water path into a surface rainfall rate. As a result, the microwave retrievals are prone to errors if the vertical structure of clouds and precipitation change in concert with the climate. Only active sensors can determine if there are changes in the vertical structure.

Until April 2006 when CloudSat was launched, only one radar had flown in Earth orbit to observe precipitation, the TRMM Precipitation Radar (PR). TRMM, which carries a suite of infrared and microwave passive sensors as well as a Ku-band radar, was launched in November 1997, and has acquired useful precipitation profile data together with simultaneous passive images in the infrared and microwave spectrum for more than 8 years. Since the PR has a rather narrow swath of measurements, it samples data only in a very small fraction of the space-time in which it may rain. To estimate a global or regional rain accumulation, we need to collect many orbits of data to reduce the statistical error. Even though the spaceborne precipitation radar has such disadvantages, it still provides much more information than a passive microwave radiometer.

The absolute bias error of PR measurements is believed to be less than 1dB based on the statistical analysis of the internal calibration data and the external calibration with an active radar calibrator placed on the ground. 1dB error in the measurement of radar echo corresponds to an error of about 20% for light rain for which the attenuation correction is not essential, provided that the assumed Drop Size Distribution (DSD) model has no error so that the radar reflectivity-to-rain rate (Z-to-R) conversion is accurate. The error of 20% in rain estimates may seem to be too large for the estimation of global rain, but it is important to recognize that the absolute bias error can be detected and corrected with validation data, and that it is not the absolute accuracy but the long-term stability that is needed to detect climate change.

The TRMM/PR uses only solid state components in its electronic circuits and its overall performance is very stable. In fact, a long-term trend of the sea surface echoes indicates that the PR’s sensitivity has not changed more than 0.05 dB over the mission (Figure 23). This means that if the statistical and algorithm errors are suppressed, PR can detect a change of rain accumulation less than 1.5%. In other words, the TRMM/PR is stable enough to detect a few percent change of rain rate or the change of 0.002mm/h listed in Table 7, if it is operated long enough as far as its stability is concerned.

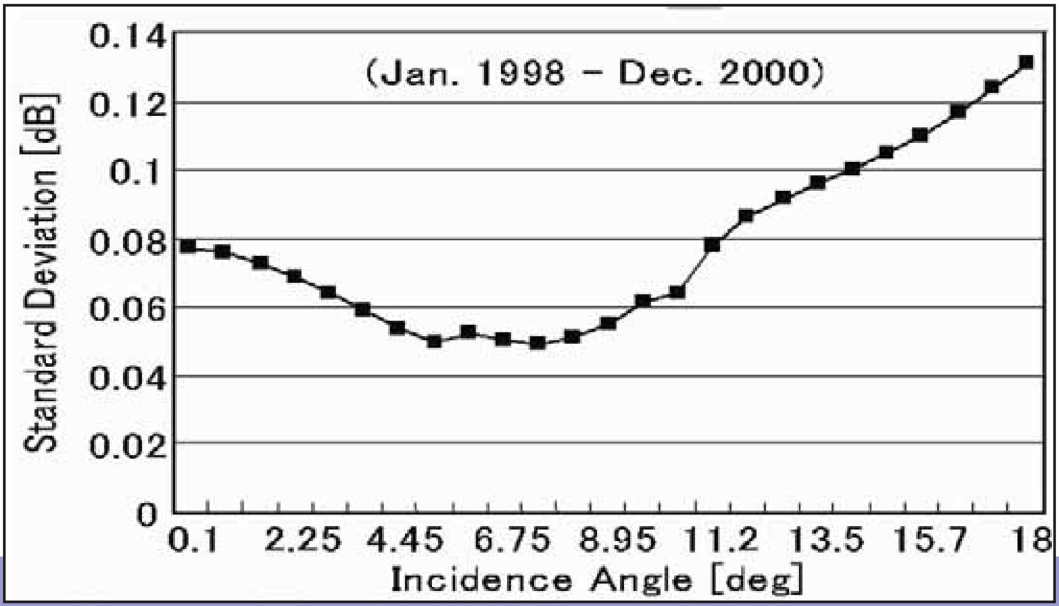


Figure 23 Standard deviation of monthly radar cross sections of rain-free sea surface at different incidence angles derived from the TRMM/PR measurements. The data include 36 months of data taken from January 1998 to December 2000. The standard deviations include both the natural variations of sea surface cross sections and the variations of radar sensitivity. The data show that the long-term stability of the radar itself is better than 0.05 dB. (Okamoto et al, 2002)

In reality, however, there is a large sampling error, as mentioned above, in addition to the natural fluctuation of global or regional rain accumulation and uncertainties in the attenuation correction and Z-to-R conversion. If the rain estimates from radar change with time because of the changes in the Z-to-R conversion factors or in the histogram of rain intensity, we can safely say that the precipitation characteristics have changed even if the rain estimates themselves may not be quantitatively very accurate. Therefore, unless these effects happen to cancel each other in the end, we should be able to detect the effect of global warming in precipitation amount estimated from radar data. The magnitude of sampling error depends not only on the dimensions of the space-time over which the estimates are averaged but also on the histograms of rain intensity and duration. In the case of TRMM/PR, the sampling error in a monthly rain estimate over a region of 500 km by 500 km in mid-latitudes is approximately 20% to 30% (Oki and Sumi, 1994). Therefore, PR data alone are not sufficient to detect a small change in a seasonal or regional scale, although they may have sufficient accuracy for estimating global annual rain trends.

Increasing the number of spaceborne precipitation radars is a solution for reducing sampling error, but it is very unlikely that any space agency can support such a program because of the cost. A more realistic solution is to utilize spaceborne passive sensors, especially microwave radiometers, with which we can estimate rain rate reasonably well, to reduce the sampling errors. Rain estimates from a microwave radiometer can be improved significantly if we properly use the information provided by radar measurements, in particular the storm structure information. This process can be regarded as a calibration of a microwave radiometer's algorithms by radar data. The idea of combining both multiple satellite-borne radiometers and a dual-frequency radar is the basic concept of the Global Precipitation Measurement (GPM) mission. The Dual-frequency Precipitation Radar (DPR) on the GPM's core satellite can be expected to provide better estimates of rainfall rates than the TRMM/PR by the use of increased information due to the addition of the Ka-band radar.

CloudSat, which carries a 94-GHz cloud profiling radar, was launched in April 2006. Although the radar is designed to measure clouds, and rain echoes often disappear near the surface because of large attenuation when rain is heavy, it still provides very useful information about storm structure and path attenuation statistics. One challenge is how to establish the intercalibration standard for vertical profiles of radar echoes measured at different wavelengths and transfer the storm structure information to radiometer and other algorithms. This would enable estimation of global rain distribution measured by different sensors on different satellites at different time periods without large biases among them. For inter-calibrating different satellite-borne radars, sea surface echoes can be used as a calibration standard since the globally averaged radar cross section of the sea surface at incidence angles between 5 and 10 degrees is very stable, as indicated in Figure 23.

8.3 Recommendations to Accelerate Progress

8.3.1 High level initiative

Radar altimetry has been shown to be capable of observing the long-term trend of sea level height, a critical climate parameter that acts to integrate many inputs into the climate system, including the global heat budget and hydrologic cycle. Measurements from radar altimeters have been shown to be very stable, but significant intersatellite biases are evident when time series from different instruments are compared. To monitor sea level trends and improve model predictions of sea level rise it is essential to continue the record begun by Jason with additional missions beyond Jason-2 (launching in 2008). Overlap of these future altimeter missions is essential to allow for the correction of systematic biases between satellite instruments and ensure the ability to construct a continuous long-term record of global sea level measurements.

8.3.2 Additional Recommendations

Experience over the last two decades has shown that post-launch calibrations of satellite altimeters, based on tide gauge networks, is essential to ensure that altimeter estimates of sea surface height are not contaminated by instrumental biases and drifts. Calibration procedures developed for the current existing calibration sites have limitations making it difficult to monitor accelerations in the rate of sea level rise. Roughly half the present error in the calibration of altimeter drift is probably due to uncorrected vertical land motions at tide gauge sites. There are presently only a few tide gauge sites that are geodetically controlled using GPS and VLBI measurements and thus able to determine altimeter biases with respect to a terrestrial reference frame. The existing network needs to be expanded and improved to establish a global network of reliable in-situ calibration sites for sea level.

Efforts should be made to derive climate benchmarks from lidar measurements, taking advantage of those characteristics of lidar observations which are inherently accurate and stable. For the current generation of satellite lidars, benchmark measurements of cloud height, cloud cover, and cloud ice/water phase are the most attractive possibilities. As future lidar missions could have inconsistent wavelengths, orbits, or other characteristics representing impediments to the construction of a long-term benchmark time series, this implies the need to define minimum requirements for an instrument from which a long-term climate record is to be derived. One objective of the Global Earth Observation System of Systems (GEOSS) and the Global Climate Observing System (GCOS) initiatives is to ensure long-term measurement comparability to obtain data continuity across multiple satellite missions. GEOSS and/or GCOS could perhaps be used as the framework for establishing standards and compatibility between various satellite lidar missions to support the creation of long-term climate records.

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Intercalibration of Instruments

9.

9.1 Introduction

Given a satellite radiometer's typical design life of about five years, the detection of decadal climate trend relies on observations from a series of satellites. It is well known that despite the best effort in pre-launch and post-launch calibration, the same series of radiometers on different satellites, such as the Microwave Sounding Units (MSU) on NOAA satellites, do not necessarily produce consistent measurements. This leads to the intersatellite biases which have become major concerns in constructing time series for climate trend detection. As has been demonstrated in the tropospheric temperature trend study using MSU channel 2 observations, the intersatellite biases can become so critical that depending on how the biases are handled, different conclusions about tropospheric warming may result (Zou et al., 2006; Vinnikov and Grody, 2003; Mears and Wentz, 2005; and Christy et al., 2003). Unlike instrument noise which can be quantified precisely with on-orbit calibration targets, biases are very difficult to characterize due to the lack of commonly traceable on-orbit absolute calibration standards, and the variable nature of biases in time and space both short term and long-term in response to the spacecraft and instrument thermal dynamics. Several methods have been developed to address the intersatellite calibration issue and each has its advantages and limitations.

9.2 Current Status

The Simultaneous Nadir Overpass (SNO) method (Cao et al., 2004, 2005a) was developed in recent years for quantifying intersatellite biases initially for instrument performance monitoring and has been tested by scientists in constructing time series for climate change detection studies (Zou et al., 2006). This method is relatively simple and robust, and is based on the fact that any pair of polar-orbiting satellites with different altitudes can regularly observe the earth at orbital intersections at nearly the same time, and that these events are predictable with orbital perturbation models such as SGP4. The frequency of occurrence is a function of the altitude difference between the two satellites (typically once every 2-10 days). Observations from the two satellites at the SNOs can then be collocated pixel-by-pixel and the biases between them quantified. The uncertainties in the SNO analysis are further reduced in a SNO time series where the intersatellite biases at the SNOs are shown as a function of time (Figure 24).

Applications of the SNO method to microwave instruments have shown very promising results for climate trending analysis. Several factors contribute to this success. First, the intersatellite biases for microwave instruments appear to change little over the short-term and slowly over the long-term. Second, the microwave channel center frequencies between instruments are made to match precisely, which significantly reduces or eliminates uncertainties related to spectral differences. Third, each microwave instrument has its own onboard blackbody calibration, which keeps track of the instrument degradation independently. It is found that the SNO method works very well for microwave instruments sensing the mid-troposphere to upper stratosphere, where the uncertainty in the bias of the SNO time series is much smaller than the instrument noise. Figure 24 demonstrates the excellent agreement on the order of 0.1 K for the 53.6GHz channel of AMSU on NOAA-16 and -17.

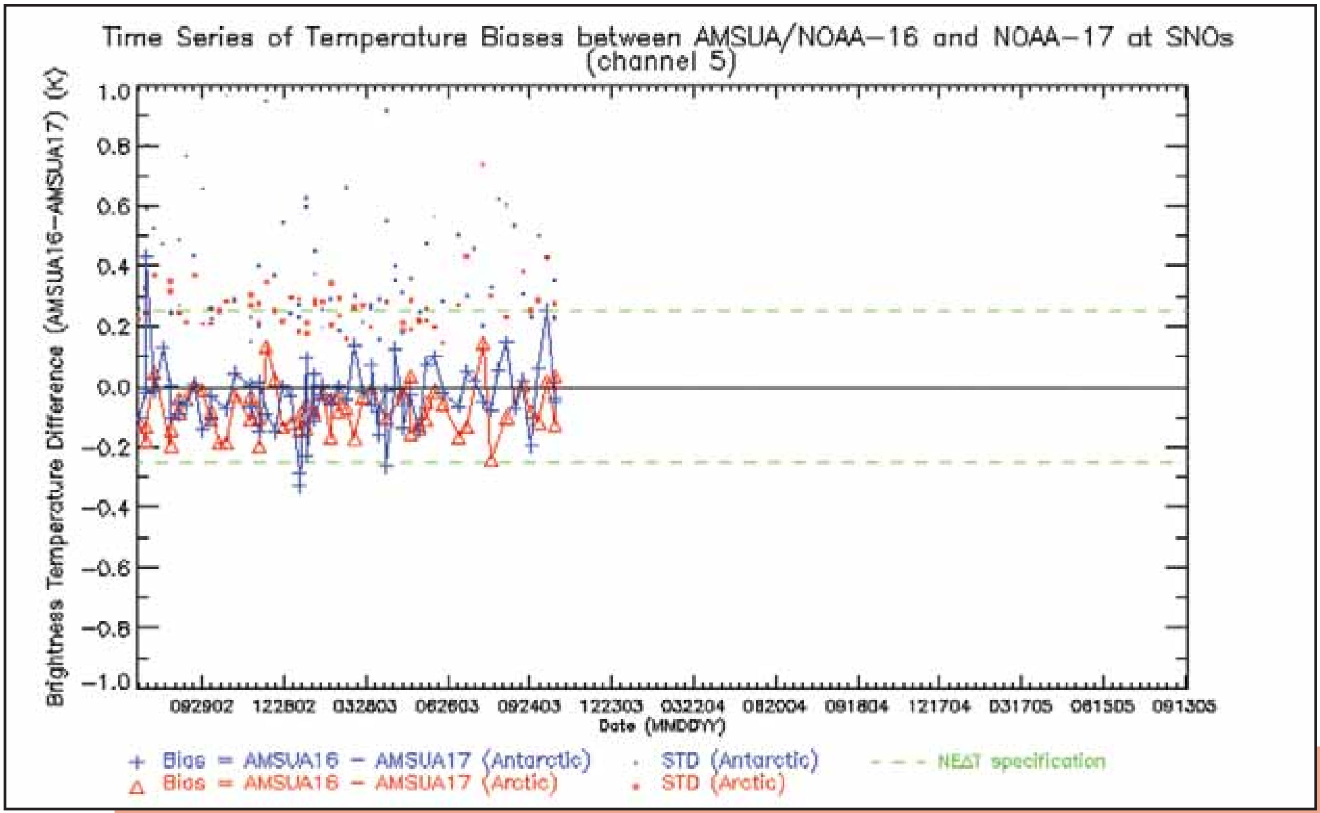
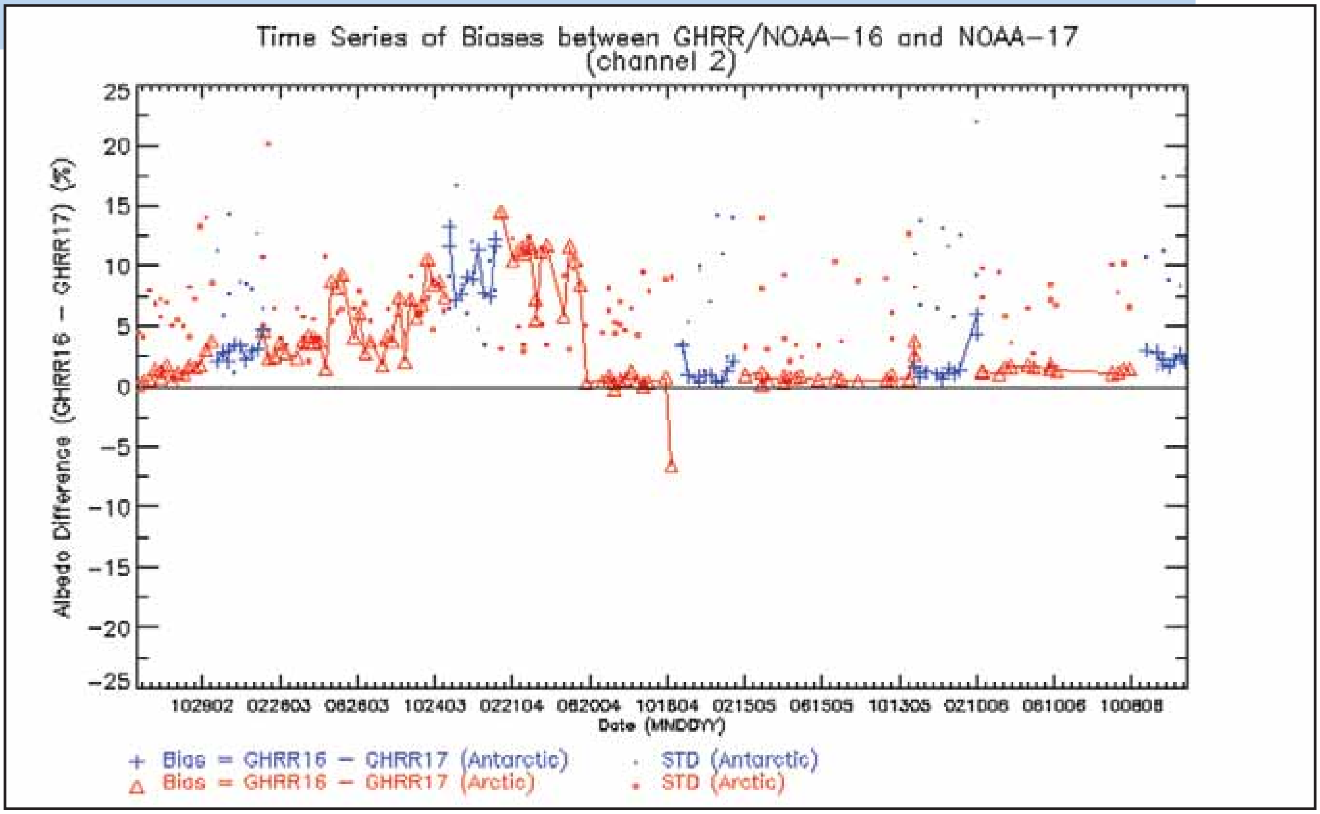


Figure 24 NOAA-16 & -17/AMSU Simultaneous Nadir Overpass time series for channel 5.

In addition to the SNO, the Simultaneous Conical Overpass (SCO) method is also developed for conical scanners (or imagers) such as SSMI on the DMSP satellites, where additional uncertainties may be introduced because of surface non-uniformity and atmospheric path differences.

The application of the SNO method to the visible/near-infrared and infrared radiometers has yet to reach its fullest potential. Studies have shown that the SNO method is very effective in quantifying the intersatellite biases for these channels. Since the biases are short-term invariant for the visible/near-infrared instruments, they can be used for inter-calibrating the satellites for global data. The dry atmosphere and highly reflective surface for a broad range of solar zenith angles at the SNO sites in the Polar Regions are advantageous for calibrating these channels (Jaross et al., 1998; and Masonis and Warren, 2001). Figure 25 shows that the agreement in the calibration between NOAA-16 and -17 AVHRR channel 2 at 0.86 um became much better after the calibration coefficients for NOAA-17 were updated, although a small difference still exists after the update. However, since the SNO method only provides a relative calibration between two satellites, and none of the NOAA satellites have onboard calibration for the visible/near-infrared channels, the SNO calibration alone is not sufficient to produce a long-term time series for these channels. This method is more useful if one satellite can be relied on as a stable standard, such as in the intercalibration of MODIS and NOAA radiometers (Heidinger et al., 2002), but the difference in the spectral response functions between them introduces uncertainties and makes the intercalibration difficult.

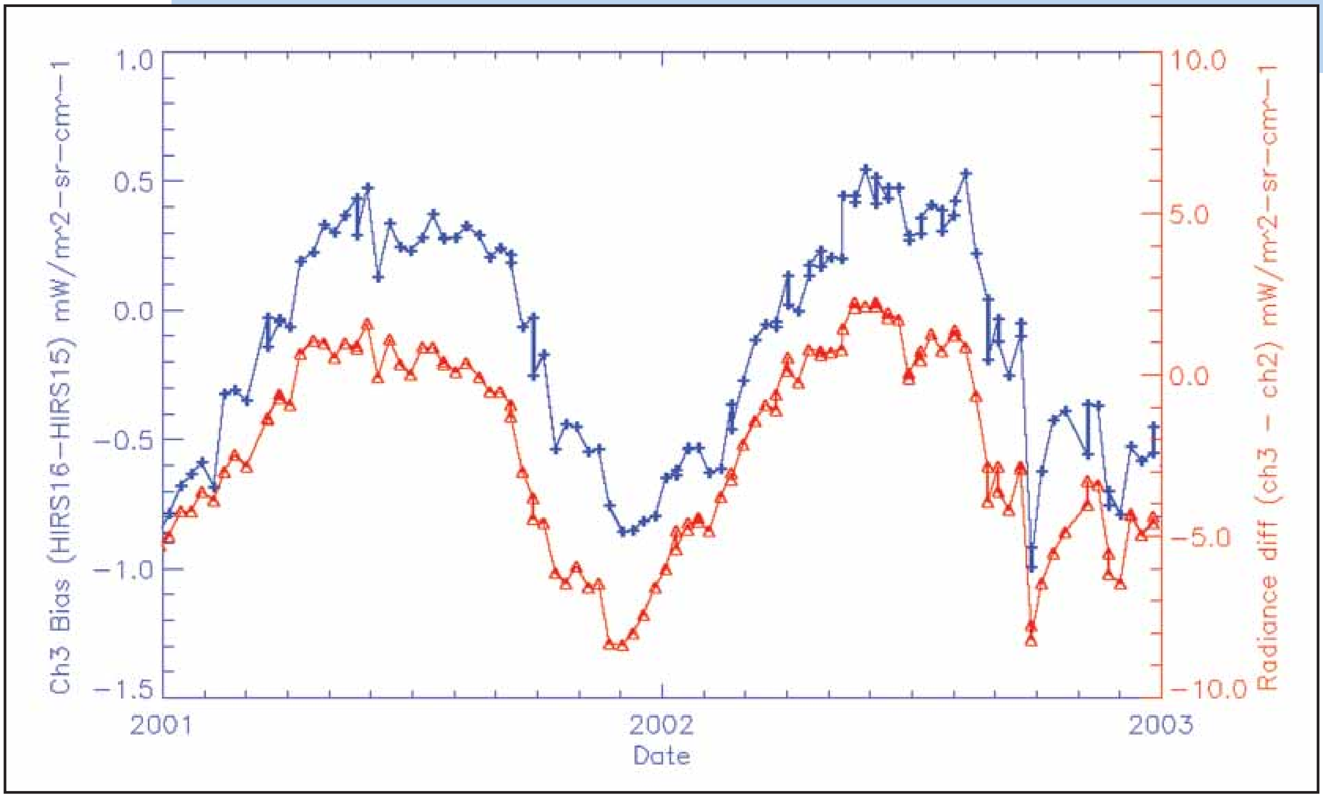
Figure 25 Simultaneous Nadir Overpass time series shows significant improvement in the agreement between NOAA-16 and -17 Global Area Coverage (GAC) Advanced Very High Resolution Radiometer (GVHRR) channel 2 (0.86 um) calibrations after the NOAA-17 GVHRR coefficient update in June 2004.



For infrared radiometers, studies have shown that the SNO method can quantify intersatellite biases with uncertainties smaller than the instrument noise (Cao and Heidinger, 2002). However, additional uncertainties exist when compared to that of the microwave and visible instruments. First, the calibration accuracy may vary over an orbit, as has been found with AVHRR. Biases found at the SNOs may not be the same in other parts of the orbit, and the bias may be orbital and seasonal dependent. The calibration accuracy may also change long-term in response to a number of factors such as degradation and orbital drift. Second, for infrared sounders, small differences in spectral response functions may mean that a different layer of the atmosphere is observed, thus producing seasonal biases (Figure 26; Cao, et al., 2005). It is expected that this effect will be significantly reduced with hyperspectral sounders such as AIRS and IASI.

Studies have shown that the SNO method is able to resolve intersatellite biases on the order of 0.1 K in the sounding channels of the microwave and infrared instruments, and 1% in the visible/near-infrared imagers with a 1 km resolution or better. Larger uncertainties are found for low resolution surface channels where surface inhomogeneity and pointing accuracy become problems.

Figure 26 Seasonal biases (blue +, left hand scale) are highly correlated with a lapse rate index (red Δ, right hand scale) suggesting that the small difference in the spectral response functions is an important contributor to the biases (Cao, et al., 2005).



Intercalibrating GOES and POES radiometers has been implemented for many years with promising results (Gunshor et al., 2004). Conceptually, since the GOES nadir is fixed at a given location and the POES satellites pass the GOES nadir point regularly, it would be an ideal configuration for intercalibration. However, this method also has its limitations. First, the GOES radiometers have a lower calibration accuracy than that of their polar counterparts. For example, the current GOES imager calibration accuracy is 1 K, compared to 0.5 K for AVHRR. The large diurnal variation in the GOES instrument temperature, on the order of nearly 30 K, presents a challenge in intercalibration with POES radiometers, which have an orbital temperature variation of 2-3 K. Second, although the GOES nadir has a fixed location on the earth, it does not necessarily observe the nadir at the time of POES overpass because it takes ~30 minutes for GOES to perform a complete scan of the earth. As a result, the simultaneity between POES and GOES is typically around 15 minutes, compared to 30 seconds in the SNO method. The meso-scale scanning capability on future GOES-R will significantly improve the simultaneity by pointing and scanning a desired location on demand, assuming that GOES-R will have the same spectral coverage as that of the POES instruments.

In addition to the Simultaneous Nadir Overpass Method, the overlapping time series technique is a popular traditional approach to intersatellite calibration that has generated both impressive and controversial results. Typical analyses involve pentad global mean values such as channel brightness temperature (Vinnikov and Grody, 2003). Advocates of this method believe that the effect of observation time differences between satellites can be reduced and the signal to noise ratio in the observations can be improved. A major drawback of the method is the inability to separate biases resulting from diurnal cycles vs. biases due to instrument calibration vs. actual changes over time. This mixing often leads to ambiguities in the analyses and controversies in interpretation.

Pre-launch and onboard calibrations are both prerequisites for accurate calibration, but with the current technology neither one can guarantee consistent calibration across satellites post-launch. NIST traceability is very useful for pre-launch testing in thermal vacuum under thermal equilibrium conditions, but in-orbit thermal equilibrium is rarely reached for most instruments, and the instrument response might change after launch. Also, pre-launch tests are typically performed many years before launch and degradation has been observed on some flight models during years of storage. On-orbit absolute calibration traceability is critical for resolving intersatellite calibration biases. In the infrared and microwave, the quality of the blackbody (such as emissivity, and skin vs. bulk temperature difference) plays an important role in the intersatellite biases.

Earth targets such as the Libyan Desert, Greenland, Antarctica, deep convective clouds, and instrumented sites such as the Railroad Valley in Nevada, have been used for vicarious calibration of visible/near-infrared channels. However, this strategy for intersatellite calibration is affected by observation time differences, and uncertainties introduced by bi-directional reflectance factors of the surface and the intervening atmosphere. Vicarious calibration can achieve inter-sensor calibration with ~2 % accuracy, but differences of 4-10 % are not uncommon (Green and Pavri, 2002; and Thome, 2006, personal communication).

Aircraft and ground based campaigns are typically used for the validation of newly launched instruments. Airborne instruments have the advantage of performing frequent calibration that is traceable to an absolute standard before and after the flight. High measurement accuracy has been demonstrated by the AVIRIS in the visible/near-infrared (Green and Pavri, 2002) and Scan-HIS in the infrared (Revercomb et al., 2003). Dedicated aircraft campaigns provide accurate comparisons, but they have small sample sets and short time durations.

It is possible to use the Moon for intercalibration of radiometers on different satellites, as has been demonstrated in studies with MODIS, SeaWIFS and other instruments (Barnes et al., 2004; Barnes et al., 2006; and Xiong, et al., 2005). There are significant advantages with this approach. The Moon has a stable reflectance (Kieffer, 1997), and inter-satellite calibration using the Moon is not affected by observation gaps between satellites if the Moon is used as an absolute calibration standard. Consistency at the 1% level has been demonstrated for intercalibration of the MODIS on Aqua and Terra using the Moon. Instrument design can impose a potential limitation to using the Moon for calibration. For example, the AVHRR space clamp circuitry makes the lunar calibration approach difficult, if at all possible. Spacecraft maneuvers to view the Moon are possible for some missions, but may be impractical for other missions. Currently, the Moon is only used for the calibration of the visible/near-infrared channels. There are significant challenges to using the Moon for calibrating infrared instruments, and the feasibility of lunar calibration for microwave instruments has yet to be investigated.

NWP model simulations have been used by NWP centers to monitor satellite radiometer radiances especially for the microwave and infrared sounders. While the model simulations are very useful for identifying calibration anomalies and quantifying biases between the model and the satellite observations, the models are not without problems and not all biases are due to satellite calibration. However, as the accuracy of radiative transfer models further improves, model simulations will play a more important role in quantifying intercalibration biases.

9.3 Impediments to Progress

A major impediment to intercalibration is the scarcity of common and stable on-orbit calibration targets of climate quality. The Moon has successfully been used as a calibration target for visible/near-infrared channels for stability monitoring, but further work is needed to use it for absolute calibration. Techniques to use the Moon for calibrating infrared and microwave instruments have not yet been developed.

Another major impediment is the lack of tools for analyzing intersatellite biases with the desired accuracy, which limits our understanding of the biases. The SNO/SCO method developed in recent years represents major progress in this area. However, the method has limitations. First, since the SNOs for polar-orbiters occur only at different locations in the Polar Regions, the spectral characteristics of the SNO sites are currently not well quantified, which introduces uncertainties in the intercalibration of window channels. Second, while the SNO method works well for the sounding channels in the microwave and infrared, it does not work as well for the surface channels where inhomogeneity becomes a major factor for these instruments. For the infrared window channels, the temperature at the SNO is limited to a range smaller than the full range of surface temperature over the globe. In addition, as discussed previously, for the infrared instruments, intersatellite biases at the SNO points may not be representative of the biases over an orbit due to orbital variations of calibration accuracy in response to fluctuations in instrument temperature and stray light in certain parts of the orbit. Finally, the SNO method is very sensitive to geolocation and sampling errors. For example, the AVHRR 4 km GAC pixel data do not match with the MODIS 1 km data due to the sampling scheme used in AVHRR; this introduces uncertainties in intercalibrating AVHRR and MODIS. Some of these issues can be resolved in the near future, once the SNO sites are better characterized. The availability of global 1 km AVHRR data starting with MetOP-A will be a major step forward for SNO intersatellite calibration that will lead to significant reductions in uncertainties.

For optical instruments, additional major impediments to progress are issues related to the spectral response functions (SRF), including the pre-launch measurement uncertainties, SRF differences between instruments, and SRF changes over time. The lack of stringent requirements in the pre-launch testing, the inability to make identical SRFs, and the lack of on-orbit spectral calibration devices are the root causes of these problems. New technologies are desirable to introduce fundamental changes in these areas. One technology on the horizon is the quantum cascade laser calibration system, which potentially will allow us to perform on-orbit spectral and radiometric calibration for infrared radiometers (Myers et al., 2005).

Due to the problems discussed above, current knowledge of intersatellite biases is limited. Study of intersatellite biases is typically conducted in short term projects, and the findings may contain large uncertainties. The short term duration of these projects makes it difficult to understand the nature and the root cause of the intersatellite biases, and the findings are usually not well documented. Data users may be insensitive to small biases which can persist for many years. A case in point is the bias on the order of 10 % between AVHRR and MODIS for channel 1 at 0.63 um, which has existed since the MODIS launch but was not recognized until recently in SNO studies. The uncertainty in the intercalibration methods in the past greatly limited the ability to inter-calibrate satellites. Understanding the root cause of the biases requires close collaboration between scientists and instrument engineers but in many cases such collaboration is lacking.

Finally, the lack of understanding of climate quality measurement requirements and lack of high priority for climate measurements in mission requirements are major impediments to progress. While the legacy meteorological instruments were developed to meet requirements for weather applications, the applicability of the next generation instruments for climate studies is neither well defined nor well understood. When it comes to instrument performance, there is often a discrepancy between the user expectation and instrument specification. Typically, the instrument manufacturers build the instrument according to a specification that may not be sufficient for climate application, while the data users are expecting climate quality data from the instruments.

9.4 Recommendations to Accelerate Progress

9.4.1 High level initiative

Aside from dedicated benchmark calibration missions, which may not be available for some time, a practical and cost-effective initiative is to develop and maintain an on-orbit calibration reference database. Such a database would keep track of the long-term time series of inter-satellite biases at the SNOs, GEO/LEO coincident observation points, and selected vicarious sites for a constellation of operational satellites. Even without an absolute scale, this will tie the calibration of all the satellites together to provide traceability of individual satellites to the calibration reference database. It is difficult to know which radiometer produces the correct absolute radiance, but truth is likely among the measurements from the satellite constellation. Ongoing efforts to reduce uncertainties in the absolute radiometric scale of the Moon will allow using the Moon as an absolute calibration check of the visible/near-infrared channels for long-term time series. In addition, airborne radiometers can be used as checking points to provide calibration links to absolute standards. Techniques to use the Moon for calibration in the UV and IR should be developed, and the possibility of lunar calibration in the microwave should be explored.

9.4.2 Additional Recommendations

Satellite mission overlap is essential to most intercalibration techniques. This requires not only time overlap and consistency in local observation time, but also assurance of spectral continuity in channel selection between satellites. For example, channel discontinuities were created when some HIRS channel center wavenumbers were changed in the history of the NOAA satellite series. The small frequency change from MSU channel 2 to AMSU channel 5 also created problems in climate trending. Such changes should be strictly avoided, if possible, in mission requirements.

Uncertainties in the SNO method can be further reduced with SNO site characterization using highly accurate spectral, spatial, BRDF, and elevation models. This will be especially helpful for the window or surface channels. The reduced uncertainty will allow us to better quantify the intersatellite biases and small trends in the satellite measurements. Long-term observation of vicarious sites such as the Dome Concordia in Antarctica, Greenland, the Libyan Desert, the Railroad Valley in Nevada, and other sites with stable instruments will provide independent site stability and calibration accuracy assessments. International collaboration under the GEOSS should facilitate data sharing and allow us to inter-calibrate radiometers globally to establish a calibration reference database and a quasi on-orbit standard.

Further improvements in onboard calibrators, i.e., blackbody in the infrared and microwave, and solar diffusers in the visible/near-infrared will reduce calibration uncertainties and facilitate the establishment of on-orbit calibration standard. For instruments with onboard calibration, not only the biases between satellites, but also the root cause of the biases, should be investigated. This is because bias correction without knowing the root cause could be unreliable. Once the root cause is identified, this information can be used as feedback to the instrument development process to improve the calibration for future models.

The efforts to utilize the Moon as an on-orbit absolute calibration standard for the visible/near infrared channels should be continued. Currently the Moon can be used for stability monitoring that meets climate-level requirements, but uncertainty in the absolute accuracy limits its use as an absolute standard. The Moon as a temperature standard is not well understood and requires further exploration.

For the visible/near-infrared channels, vicarious site characterization using hyperspectral data (such as Hyperion and AVIRIS) is highly desirable especially for inaccessible sites with no ground measurements. This will further reduce the uncertainties and allow us to quantify the inter-satellite biases due to spectral response differences.

For the microwave instruments, further improvement in the pre-launch nonlinearity and side-lobe characterization is highly desirable. Knowledge of nonlinearity is critical for decadal climate change detection as is demonstrated in recent studies (Zou et al., 2006). Further improvements in instrument NEDT would significantly reduce the uncertainties in the SNO analysis, since, because of relatively large pixels, sample size is relatively small at the SNOs for these sensors. Also, the possibility of long-term nonlinearity change and frequency drift should be investigated.

For both visible/near-infrared and the infrared instruments, more stringent requirements should be made for the pre-launch measurement of spectral response functions, and technologies to make identical spectral response functions between instruments should be developed.

For infrared instruments, intercalibrations between sounders and imagers are very valuable. Since both types of instrument are on the same spacecraft and simultaneous Earth views are available globally, accurate intercalibration both radiometrically and spectrally is possible (Tobin et al., 2006). As more and more hyperspectral sounders become available, this type of intra-satellite calibration or inter-sensor calibration should be encouraged and supported.

For the ultraviolet instruments, comparisons are now mainly performed at level-2 (products, e.g., total column ozone). When comparing different instruments, such as TOMS vs. GOME, intercomparison results are affected by retrieval algorithms. Comparison of radiance residuals has high sensitivity to surface albedo. It is recommended that more attempts be made to inter-compare radiances—in addition to products—with the goal of developing a coherent approach to radiometric intercalibration of the sensors.

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10.

Roadmap for Establishing a National Center for Calibration (NCC)

10.1 Introduction

The ASIC^3 workshop discussed the critical nature of global climate change; the importance of accurate climate records and credible long-term climate forecasts for informed decisions on mitigation and adaptation policies; the goals and attributes of an observing system to reliably detect climate change and permit testing of climate model predictions; the current state of satellite instrument calibration and intercalibration; and recommendations to accelerate progress in achieving the observational goals.

Two overarching recommendations emerged from the workshop. The first calls for a suite of climate benchmark instruments whose accuracy, through traceability to international standards, can be proven on-orbit. This is a new paradigm for achieving satellite instrument calibration for measuring long term global climate change. The basic concept is to place in space a series of highly accurate benchmark instruments to measure with high spectral resolution the energy reflected and emitted by the Earth. These instruments would not only provide reliable long term records in their own right, but would also serve as a reference standard in space against which other environmental satellite sensors would be calibrated. These spectral instruments would be joined in space by several other critical benchmark measurements.

The second overarching recommendation calls for the establishment of a U.S. interagency National Center for Calibration. This recommendation is based upon the realization that implementation of the recommendations of the ASCIC^3 workshop can only be accomplished through an integrated national effort in instrument calibration involving the two U.S. agencies engaged in environmental satellite observations—NOAA and NASA—and the U. S. agency responsible for establishing measurement standards—NIST.

Our purpose here is to lay out a roadmap for radically improving the accuracy of satellite observations. The roadmap begins by summarizing in section 10.2 some of the grand environmental observing challenges that can be overcome with more accurate observations. These include not only monitoring global climate change, but also improving weather prediction, achieving more reliable short term climate forecasts, and assuring inter-comparability of observations from the Global Earth Observation System of Systems (GEOSS). If we satisfy the stringent observational accuracy requirements of climate change with a system of climate benchmarks, we anticipate that other GEOSS systems inter-calibrated with the climate benchmark system instruments will meet the generally less rigorous accuracy requirements of other environmental applications. In section 10.3 the roadmap discusses the nature of the problem—lack of a national dedication to achieving high quality measurements, and its consequences for meeting the observing challenges. Section 10.4 describes the solution—the establishment of a NOAA NASA-NIST National Center for Calibration. The NCC would be patterned after the very successful Joint Center for Satellite Data Assimilation (JCSDA), a distributed interagency center formed by NASA, NOAA, and DoD to improve and accelerate the use of satellite data in numerical weather prediction. This section outlines the vision, mission, goals, agency roles, structure, management, and operation of the Center. Additional sections summarize the Center's key technology activities, R & D programs, performance targets, and benefits to the user community and to the partner agencies.

This roadmap is being prepared concurrently with the initiation of a new international program by the World Meteorological Organization (WMO) to inter-calibrate the satellite sensors of the Global Observing System. The objectives of the Global Space-based Inter-Calibration System (GSICS) and the role of the NCC in carrying out the U.S. component of the GSICS are outlined in section 10.4.6.

10.2 Grand Environmental Observing Challenges

This section reviews some of the outstanding environmental observing challenges facing the community—and implications for satellite instrument calibration.

10.2.1 Assessing global change

Is the Earth's climate changing? Is the Earth's land cover changing? If so, at what rates? Are the causes natural or human-induced? What will the climate be like in the future? These are critical environmental and geopolitical issues of our times. Increased knowledge, in the form of answers to these questions, is the foundation for developing appropriate response strategies to global change. Accurate observations from space are a critical part of the needed knowledge base. But, measuring the small changes associated with long-term global change from space is a daunting task, and current systems are not, for the most part, up to the job. For example, a recent evaluation (Karl et al., 2006) of the best satellite measurements of atmospheric temperature trends concludes "Thus, due to the considerable disagreements between tropospheric data sets, it is not clear whether the troposphere has warmed more than or less than the surface." Achieving satellite instrument calibration to minimize uncertainties in measurements and assess global change remains a major challenge.

10.2.2 Testing climate model predictions

Climate models differ by nearly a factor of two in their predictions for response to a doubling of carbon dioxide, thus demonstrating our current inability to predict climate change with useful fidelity. If climate models, our best tools for climate prediction, are to be useful to officials public and private in making decisions on strategies for dealing with climate change, it is of paramount importance that the models be tested according to the accuracy and precision with which they predict long-term trends. It is also necessary to collect a broad enough range of data types to assure that climate models, when they do accurately predict trends, do so by correctly simulating the relevant feedback mechanisms. Obtaining space-based measurements with the accuracies required to test the model predictions of evolving climate change is a demanding task.

10.2.3 Improving weather and short term climate forecasts

Satellite measurements provide more than 90 % of the observations used to initialize weather prediction and short term climate forecast models. Improved satellite observations and data assimilation systems have contributed to substantial increases in weather forecast accuracy: today's 5-day forecasts are as accurate as 3-day forecasts were just 25 years ago. Increasing forecast skill still further is an outstanding challenge. Forecast centers remove biases of satellite instruments by comparing satellite observations with those simulated from Numerical Weather Prediction model calculations and assuming the models are correct. If instrumental accuracies can be improved to meet climate monitoring applications, the need to correct such observations for use in weather prediction would be minimized, if not eliminated. In addition, it would then be possible to assume that the observations are correct, thus facilitating discovery of model errors, and their correction. In both cases, further gains in forecast accuracy can be expected.

10.2.4 Assuring comparability of GEOSS satellite data

The Global Earth Observation System of Systems (GEOSS) is an international collaboration with the aim of integrating information from various Earth observing systems to provide better information and understanding, which then enables the public, private sector, and governments to benefit from informed decision-making. GEOSS will link data from more than 50 satellites carrying more than 100 instruments. Achieving the GEOSS societal benefits requires the integration and understanding of these space-based observations along with conventional Earth observations. To integrate observations and products from different satellite systems, the measurements must be inter-calibrated. Without intercalibration, inconsistent data and products will be delivered, applications will be degraded, and the full benefit of the huge investments in space systems will not be realized.

10.2.5 Achieving traceability to SI units

Measurements that are traceable to international standards on-orbit are required to achieve climate monitoring and prediction goals. In many cases, uncertainty statements on satellite measurements have not been rigorously validated with pre-launch and on-orbit sensor calibrations using scales traceable to international standards (SI traceability). This scenario is slowly changing around the world because of concentrated efforts of satellite launching agencies such as NASA and NOAA to work closely with national measurement institutes such as NIST in developing SI traceable transfer standards and methods for the sensor calibrations, and adopting the ISO guide to the expression of uncertainty in measurement. However, there are major challenges to achieving SI traceability for sensor measurements on orbit. Physically, most sensors degrade while on-orbit. Achieving SI traceability thus demands instrument design capable of demonstrating SI traceability on-orbit. Technically, the path to SI traceability remains a research topic for all but a few measurement types. To complicate matters, no universally accepted on-board or extra terrestrial calibration standards exist to absolutely calibrate the sensor measurements to maintain SI traceability. Finally, budgetary limitations and time constraints often cut short pre-launch calibrations.

10.3 The Nature of the Problem

The lack of a national strategy and approach for satellite instrument calibration is a major impediment to meeting today's environmental observing challenges. Satellite instrument calibration is done in an ad hoc fashion within the agencies:

- No coordinated national program among the environmental research satellite agency, NASA, the environmental operational satellite agency, NOAA, and the agency responsible for establishing measurement standards, NIST
- Inconsistent calibration across satellite platforms resulting from lack of common practices among satellite agencies and instrument vendors
- Insufficient application of the fundamentals of NIST-established metrology standards in satellite environmental observing instruments
- Lack of end-to-end instrument requirements/design to pre-flight calibration to in-flight calibration to post-flight analysis-cal/val system for each instrument

In this section we detail some of the consequences of not having an effective national program in satellite instrument calibration.

10.3.1 Poor instrument calibration/characterization

Since most environmental sensors have been designed for non-climate applications, with less demanding accuracy requirements than climate trend detection, high absolute accuracy has not been a priority. Because calibration comes late in the development cycle, instrument calibration/characterization is often compromised to meet budget constraints. At shorter wavelengths from ultraviolet to near infrared, poor performance in calibration often results from lack of quantitative understanding of the mechanisms for on-orbit changes in optical component behavior, such as decay in the solar diffuser reflectance and deterioration in mirror reflectance. At thermal wavelengths, current operational infrared sensors exhibit discrepancies in calibration accuracy larger than the instrument specification. In the microwave region, inadequate characterization of non-linear instrument sensitivities has led to critical observational uncertainties in the data record. In addition, antenna and calibration target anomalies in the Special Sensor Microwave Imagers (SSMIs) of the DoD's Defense Meteorological Satellite Program weather satellites have caused major problems in all applications.

10.3.2 Lack of comparability across platforms

Satellite instruments are built and calibrated by the individual space agencies. There is a lack of common implementation standards as each agency has its own procedures. There is no cross-calibration across systems prior to flight. In space, the offsets between two satellite instruments that obtain common observables cannot be ascribed to any one instrument because of the lack of traceable on-orbit absolute calibration standards. That this is a problem is manifested by the variable nature of inter-compared instrument observations, on both short and long timescales. Intercalibration at least guarantees that like satellite instruments flown at the same time will be consistent with one-another, yet intercalibration of instruments is not performed routinely today. The lack of comparability of measurements from different instruments—or agreement of their observations—is an impediment to achieving the societal benefits that could be derived from their measurements.

10.3.3 Lack of standards and oversight for instrument calibration procedures

The lack of required accuracies in most of the current sensor data from space can be attributed to non-adherence to the principles of measurement. The key principles such as developing an uncertainty budget based on a uniform definition of accuracy, precision and bias and achieving SI traceability for all calibrations to meet the requirements have not been closely followed. There is often no oversight or participation of calibration experts from the beginning of the sensor development to the final system level calibration. As a result, the individual satellite sensors today are characterized and calibrated to different levels of fidelity often driven by budget and schedule constraints and poor sensor design for calibration to start with.

10.3.4 Lack of credibility of long term trends

The shortcomings of much historical satellite data in developing credible time series of climate trends ultimately derive from the fact that those historical satellite instruments were not designed with SI traceable accuracy as a requirement. In the past decade attempts have been made to back-calibrate satellite data sets using a method of periodic instrument intercalibration and an implicit assumption of stability. The results of these efforts convey doubt that ultimately stems from uncertainties about long term instrument stability in space. The concept of instrument stability holds that even though an instrument can contain an unknown bias or inaccuracy, that bias does not change over the lifetime of the instrument, yet one cannot prove that a bias does not change with time without frequent absolute calibration of the instrument. This absolute calibration must be done through SI traceability.

10.3.5 Inability to correct NWP model defects

As indicated earlier, before satellite observations are assimilated into NWP models, systematic differences between the actual observations and simulated observations, which are calculated from model analyses of the atmospheric and surface state, are used to correct the satellite measurements. The underlying basis for this procedure is the implicit assumption that the model's atmospheric/surface state and its radiative transfer scheme are correct. As a result it is difficult, if not impossible, to detect and correct model defects using the observations. Achieving absolute accuracy of the constellation of environmental instruments in orbit by SI traceability and intercalibration would lead to more reliable assimilations and the potential to detect and correct model analysis and radiative transfer defects.

10.3.6 Slow transition of research to operations

In general, the transition from research and development (R&D) to operations is a complex and difficult problem. Successful transitions from R&D to operational implementation always require: (1) an understanding of the importance and risks of the transition, (2) development and maintenance of appropriate transition plans, (3) adequate resource provision, and (4) continuous feedback between R&D and operational activities.

Significant impediments exist to the rapid transfer of NASA advances in instrument calibration to NOAA's operational environment. There is no comprehensive joint program and common infrastructure to accomplish the necessary tasks. NASA and NOAA develop their calibration systems independently, NASA working in the research environment and NOAA in the operational world. There are significant differences between these two environments and technology transfer is not an easy activity. For example, in the case of lunar calibration, all NASA studies required routine spacecraft maneuver to view the Moon at the same phase angle in order to achieve high calibration accuracy. While spacecraft maneuver is a relatively simple matter for a small spacecraft with a focused mission such as SeaWiFS, it becomes a major issue for an operational polar-orbiting spacecraft with many payloads. The research community must understand the constraints of the operational satellites and work with the operational community to overcome such problems. For example, the NASA-NOAA-DoD Joint Center for Satellite Data Assimilation (JCSDA) has demonstrated the benefits of a joint, focused activity in improving and accelerating the use of satellite data in weather prediction.

10.4 The Solution: The National Center for Calibration (NCC)

The National Center for Calibration will synergistically integrate the expertise of the nation's two satellite agencies—NASA and NOAA—and the nation's premier organization for measurement science—NIST—to implement a coordinated national program to improve satellite instrument calibration. This section lays out the plan for the Center, including its Vision; Mission; Goals; Partners and their Roles; and Organizational Structure, Management and Operations. It also describes the emerging international program in satellite instrument calibration—the WMO's Global Space-based Inter-Calibration System (GSICS)—and the role of the NCC in carrying out the U.S. component of that program.

10.4.1 Vision

Satellite observations of the Earth that are intercomparable and tied to international standards

10.4.2 Mission

The National Center for Calibration develops the satellite instrument calibration systems needed to assure high-quality satellite measurements for weather, climate, ocean and other environmental applications.

10.4.3 Goals

- Achieve GEOSS societal benefits through implementation of a robust instrument intercalibration program
- Reduce the uncertainty in climate trend detection and prediction through state-of-the-art instrument calibration science
- Increase accuracy of satellite data for weather and environmental prediction models
- Smoothly transition research advances in calibration to operations
- Develop common practices for calibration of Earth observation sensors
- Achieve traceability to the International System of Units (SI)
- Optimize sensor choice and design for achieving these goals

Accomplishment of these goals is consistent with improved fulfillment of the missions of NOAA, NASA, and NIST and will: 1) enable improved assessment, understanding, and prediction of climate, weather, and the environment; 2) assure the delivery of accurate, needed, and trusted information to policy and decision makers, and 3) enhance society's ability to plan and respond to both short and long-term environmental events.

10.4.4 The NCC Partners: Organizational Capabilities and Roles

NOAA

NOAA operates the nation's operational environmental satellite systems, including those in Low-Earth Orbit (LEOs) and those in Geostationary Earth Orbit (GEOs). NOAA is the nation's source of weather and other environmental observations and forecasts. It has a wealth of experience in all aspects of calibration and validation of operational instruments and the generation of environmental products from the observations. NOAA specifies instrument measurement attributes, oversees vendor pre-launch calibrations, develops calibration algorithms, checks out instrument performance after launch, monitors instrument performance on-orbit, performs vicarious calibration using Earth targets, checks instrument observed radiances against those computed from atmospheric radiosondes and NWP model analyses, and develops and applies inter-satellite calibration techniques. NOAA will work with NCC partners NASA and NIST to transition to operations new developments in satellite instrument calibration, advise, as lead agency in the nation's Climate Change Science Program, on the completeness of a suite of climate benchmark instruments, and inter-calibrate environmental observing instruments to gain cross-platform comparability of measurements.

NASA

NASA is the nation's space research agency and conducts an extensive Earth observations program. NASA has extensive experience, based on the EOS and Landsat programs, in calibration of Earth observing sensor systems for fulfilling scientific measurement requirements. NASA has supported Earth observing instrument operations with extensive calibration-validation campaigns with agency and independent researchers. Many of NASA's data products have been used in detecting trends in the climate system. As part of NCC, NASA will develop a new class of instruments that have absolute accuracy established through SI traceable instrument design. These instruments will become climate benchmarks. Design of the new class of instruments will be undertaken with NIST through the NCC. A current letter of agreement between NASA and NOAA facilitating flow of techniques and technologies from Research to Operations (R to O) can be expanded to serve as the basis for NASA's participation in the NCC.

NIST

NIST is the nation's premier measurement science laboratory and maintains the international standards of measurement in support of U.S. scientific research. As such, its expertise in designing SI traceable instrument design is extensive. NIST has already played a role in establishing traceability chains for non-NIST instruments. NIST has the responsibility to support calibration standards development and dissemination to satisfy the requirements of the satellite agencies for remote sensing instrumentation. NIST has developed state of the art cryogenic radiometers as absolute standards and uniform sources (SIRCUS) with continuously tunable lasers covering the ultraviolet, visible and near-infrared spectral regions with unique capabilities to provide spectral irradiance and radiance calibrations. For the infrared, NIST has built cryogenic chambers to provide the Low Background and Medium Background capabilities for characterizing and calibrating user blackbodies and optical components. NIST's capability to measure the optical characteristics of filters, diffusers, mirrors, lenses, paints, and cavities through the entire optical spectral region is unsurpassed in the world. It has built state of the art transfer radiometers and is currently building hyperspectral sources and radiometer standards to achieve the highest accuracy possible by pushing the calibration technology to its limits. As part of the NCC, NIST will advise and assist NASA in the design of the new class of SI traceable instruments to become climate benchmarks, will qualify by uncertainty estimate the traceability of this new class of instruments, will develop new international standards and improve other standards in support of NASA and NOAA observations where necessary, and advise in the transfer of instruments from research to operations (NASA to NOAA) so that SI traceability is maintained.

10.4.5 Organizational Structure, Management and Operations

The National Center for Calibration will be a distributed Center, with activities taking place at the three partner agencies: NOAA, NASA, and NIST. A small Headquarters Staff, housed at NOAA/NESDIS, will serve as the administrative arm of the Center. The full time staff of the Center will be small, consisting of a Director and a Secretary (possibly part-time initially). Each participating agency would appoint a Deputy Director. The Director and Deputy Directors will constitute the management team. Technical liaisons from each of the participating agencies will provide much of the technical guidance and coordinate the joint projects of the Center. A Science Steering Committee consisting of external experts from the fields of instrument calibration, remote sensing, metrology, and the environmental applications areas will provide high level technical guidance and review the Center's program annually. The Center will also organize discipline workshops to obtain advice from the user communities in the relevant applications areas, e.g., climate monitoring and prediction, weather prediction, ocean prediction, etc.

The Center management will report to a Management Oversight Board consisting of the Directors of NOAA/NESDIS/STAR, NIST/Physics Lab., and NASA/GSFC/ ESD. The Center will carry out its program as agency activities and through coordinated interagency grants and internal R&D efforts that will encourage joint projects.

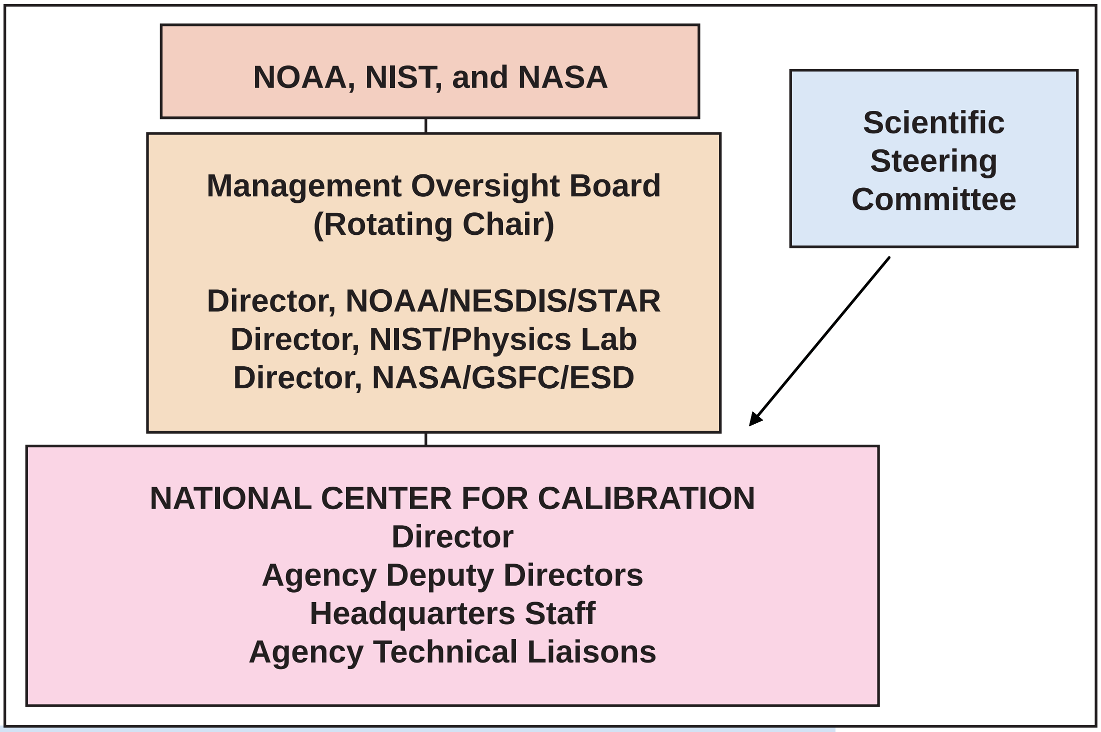

Figure 27 Structure of the proposed National Center for Calibration

10.4.6 The Role of the National Center for Calibration in the Global Space-based Inter-Calibration System (GSICS)

The NCC will carry out the U.S. component of the Global Space-based Inter-Calibration System (GSICS). The GSICS is a new international program to assure the comparability of satellite measurements provided at different times, by different instruments under the responsibility of different satellite operators (WMO-CGMS, 2007). Sponsored by the World Meteorological Organization and the Coordination Group for Meteorological Satellites, GSICS will inter-calibrate the instruments of the international constellation of operational low earth orbiting (LEOs) and geostationary (GEOs) environmental satellites and tie these to common reference standards. The inter-comparability of the instruments will result in more accurate observations for assimilation in numerical weather prediction models, the construction of more reliable climate data records, and achieving the societal goals of the Global Earth Observation System of Systems. The United States, the European Organization for the Exploitation of Meteorological Satellites, the Centre National d'Etudes Spatiales (CNES), the Russian Federation, Japan, and China will participate in the undertaking.

The GSICS consists of a GSICS Executive Panel, GSICS Coordination Centre (GCC), and GSICS Processing and Research Centers (GPRCs) located at the satellite agencies participating in the program. GSICS also includes critical Calibration Support Segments (CSS). Some CSS are performed directly by GSICS participating agencies while others are performed by external contributing entities.

NOAA is taking a leading role in implementing the System and will continue this activity as part of the NCC. NOAA serves as Chair of the GSICS Executive Panel, operates the GSICS Coordination Center, and serves as one of the GSICS Processing and Research Centers.

10.5 NCC Technology Areas

The National Center for Calibration will engage in a number of technology areas to increase the quality of the nation's space-based observations. Many of these technology areas align themselves with the Global Space-based Instrument Calibration System (GSICS) Calibration Support Segments, which are intended to be undertaken by various national research laboratories to support calibration of GSICS instruments.

10.5.1 Benchmark Measurements

Benchmark measurements in the context of long-term climate monitoring include the following characteristics (Goody, 2001):

- Accuracy that extends over decades, or indefinitely
- Measurements that are tied to irrefutable standards, usually with a broad laboratory base
- Observation strategy designed to reveal systematic errors through independent cross-checks, open inspection, and continuous interrogation

One of the overarching recommendations of the ASIC^3 workshop was to place in space a series of highly accurate benchmark instruments to measure with high spectral resolution the energy reflected and emitted by the Earth. These instruments would not only provide reliable long term records in their own right, but would also serve as a reference standard in space to calibrate other environmental satellite sensors. These spectral instruments should be joined in space by several other critical benchmark measurements, namely solar irradiance, Earth Radiation Budget, sea level, and atmospheric aerosols. Additional possibilities for benchmarks include instruments to monitor the state of the biosphere and the mass and extent of the cryosphere. The NCC will participate in the design of climate benchmark instruments, assure their SI traceability, provide uncertainty estimates, evaluate accuracy throughout instrument lifetime, and champion new climate benchmark instruments in response to demands of the scientific community.

10.5.2 Pre-launch Calibration

Satellite instrument calibration begins in the laboratory where the instrument views a target whose radiative characteristics are known by independent measurements. Instrument characterization requires extensive calibration tests of components to develop the model for sensor performance, and end-to-end system level measurements based on SI traceable standards to validate the model and develop the uncertainty budget. Ideally instruments should meet thresholds for spectral coverage and resolution, and radiometric performance (accuracy, precision and long-term stability). The absolute cryogenic standards at the national laboratories such as NIST are intrinsically SI traceable, achieve uncertainties that are as low as 0.01%, and serve the accuracy requirements for the optical wavelength region. For sensor calibration in the microwave region, variable temperature targets with contact thermometers are used and the uncertainties are large because of the lack of full radiometric characterization of the targets. In the ultraviolet, visible and near infrared the technology of tunable laser sources that provide Spectral Irradiance and Radiance Calibration with Uniform Sources (SIRCUS) for an end-to-end test as built by NIST provides the best solution to achieve the high degree of accuracy for the system level characterization. The pre-launch component of NCC will rely on NIST technological developments to ensure that pre-launch calibrations are traceable to the accepted international standards.

10.5.3 On-orbit Calibration

Since pre-launch calibrations are usually changed in space, the calibration process continues on-orbit. Many environmental factors influence calibration changes of an instrument in orbit, including but not limited to launch shock, outgassing, and the space radiation environment. In general, the major challenge for onboard calibration is enabling a detection of degradation of an instrument's system-wide calibration. An instrument's calibration can degrade by deterioration of sensors or changes in calibration sources. On-orbit (post-launch) calibration has been approached through a variety of schemes. Onboard lamps, diffusive reflectors, and blackbody sources—some with traceability to internationally recognized standards—have been traditionally used for radiometric calibration. Yet few existing flight instruments have the ability to monitor degradation of their calibration systems let alone distinguish between deterioration of sensors and deterioration of on-board calibration targets. On-orbit calibration is only possible if the instrument's original design permits it.

Two additional approaches have been used to assist in on-board calibration. Stable extraterrestrial sources, such as the Moon and stars, can be used to measure long term trends in sensor performance, since such objects can be viewed directly through the same optical path as used for Earth viewing. Such observations can be used to unravel and characterize changes in the output of onboard lamps and the optical properties of diffuser surfaces. A second approach employs vicarious calibration (validation) using stable and/or well-characterized Earth targets with information available on surface reflectance properties and atmospheric optical properties).

10.5.4 Earth-based Reference Sites

Use of earth-based reference sites involves comparing a satellite instrument's observed radiances or derived products with collocated surface measurements, or with observations from long-term specially equipped ground sites, and intensive field campaigns, special aircraft observations, highly accurate radiosonde measurements, ozone observations, etc. A number of agencies world wide have developed capabilities and instruments to conduct special ground-based and aircraft field campaigns to help calibrate satellite sensors.

Earth surfaces whose reflective properties are not expected to change significantly with time are used to monitor the stability of visible and near infrared radiometers lacking on-board calibration devices. Instrumental drift is determined from analysis of time series of the instrument's observations of these sites. In a more robust technique, the ISCCP has assumed that the Earth's surface reflectance as a whole does not change from year to year.

A number of long-term ground sites around the world are used to calibrate satellite instruments. The Chinese Meteorological Administration operates radiometric calibration sites in the Gobi Desert, located west of Dunhuang in northwest China's Gansu Province, and at Qinghai Lake in northwest China's Qinghai Province NOAA's Marine Optical Buoy (MOBY) provides values of water-leaving radiance for the calibration and validation of satellite ocean-colour instruments. The DoE's Atmospheric Radiation Measurement (ARM) Program operates three field research sites that conduct a wide variety of measurements with instruments such as radiometers and interferometers, radars and lidars, and a balloon-borne sounding system. Other long term sites include the Global Climate Observing System (GCOS) Upper Air Network (GUAN), the Baseline Surface Radiation Network (BSRN), the Global Atmosphere Watch (GAW), drifting ocean buoys, and the Network for the Detection of Stratospheric Change (NDSC). A number of agencies have capabilities and instruments to conduct special ground-based and aircraft field campaigns to help calibrate satellite sensors. The NCC will use data from such sites in providing checks on the calibration of satellite instruments.

10.5.5 Extra-terrestrial Calibration Sources

Extraterrestrial objects such as the Sun, Moon, and stars are stable sources of radiant energy that can be used to calibrate or monitor the stability of on orbit optical sensors. The Sun can serve as a source for on-orbit calibration of visible and ultraviolet channels in conjunction with on-board S.I. traceable diffusers that are calibrated prior to launch and monitored for degradation on orbit. The Moon is an effective object for tracking instrument drift. The current technique applies a model of the Moon's solar reflectance spectrum based on observations at moderate spectral resolution of the Robotic Lunar Observatory (ROLO). In comparison to the Sun, the Moon is especially well suited as an S.I. traceable transfer standard because the dynamic range of reflected solar radiance by the Moon is similar to the dynamic range of the reflected solar radiance by the Earth. However, the accuracy of Lunar Spectral Irradiance measurements must be significantly improved beyond the ROLO data to use the Moon as an S.I. traceable radiometric standard. Extension of use of the Moon to the near-infrared spectral range presents significant challenges. By way of benefit, current uncertainties in the measurement of total solar irradiance could be reduced substantially through focused technical research to make best use of these naturally available stable sources for on-orbit calibration.

10.5.6 Model Simulations

The major NWP centers around the world continuously monitor satellite radiance observations by comparing radiances computed from the model's output with the observations. The model's output consists of an analysis of atmospheric conditions based on assimilating all available observations. In current operations, these comparisons are made only for IR and microwave channels and only for clear sky conditions. Analysis of the differences between the observed and modeled radiances yields the relative bias of the instrument with respect to the model. In principle, time series of these differences could reveal drifts in satellite instruments. Model simulations are a powerful tool for monitoring and inter-comparing satellite instruments. Accurate radiative transfer models are essential to this technique, and improvement of such models is a key objective of the NASA/NOAA/DoD Joint Center for Satellite Data Assimilation.

10.5.7 Instrument Intercalibration

Intercalibration of satellite instruments involves relating the measurements of one instrument to those of another. Two techniques are typically employed for instrument intercalibration. The first is the collocation technique wherein instruments are inter-calibrated when they are viewing the same Earth scenes at the same times from the same viewing angles. The second is the time series technique wherein the overlapping records of two satellite instruments can be compared. Generally, the time series of large-scale spatial and temporal means are intercalibrated. New collocation techniques for LEO to LEO instrument intercalibrations—Simultaneous Nadir Observations (SNO) and Simultaneous Conical Observations (SCO)—have been demonstrated at NOAA/NESDIS. For LEO to GEO, simultaneous observations from collocations between a LEO and all GEO sensors have been used on a routine basis for more than 20 years within WCRP's International Satellite Cloud Climatology Project (ISCCP) as a means to inter-calibrate GEO satellites. While the result of an intercalibration is consistency between satellite instruments, the absence of S.I. traceability in the constellation of inter-calibrated would inhibit climate signal detection studies. The NCC will inter-calibrate like satellite instruments as described in the Global Space-based Inter-Calibration System (GSICS) implementation plan in order to benefit GEOSS.

10.5.8 Product Validation

Product validation is an additional tool that can be used to detect and correct problems in instrument calibration. Geophysical products are generated from satellite radiance measurements by applying an algorithm—either physically or empirically based—to the radiances. By comparing the retrieved products and their trends with in-situ observations, it is possible to monitor the instrument's performance. If a problem is detected, it can be corrected either by a careful analysis of the satellite instrument's characterization and environmental data or empirically. An equally important benefit of product validation is establishing the credibility of the retrieval algorithms.

10.6 NCC Research and Development Program

Complete NCC strategic and program plans will be developed when the Center is established. Some idea of the R & D projects to be undertaken by the center is highlighted below.

10.6.1 UV to microwave: Benchmark instruments

For a given data type to be made SI traceable and thus suitable for benchmarking, two technological hurdles must be surmounted. First, appropriate methods must exist for realizing an SI traceable calibration scale with a lower uncertainty than is dictated for the climate requirements. Second, instrument designs that are capable of achieving the required uncertainty for climate and demonstrating on-orbit that this uncertainty has been achieved must be devised and critically reviewed. Because of these restrictions, just a few methods with traceability to international standards have been implemented or proposed to date. Among those are atmospheric refractivity by active microwave limb sounding (radio occultation), ocean topography by nadir radar, longwave feedbacks and forcing by high spectral resolution infrared nadir sounding, Earth's gravity field by satellite orbital analysis and inter-satellite ranging, shortwave forcing and feedback by passive visible and ultraviolet nadir sounding, and solar irradiance from the ultraviolet through the near infrared by direct observation of the Sun. Taken together as a climate monitoring constellation, these can form a powerful benchmark for the state of the climate system against which subsequent benchmarks can be used to establish trends in the climate system and the mechanisms responsible for those trends with universal credibility. In the absence of the instrumentation needed to benchmark longwave and shortwave forcing of climate, though, fair testing of climate models becomes impossible. The NCC will develop the calibration tools needed for benchmark accuracy and champion the flight of benchmark instruments.

Traceability to SI units is the foundation for benchmark measurements. While SI traceability is currently achieved in pre-flight calibrations for most environmental satellite sensors—microwave instruments are a major exception—attaining SI traceability in orbit remains an R & D challenge. The NCC will explore promising strategies for on-board traceability to SI units, including development of: diagnostic tests of calibration system performance, direct realization of primary units of measurement, SI transferable standards, and redundant and independent calibration components. The NCC will also develop SI standards for microwave instruments.

10.6.2 Development tasks from ASIC^3 Workshop

The ASIC^3 workshop made a large number of detailed technical recommendations for improving the calibration of passive instruments observing in spectral bands from the UV to the microwave, of active instruments, of Earth radiation budget instruments, and for improving the intercalibration of satellite instruments. The NCC R & D program will address these problems.

10.6.3 R & D for GSICS

The goal of GSICS is to achieve the inter-comparability of operational satellites. During the GSICS processing, it is important to establish reference sensors that have relatively high spectral resolution and accuracy to serve as calibration standards for operational satellite instruments. Examples of such sensors are the NASA EOS AIRS or MetOp IASI as a reference for IR instruments, and the NASA EOS MODIS as a reference for solar reflectance instruments. Once benchmark instruments that cover the Earth's emission and reflectance spectrum are in space, they can be used as the reference instruments for GSICS intercalibrations. GSICS intends to perform LEO-LEO and LEO-GEO intercalibrations and will require an on-going program to develop and implement inter-comparison methodologies and carry out GSICS Calibration Support Segments. The NCC will carry out the needed program.

10.7 NCC Performance Targets

While the NCC Strategic and Program Plans will develop the Center's Performance Targets, these are some initial thoughts on measures of performance for the Center.

10.7.1 Benchmark instruments in space

An important measure of success will be the implementation of a climate monitoring system founded on benchmark systems in space that serve the dual purpose of providing high quality climate monitoring in their own right but also are used to calibrate other environmental satellite sensors in orbit.

Of highest development priority are systems to measure with high accuracy and spectral resolution the Earth's emission and reflectance spectrum:

- Emission spectrum: A high spectral resolution, high accuracy instrument to measure changes in the Earth's emission spectrum, enabling analyses of greenhouse gas climate forcings and response in the infrared, and cloud and water vapor feedbacks
- Solar reflectance spectrum: A high spectral resolution, high accuracy instrument to measure changes in the Earth's solar reflectance spectrum, enabling analyses of climate forcings and response in the ultraviolet, visible, and near-infrared, and cloud, snow/ice, and land surface feedbacks.

In addition, existing benchmark measurements should be continued indefinitely:

- Radio occultation obtained by the COSMIC project is currently providing a benchmark on the bulk dynamic and thermodynamic response of the atmosphere to greenhouse forcing. GPS radio occultation, which is directly traceable to the international definition of the second, requires continuation.
- Ocean altimetry as performed by TOPEX and JASON-1 provides a benchmark relevant to response of the ocean to climate forcing. Such ocean altimetry, traceable to the international definition of the second, requires continuation.
- Total and spectral solar irradiance measurements provide a climate benchmark for shortwave solar forcing of climate. Several such instruments have been deployed over recent decades, one with assured SI traceability, but significant disagreements between their absolute observations persist. Resolution of these disagreements should be pursued.
- Earth radiation budget observations provide information on the total net radiative forcing and response of the Earth system and should be continued indefinitely.

10.7.2 GSICS up and running

An important measure of success of the NCC will be a fully implemented GSICS. This would mean a fully functioning GSICS Coordination Center and Processing and Research Center (GPRC) as part of the NCC.

The GCC will coordinate the development of technical specifications for intercalibration procedures, transmit satellite collocation data (times and locations) to the satellite agencies, receive, archive and distribute intercalibration results from satellite agencies and reference sites, and coordinate the development of software tools to be used in the GSICS Processing and Research Centers (GPRCs) at the participating international satellite agencies.

The GSICS Coordination Center will serve as a one-stop source for information on all satellite instruments. It will provide easy, near real-time access to calibration information, issue special assessment reports of instrument trends, communicate to satellite agencies GSICS guidance on satellite instrument calibration. To inform and unify the international satellite calibration and user community, the GCC will publish and distribute an electronic GSICS Quarterly Newsletter with news and notes on satellite calibration activities throughout the world.

The GSICS Processing and Research Center (GPRC) will perform inter-satellite calibration using collocated satellite observations and overlapping satellite records to achieve comparability of sensors on different satellites, insure that pre-launch calibrations are traceable to the accepted international standards, support research activities in the framework of the distributed research component of GSICS, and participate in GSICS Calibration Support Segments.

10.7.3 Standard calibration procedures and SI traceability for all environmental satellite instruments

It has been a common conclusion of this ASIC^3 workshop and its predecessor in 2002 that achieving SI traceability for all satellite instruments is of utmost importance. Only then will we establish the climate change trends through time-series measurements and interlink and inter-compare different satellite platforms at different spatial locations that are launched in different times. In this regard one of the strong recommendations of the ASIC^3 workshop is to quickly implement the proposed project with NIST to absolutely measure the Lunar Spectral Irradiance (LUSI) and provide SI traceable data on the moon for on-orbit calibration of satellite sensors.

The guiding principles for climate benchmarks from space should be the application of independent methods and SI traceable sensor systems. The performance targets for each satellite sensor system are:

1. A complete list of sensor specifications, including calibration protocols.
2. SI traceable system level pre-launch calibration of sensor responsivity to meet the requirements.
3. Complete uncertainty budget based on NIST established calibration procedures and ISO guide to the expression of uncertainty in measurement.
4. Strategies for SI traceable on-orbit calibration of sensor performance using on-board pre-calibrated SI traceable standards and extraterrestrial sources.
5. Preservation of witness samples of all critical components, on-board calibration devices and a sensor prototype, if at all possible, for further evaluation of systematic uncertainties during the lifetime of the mission.

The long range performance target of the NCC is SI traceability for all environmental satellite instruments

10.8 Benefits to the User Community and Partner Agencies

The benefits to end users of implementing a national program in satellite instrument calibration through a NOAA—NASA—NIST National Center for Calibration would be:

- Early, irrefutable detection of climate change

- Facilitation of accurate climate data and estimates of climate trends to underpin policy decisions

- Verification of climate model predictions

- Improved weather prediction
- More reliable short term climate forecasts
- Achieving the nine societal benefit goals of the Global Earth Observation System of Systems (GEOSS)
- Ability to make sound policy decisions based on accepted accurate information

As illustrated above, the user community would reap substantial benefits from the NCC—but so would the partner agencies:

NOAA

- Improved operational satellite observations
- Improved satellite data and products
- Achieve NOAA strategic goals

NIST

- Development of advanced measurement standards
- Development of NIST capabilities in satellite instrument calibration sources and standards
- Achieve NIST strategic goals

NASA

- Improved transition of R2O in instrument calibration area
- Potential of R2O2R to benefit NASA mission
- Achieve NASA strategic goals

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Appendix A: Definitions of Measurement Uncertainty Quantities

Accuracy is a "Measure of how close the result of an experiment comes to the 'true' value" (Bevington and Robinson, 1969). It is the measure of the random and non-random or systematic errors that are the offset between an experimental result (a measured value) and a "true" value for that result. A "true" value constitutes an International System of Units, SI, standard; is the result of physical measurement and analysis; and, is "known to be true" with some uncertainty. An International Convention of Weights and Measures has adopted seven base units, the ampere, the Kelvin, the second, the meter, the kilogram, the candela and the mol as dimensionally independent. These units form the statistical foundation for weights and measures throughout the world. (See the information at http://www.bipm.fr/en/si/. "The Convention of the Metre (Convention du Mètre) is a diplomatic treaty which gives authority to the General Conference on Weights and Measures (CGPM), the International Committee for Weights and Measures (CIPM) and the International Bureau of Weights and Measures (BIPM) to act in matters of world metrology, particularly concerning the demand for measurement standards of ever increasing accuracy, range and diversity, and the need to demonstrate equivalence between national measurement standards.") In a mathematical context, accuracy is the probability that the experimental result is the "true" result (Figure 28). In Figure 28, exaggerated for clarity, the dashed vertical line represents the "Truth" of an internationally accepted SI Standard whose uncertainty is represented by the narrow, bell shaped curve. It is important to keep in mind that an SI standard itself is imperfect and represents "Truth", usually with a smaller uncertainty than one would encounter making measurements in the field. The broader bell shaped curve labeled Result represents measurements in the field using the Standard SI to trace the field measurement uncertainty to the seven fundamental units of the International System of Units. Figure 28 implies a Standard SI has been used to measure a Result. Correlated errors, annotated as Bias in the figure, arise when the Result uncertainty is traced to the Standard SI. The identification and removal of these correlated errors is pursued vigorously to improve the accuracy of a Result, a process known as calibration. Note that the accuracy of the Standard SI is also uncertain. There are residual correlated errors between "Truth" and Standard SI that are not specifically identified and are illustrated in Figure 28. A value for each SI unit, fundamental or derived, is the result of experimental measurement and statistical analysis. All physical measurements are related to theory and extensive analyses are performed to reduce the uncertainty with which each unit is estimated to be "true". While the residual uncertainty for each physical unit is small it is included in an error analysis that claims a Result is accurate SI. For example, in 2002 the United States adopted the relative standard uncertainty of Planck's constant as 1.7×10^{-7} and of the velocity of light in vacuum as zero (Mohr and Taylor, 2005). A statement of accuracy traced to the International System of Units includes the uncertainty that the measure is the "true" value. An explicit statement that a Result uncertainty is SI should mean that the accuracy is traced to the International System of Units rather than some arbitrary standard that is not SI (see the discussion of Precision and Figure 29, which follow).

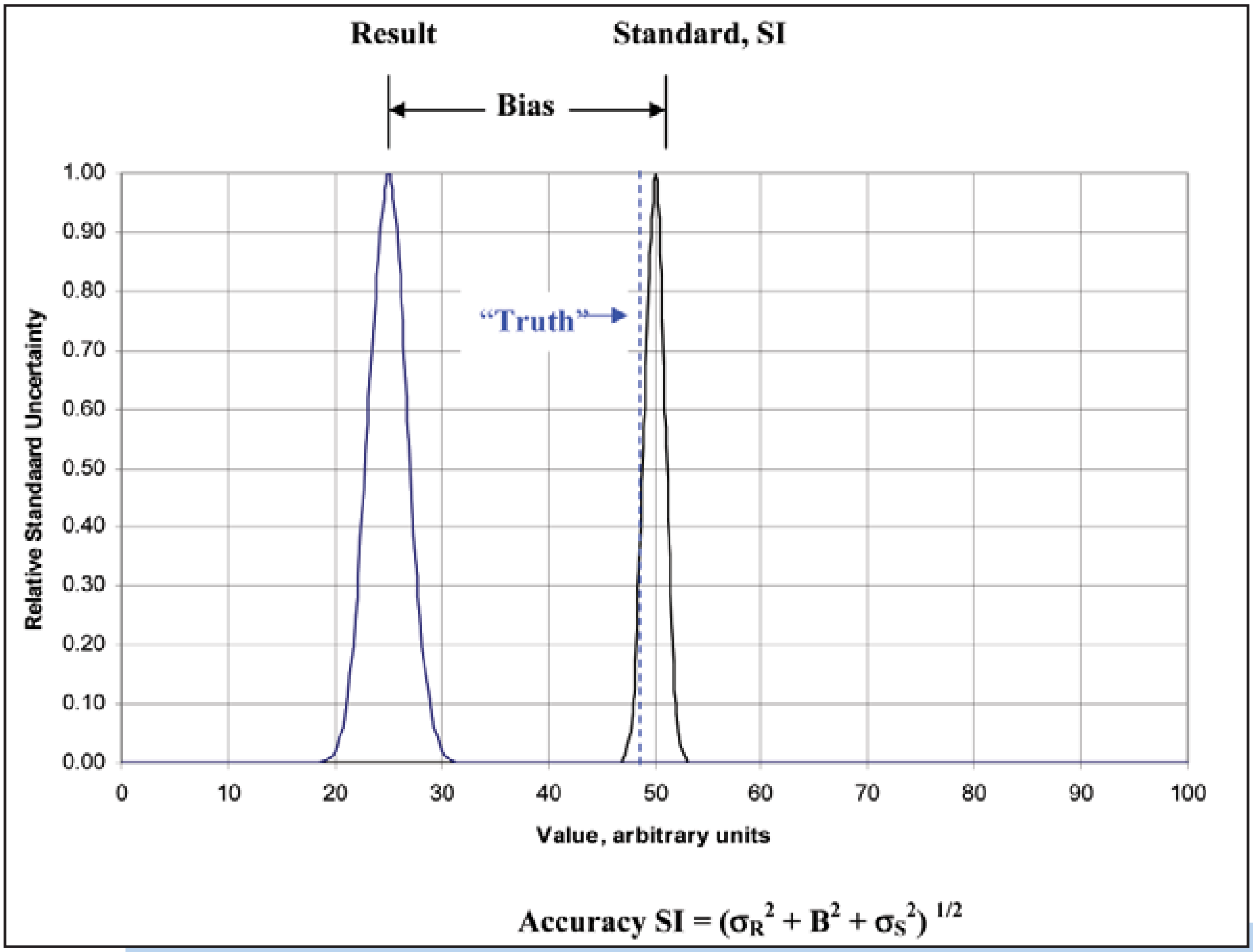


Figure 28 Accuracy traced to the International System of Units, SI. B is Bias, R is Result, S is Standard SI, and σ is standard deviation.

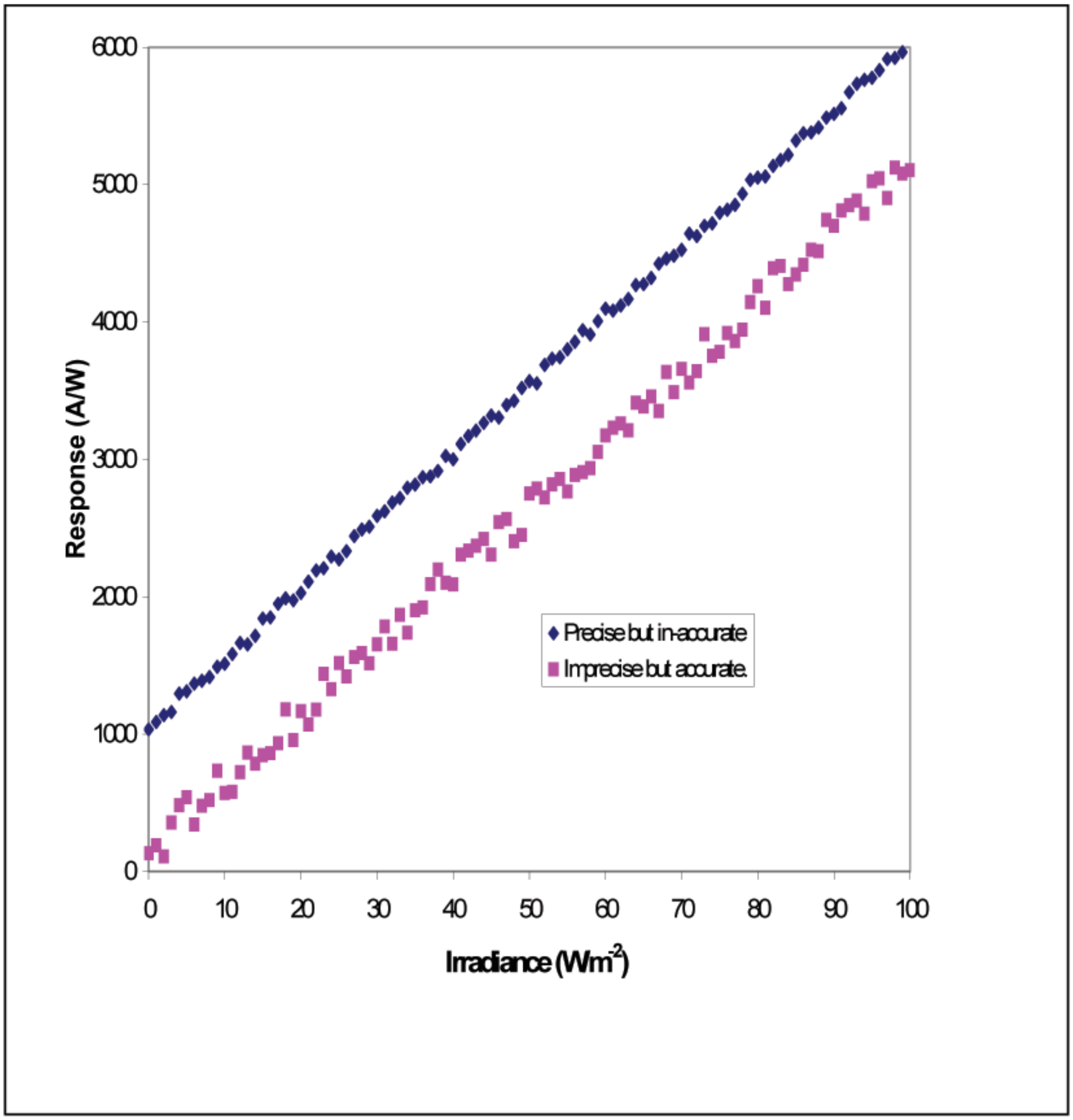
Precision, in sharp contrast, is a "Measure of how carefully the result [of an experiment] is determined without reference to any "true" value", op. cit. It is the measure of the random errors of an experimental result without regard to a "true" value. The result uncertainty is traced to an arbitrary standard either implicitly or explicitly and is not traced to SI. Experimental results can be quite precise but inaccurate and imprecise yet accurate as illustrated by Figure 29. Increasing the total number of independent results averaged may improve the precision. Accuracy traced to SI invokes unequivocal reference to an absolute standard while precision engages, in various venues, the vocabulary of stability, reproducibility, repeatability, continuity, and data record overlap, but without reference to an absolute standard. Long-term records built upon precision (or stability, repeatability, etc.) rely upon efforts to reconcile time or instrument dependent biases without reference to an internationally accepted standard to estimate how "true" the result is. Long term records built upon precision are notoriously fraught with difficulties and are, for reasons tied directly to the fundamentals of metrology, unable to withstand cross-examination.

Bias is a measure of the correlated errors in an experiment or a measurement. These errors are systematic. Mathematically they are not random. In practice every effort is made during a calibration to identify their presence in Results and to adjust the sensor response accordingly. During calibration the magnitude and the direction of a state vector within a multi-dimensional, operational envelope is deduced. The operational envelope of a radiometer is populated with characteristics such as wavelength, spectral bandwidth, transmittance, reflectance, effective collecting area, focal ratio, obliquity angle, temperature, response, gain to name some of them. While each is an independent characteristic whose value is deduced during calibration with some uncertainty, there are cross-dependencies and they are not independent variables. The detector response and amplifier electronic gain are often temperature dependent. The optical-spectral design of a radiometer is strongly dependent upon the mean spectral band as well as the bandwidth being sampled and the radiant temperature internally and externally. Within the uncertainty with which each characteristic can be deduced during ground calibration with carefully controlled experiments; their effect can be accounted for; and, the instrument response corrected to provide a more accurate SI Result. The point is that correlated errors exist. Every effort is made during either a ground or an operational calibration to hold the magnitude of the correlated errors to as small a value as possible within the constraints of program cost and schedule. When a radiometer becomes operational, pertinent, identified parameters are tracked using in-situ calibrations to remove their effects from the Results. With suitably designed experiments and data analysis the impact of correlated errors can be identified and accounted for during data reduction. This leads to a reduced bias and a more accurate Result. When carefully crafted and executed measurements are repeated by an operational instrument over a period of time, months to years, it is the correlated errors that arise as the result of changes in the instrument that can result in the bias becoming a dominant error term in the data uncertainty. It is a random walk issue. Changes occur and the state vector for the radiometer shifts. The magnitude may be small but over a substantial period of time it can point in a totally new direction with a significant change in magnitude. Yet these changes can be identified and corrected with a carefully crafted metrology plan. As an example, cross-comparisons of observations such as those made during nearly Simultaneous Nadir Overpasses, SNOs, have led to the identification and correction of correlated errors in currently operating instruments that may have benefited from a more complete ground calibration, i.e. ground calibration ceased when the quality of their results were adequate to meet their intended application, weather prediction. The reduced Result uncertainty SI that can establish Climate Data Records will require a carefully crafted metrology plan that includes the identification and removal of correlated errors. This is fundamental to arrive at accurate long-term Climate Data Records SI that are useful for the identification of the causes of Climate Trends be they man related or naturally occurring.

Stability is a measure of bias change with time. Just like *Accuracy*, *Stability* seeks to minimize systematic errors. Systematic errors that can be unambiguously identified when a specific cause produces a specific effect can be accounted for. Accounting for them reduces the Bias. But increasingly *Accurate* experiments are necessary to unambiguously identify a cause-effect relationship as the magnitude of residual systematic errors decreases. However, so long as the relationships that cause an unknown *Bias* are stable with time a Result is inferred to be stable with time.

A stable process seeks to minimize systematic errors relative to a Reference whether the Reference is arbitrarily chosen or is an absolute (SI). The process can be used to ascertain the probability a trend is in evidence. The word relative will be used to imply that an arbitrary rather than an absolute Reference is chosen. A relative Reference can be formulated as a measure and trends relative to that measure can be ascertained as illustrated by the blue plot of Figure 29. The measure itself can be well founded on scientific principles whose respective uncertainties SI are small, < 1%. However, unexplored parameter co-dependencies will yield a Result SI significantly greater than what would appear to be a “high” quality Result. The identification of and the removal of these co-dependencies (biases or correlated errors) relative to the International System of Units requires careful experiment planning and execution supported by critical data analysis. Residual correlated errors present when a stable process includes a relative Reference leads to erroneously thinking that a *stable* Result is also an *accurate* Result SI. Until the relative Reference is proven by theory or measurement either in the laboratory or in-operation that it is traced to SI units with a well defined uncertainty the Result accuracy remains an unknown. Thus, a relative Reference may be *precise* and *stable* but *inaccurate* SI. Using a relative Reference to establish the *stability* of a Result has the inherent risk of a *Biased* relative Reference SI. Without the traceability to SI the loss of the Reference ends the *stable* process because the connection to SI was never established.

Figure 29 Precise does not imply accurate.



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Appendix B:
The Critical Role of Spectral Resolution to the Achievement of Climate Objectives

Spectral resolution constitutes a central role in the achievement of three primary goals: (1) high-accuracy climate observations from space that are tested and trusted; (2) diagnosis of on-orbit shifts in the spectral response function of filter radiometers; and (3) separation of climate forcing of the Earth system from the response of the climate system that sets the foundation for the systematic testing and improvement of climate forecast models. We treat these in order.

It is well known to quantitative spectroscopists that spectral resolution provides critical diagnostics of instrument performance through the determination of instrument optical properties using line shape analysis, frequency-dependent polarization effects, spectral contrast as it is reflected in frequency-dependent offsets, analysis of off-axis scattered light, changes in the spectral response function as the instrument/detectors age, analysis of linearity of response over the dynamic range of the detectors and associated electronics, etc. While these considerations in themselves are critical for SI traceable accuracy on-orbit, which is in turn an essential goal for climate observations, these issues are clearly articulated in the metrology literature and will not be further discussed here. We focus the limited space available here on critical aspects coupling spectral resolution to accuracy for the specific case of climate observations from space. This issue was treated in a classic paper by Goody and Haskins (1998).

Spectrally resolving instruments may be calibrated more accurately than broad-band instruments for very specific reasons. Stated simply, on-orbit calibration of high resolution instruments can determine and correct for changes in the spectrally-varying instrument responsivity while broadband instruments can only determine integrated responsivity. This difference has serious consequences. To see why this is so, consider the calibration strategy that, for the purpose of developing long-term climate trends, must establish the quantitative relationship between an SI traceable radiance standard and the observed radiance $I(v)$ (units of, for example, watts/m^{2}-ster-cm^{-1}) over a chosen spectral region that is given by

$$I = \int_{v_1}^{v_2} S(v) I(v) dv \,,$$

where v_1 and v_2 define the range of spectral frequency, $S(v)$ is the frequency-dependent sensitivity of the instrument, and $I(v)$ is the frequency-dependent radiance emitted from Earth to space as observed by a nadir viewing instrument.

The on-orbit calibration is accomplished by observing a blackbody, $B(v)$, on-board the satellite with the same instrument such that the radiance, B, is given by

$$B = \int_{v_1}^{v_2} S(v)\varepsilon B(v)dv\ ,$$

where all quantities are the same, except the scene radiance $I(v)$ is replaced by the product of the Planck function, $B(v)$ and the emissivity of the calibrated blackbody, ε.

The key quantity to determine is, therefore, the frequency dependent sensitivity, $S(v)$, a quantity that changes throughout the life of the instrument and a quantity that must be determined *on orbit* against SI traceable standards throughout the life of the instrument in order to establish a climate record that is testable and trusted.

Therein lies the critical distinction between a broadband instrument and a spectrometer or interferometer with, for example, a 1 cm^{-1} spectral resolution. While $S(v)$ can be determined in the laboratory prior to launch using a scannable narrow band radiation source, the broadband instrument cannot determine its own $S(v)$ on orbit; it can only determine the integral of that function

$$\int_{v_1}^{v_2} S(v)dv\ ,$$

over the entire thermal infrared where v_1 and v_2 represent the full frequency range, usually 200 to 2000 cm^{-1} or 5 to 50 μ.

Assume that the functional form of $S(v)$ *at launch* for a longwave broadband is that shown in Figure 30. The key observed quantity of the nadir viewing satellite on-orbit is the infrared radiance, $I(v)$, emitted from the Earth to space, which has the functional form shown in Figure 31.

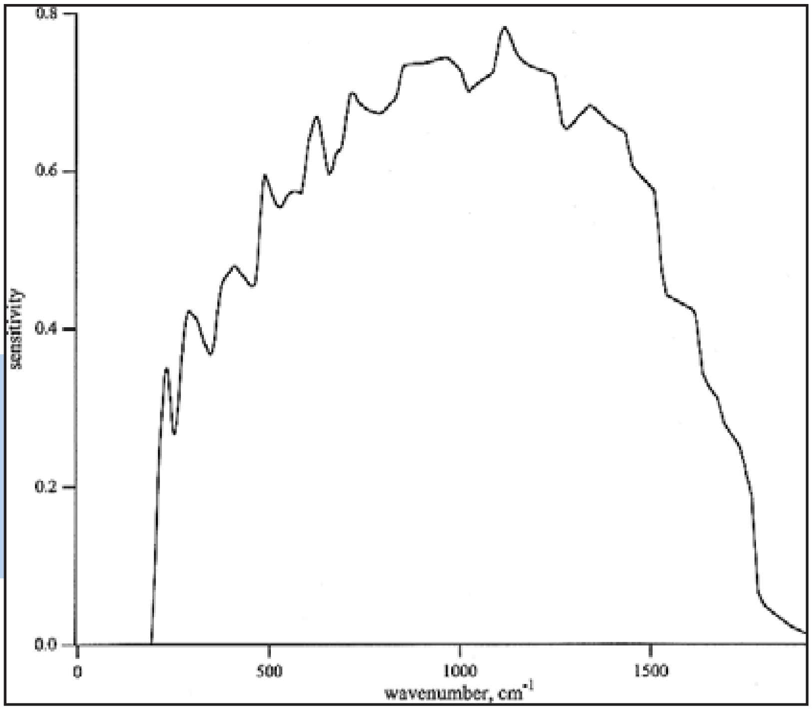


Figure 30 Assumed form of the frequency dependent sensitivity of a longwave broadband instrument at launch.

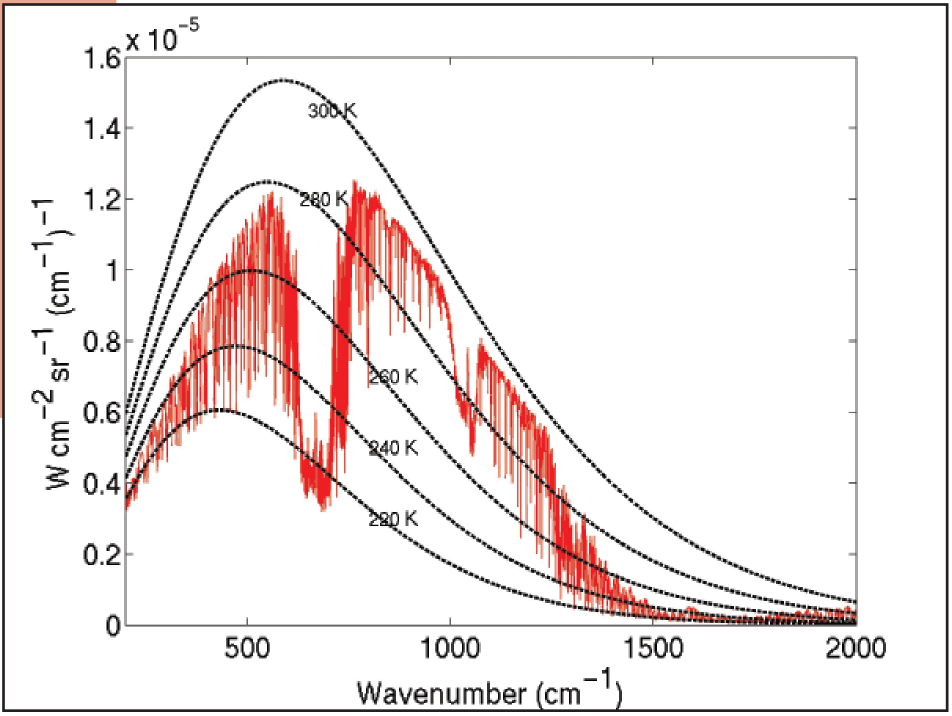


Figure 31 The thermal infrared radiance emitted by the Earth's climate system has strong spectral features that resulting in substantial variation in radiant intensity within narrow spectral regions. The convolution of such rapidly varying features with unknown spectral response function structure is a potentially critical source of measurement error.

Through the on-orbit life of the broadband instrument, or any instrument, however, $S(v)$ will change as a result of aging of materials, frequency-dependent gain changes in the detectors, etc., Thus, when long-term climate records are constructed, a first-order objective is to compare the quantity

$$I = \int S(v)I(v)dv\,,$$

in period 1, say for years 2000–2005, that we will call I_1, to the same quantity in period 2, say from 2010–2015, that we will call I_2.

In period 1 we may have the convolution integral of $S(v)$ and $I(v)$, shown in Figure 32 below.

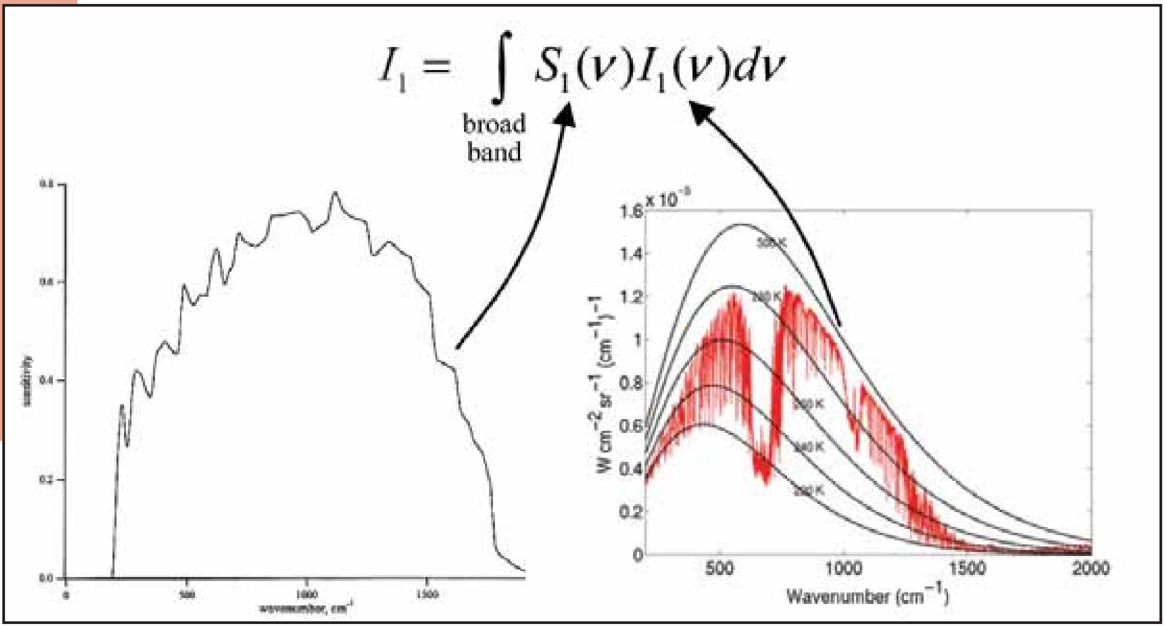


Figure 32 The radiance measured by a filter radiometer is a convolution of the incident terrestrial radiance with the spectral response function of the radiometer's optical system.

In period 2, we may well have the integral shown in Figure 33.

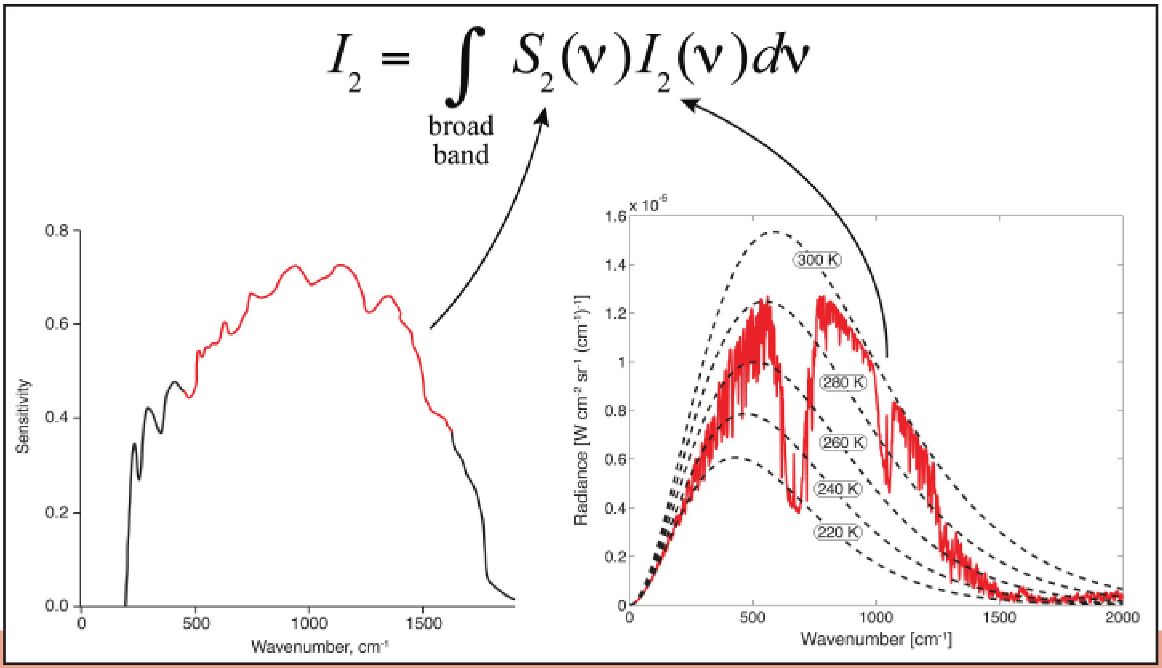


Figure 33 Aging due to environmental exposure causes alteration of the radiometer spectral response function. Since the unknown climate change signal is convolved with this unquantified change in spectral response function, definitive detection and interpretation of climate change is out of reach.

If, as may well be the case as the instrument ages on-orbit, the frequency-dependent sensitivity $S(v)$ of the broadband instrument changes, $S_1(v)$ and $S_2(v)$ will differ by some amount such as shown in Figure 34. The distortion represented by the difference between $S_1(v)$ and $S_2(v)$ cannot be uniquely determined on-orbit. As a direct result, the observed quantity

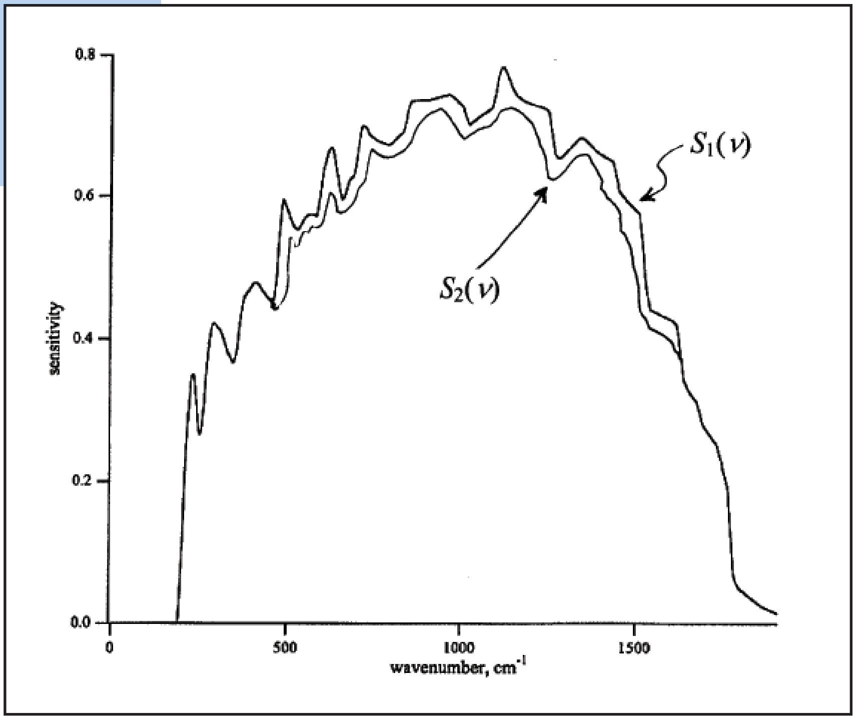
$$I_2 = \int_{\substack{\text{broad}\\\text{band}}} S_2(v) I_2(v) dv$$

will not be equal to the true quantity

$$I_2 = \int_{\substack{\text{broad}\\\text{band}}} S_1(v) I_2(v) dv$$

For example as the surface warms, thereby increasing $I_2(v)$ relative to $I_1(v)$ in the window region, $S_2(v)$, due to aging, may have decreased relative to $S_1(v)$, such that the integral is unchanged.

Figure 34 The potential change of instrument sensitivity for a longwave broadband instrument from period 1 to period 2.



Because $S(v)$ as a function of frequency cannot be uniquely determined on orbit with a broadband instrument, it is impossible to establish the (small) changes in the key quantity $I(v)$ as a function of time. In sharp contrast, the spectrally resolving instrument, by design, has the intrinsic capacity to establish the spectral response function, $S(v)$, on orbit. It does this in the following way:

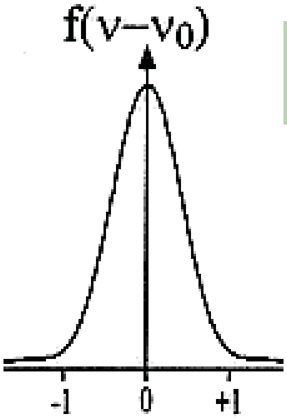


Figure 35 The lineshape for a single channel of a generic spectrometer.

The spectrometer has a spectral transfer function $f(v - v')$, or instrument line shape (ILS) as it is often referred to, as in Figure 35. With this intrinsic spectral resolution, observation of the calibration blackbody *on orbit* provides the quantity

$$B = \int_{v_1}^{v_2} \varepsilon B(v')S(v')f(v-v')dv',$$

where $B(v')$ is the Planck function at frequency v' (and temperature T!), ε is the cavity emissivity, $S(v')f(v - v')$ is the product of instrument sensitivity and the ILS such that

$$\int_{0}^{\infty} f(\nu-\nu')d\nu' = 1 .$$

Thus, as the spectrometer scans the spectrum, S(ν) is uniquely determined as a function of ν because B(ν′) is known via independent measurement of the cavity emissivity and the absolute temperature of the cavity that determines the Planck function, B(ν′), for that temperature. For each series of spectral scans of the blackbody on-orbit, the quantity

$$\int_{\nu_1}^{\nu_2} S(\nu')f(\nu-\nu')d\nu' ,$$

is determined because the Planck function is a constant over that small (~ 1 cm^{-1}) spectral interval and can be removed from the integral.

Thus, when the nadir “scene” is viewed to determine

$$I = \int_{\nu_1}^{\nu_2} I(\nu')S(\nu')f(\nu-\nu')d\nu' ,$$

the absolute calibration is known for each spectral resolving element. In addition, the spectral resolution of 1 cm^{-1} provides the following diagnostics *on orbit*:

- The detailed functional form of $f(\nu - \nu')$ is checked using molecular emission lines from the atmosphere and the line shape from an on-orbit laser
- The relationship between spectral zeros can be compared with the cold deep space view to diagnose optical performance.
- The presence of any off-axis scattered light or stray light leakage can be tested by contrasting deep space with a dynamic range of scene.
- The polarization of the instrument can be determined by scanning deep space.
- Thus, for climate studies, the instruments’ spectral response function is defined against an SI traceable reference for each spectral interval, such that the Earth’s radiance to space, $I(\nu)$, is uniquely determined as a function of frequency.

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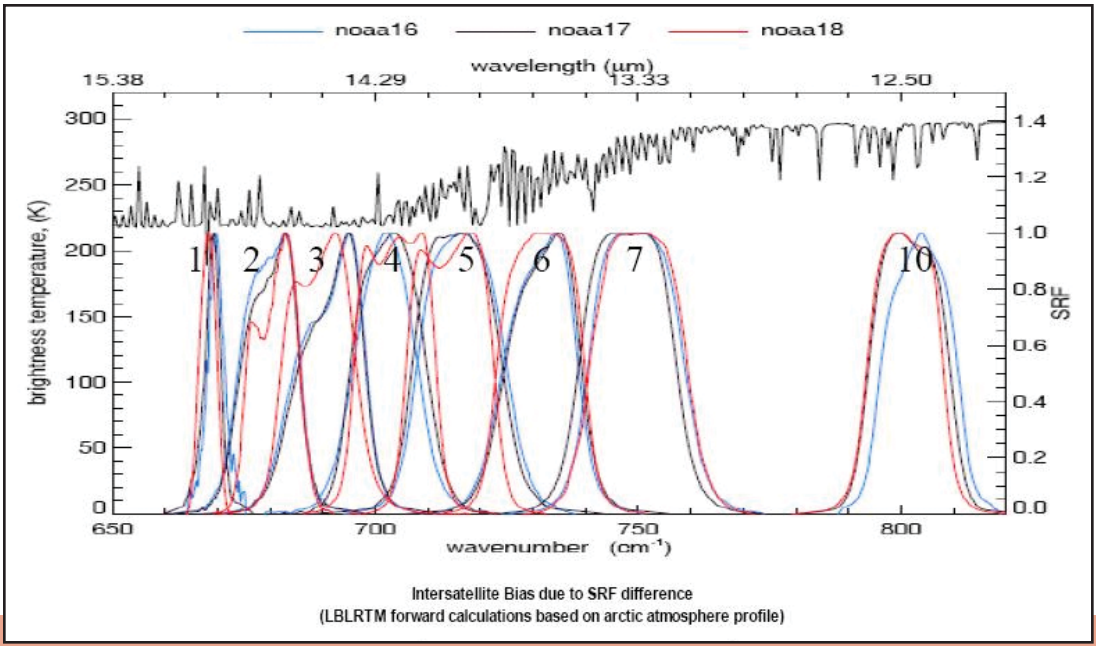
Appendix C: Relationship between a Spectrometer and a Filter Radiometer

The powerful role played by spectral resolution on the order of 1 cm^{-1} in combination with a simple spectral response function $f(v - v_0)$ that uniquely defines $S(v)$ on-orbit across the thermal infrared emerges when filter radiometers such as HIRS on NOAA 16, 17 and 18 are compared (see Tobin *et al*., 2005). Figure 36 displays the before-launch Spectral Response Functions (SRFs) (the quantity that compares with $f(v - v_0)$ for a spectrometer in Appendix B) of the HIRS instruments on the three NOAA satellites and a forward radiative calculation (LBLRTM) showing $I(v)$ for an Earth scene.



Intersatellite Bias due to SRF difference
(LBLRTM forward calculations based on arctic atmosphere profile)

Figure 36 The different spectral response functions for the NOAA-16, NOAA-17 and NOAA-18 satellites are convolved with the spectral structure shown by the solid black line. Radiative transfer calculations show that this convolution results in differences up to 3 K (see text).

By using the spectrally resolved data to simulate the brightness temperatures that each channel would report for the same scene (Wang, Ciren and Cao, 2005), the impact of differences in the SRFs on deduced temperature can be determined. The results are displayed in Figure 37, showing differences of up to 3 K with a clear correlation between the spectral detail and the degree of inaccuracy.

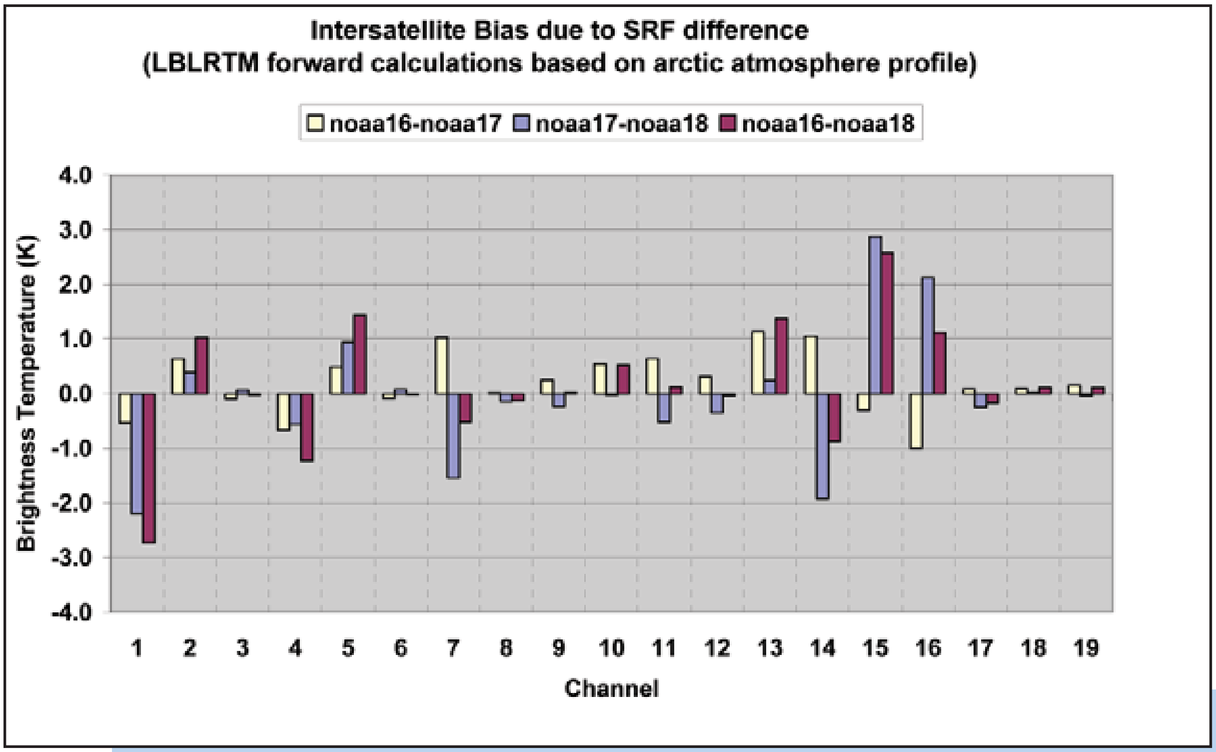


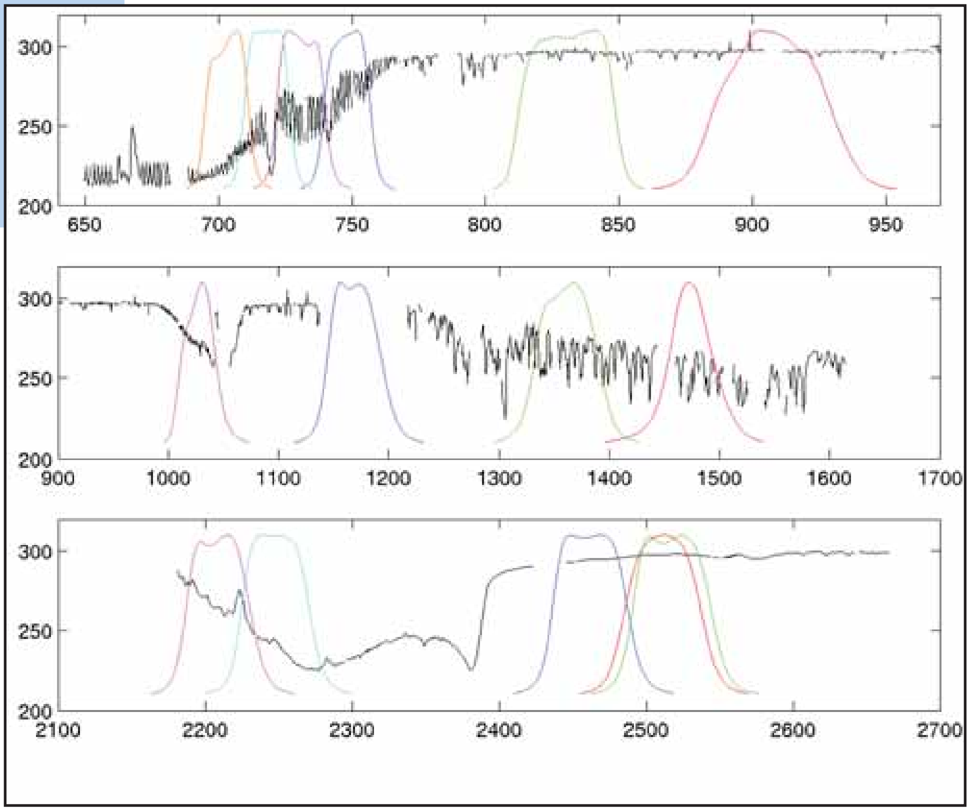
Figure 37 The histogram shows the differences in simulated Arctic radiances attributable to variation in spectral response functions among the NOAA-16/17/18 sounders.

Compounding the difficulty inherent in using filter radiometers for climate studies is the fact that the SRFs change with time on-orbit, but there is no possible way to uniquely determine changes in the SRFs on-orbit. The critical conclusions are that:

1. Differences in the SRFs for HIRS on NOAA 16, NOAA 17, and NOAA 18 are primary contributors to HIRS-to HIRS differences,
2. This represents a critical shortcoming for any climate record built from the HIRS series of measurements even if the absolute calibration was perfect.

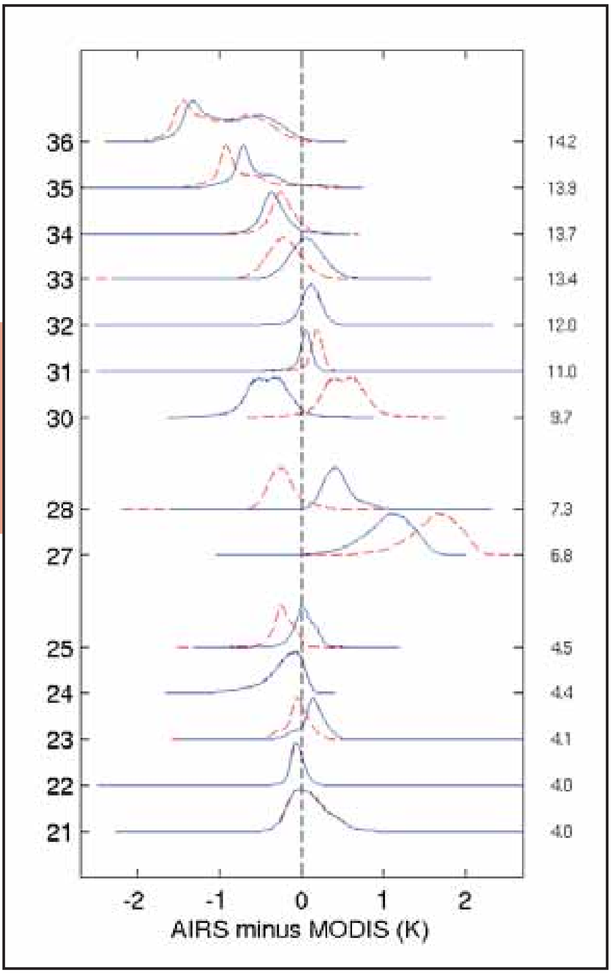
A second compelling example (Tobin et al., 2006) is afforded by a comparison between MODIS and AIRS using a similar analysis except that in this case the observed temperature for each of the filter channels on MODIS is compared with spectrally resolved data from AIRS as shown in Figure 38. MODIS bands extending from band 36 at 700 cm^{-1} (14.2 µ) to band 21 at 2525 cm^{-1} (4.0 µ) are included.

Figure 38 The spectral response functions for the infrared MODIS channels are shown together with a sample AIRS spectrum with units of brightness temperature (K).



The analysis is done in two ways: with and without accounting for convolution errors between the MODIS channels and the spectrally resolved AIRS data (see Tobin *et al*., 2006); the difference is negligible between the two cases but the conclusions are very significant for climate. Results are summarized in Figure 39, which shows differences exceeding 1 K for many channels, with the bias appearing in both positive and negative temperature differences. Not surprisingly, the largest discrepancies appear in spectral regions with the most spectral detail. What is of greatest concern for climate, of course, is that a filter radiometer *cannot determine its own SRFs on-orbit, thus irreversibly entangling shifts in spectral response with changes in radiance resulting from climate forcing and/or climate response.*

Figure 39 Histograms show the distribution of brightness temperature differences between overlapping channels of AIRS and MODIS. MODIS channel: number, left axis, wavelength in μm, right axis. The dashed curves show the results without the convolution corrections



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List of Acronyms and Abbreviations

ATSR	Along Track Scanning Radiometer
AATSR	Advanced Along Track Scanning Radiometer
ACRIM	Active Cavity Radiometer Irradiance Monitor
ABL	Atmospheric Boundary Layer
AIRS	Atmospheric InfraRed Sounder
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol Optical Depth
APS	Aerosol Polarimetry Sensor
ARM	Atmospheric Radiation Measurement program
ASIC^3	Achieving Satellite Instrument Calibration for Climate Change
ATBD	Algorithm Theoretical Basis Document
ATMS	Advanced Technology Microwave Sounder
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BIPM	Bureau International des Poids et Measures
BOL	Beginning of Life
BRDF	Bidirectional Reflectance Distribution Function
BSRN	Baseline Surface Radiation Network
BUV	Backscattered UltraViolet – radiances or technique
CALIOP	Cloud-Aerosol LIdar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCD	Charge-Coupled Device
CCSP	Climate Change Science Program
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth’s Radiant Energy System
CGPM	Conference Generale des Poids et Measures
CMDL	Climate Monitoring and Diagnostic Laboratory
CMIS	Conically-Scanning Microwave Imager
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CNES	Centre National d’Etudes Spatiales
CrIS	Cross Track Infrared Sounder
CSS	Calibration Support Segments
DIARAD	Differential Absolute Radiometer
DMD	Digital Micromirror Devices
DMSP	Defense Meteorological Satellites Program
DOAS	Differential Optical Absorption Spectroscopy
DoE	Department of Energy
DPR	Dual-frequency Precipitation Radar
DSD	Drop Size Distribution
EDR	Environmental Data Record
ENSO	El Niño-Southern Oscillation
EOL	End of Life
EOS	Earth Observing System

ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ESD	Earth Sciences Division
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FEL	Free Electron Laser
FFT	Fast Fourier Transform
FOV	Field of View
FPAR	Fraction of Photosynthetically Active Radiation
FPGA	Field Programmable Gate Array
FTIR	Fourier Transform InfraRed
GAC	Global Area Coverage
GAW	Global Atmosphere Watch
GCC	GSICS Coordination Centre
GCI	Global Cloud Imagery
GCOS	Global Climate Observing System
GEO	Geostationary Earth Orbiter
GEOSS	Global Earth Observation System of Systems
GERB	Geostationary Earth Radiation Budget Experiment
GEWEX	Global Energy and Water Cycle Experiment
GHRR	Global Area Coverage Advanced Very High Resolution Radiometer
GLAS	Geoscience Laser Altimeter System
GLOSS	Global Sea Level Observing System
GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring by Occultation of Stars
GPRC	GSICS Processing and Research Center
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRWG	GSICS Research Working Group
GSFC	Goddard Space Flight Center
GSICS	Global Space-Based Inter-Calibration System
GUAN	GCOS Upper-Air Network
HALOE	HALogen Occultation Experiment
HIRDLS	High Resolution Dynamic Limb Sounder
HIRS	High-resolution InfraRed Sounder
HIS	High-resolution Interferometer Sounder
HSB	Humidity Sounder for Brazil
IASI	Infrared Atmospheric Sounding Interferometer
ICESat	Ice, Cloud, and land Elevation Satellite
ICSU	International Council of Scientific Unions
ICT	Internal Calibration Target
IGACO	Integrated Global Atmospheric Chemistry Observations
IGOS	Integrated Global Observing Strategy
IOC	Intergovernmental Oceanographic Commission
IORD	Integrated Operational Requirements Document
IPCC	Intergovernmental Panel for Climate Change
IPO	Integrated Program Office (for NPOESS)
IR	InfraRed
ISCCP	International Satellite Cloud Climatology Project
IWP	Ice Water Path
JCSDA	Joint Center for Satellite Data Assimilation

JCSIC	Joint Center for Satellite Instrument Calibration
LAI	Leaf Area Index
LDEF	Long Duration Exposure Facility
LED	Light-Emitting Diode
LEO	Low Earth Orbiter
LIDAR	Light Detection and Ranging
LITE	Lidar In-space Technology Experiment
LNA	Low-Noise Amplifier
LOA	Letter of Agreement
LUSI	Lunar Spectral Irradiance
LUVV	Limb-scattered Ultraviolet and Visible radiation
LW	Longwave
LWP	Liquid Water Path
MAM	Mirror Attenuator Mosaic
MERIS	MEdium Resolution Imaging Spectrometer Instrument
Meteosat	European Geostationary Meteorological Satellite
MetOp	Meteorological Operational satellite
MFRSR	Multi-Filter Rotating Shadowband Radiometer
MISR	Multiangle Imaging SpectroRadiometer
MLS	Microwave Limb Sounder
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
MSU	Microwave Sounding Unit
MW	Microwave
NASA	National Aeronautic and Space Administration
NDSC	Network for the Detection of Stratospheric Change
NDVI	Normalized Difference Vegetation Index
NEDT, NEΔT	Noise Equivalent Delta Temperature
NESDIS	National Environmental Satellite, Data, & Information Service
NIR	Near InfraRed
NIST	National Institute for Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NWP	Numerical Weather Prediction
OATS	Operational Algorithm Teams
OCO	Orbiting Carbon Observatory
OLR	Outgoing Longwave Radiation
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
POAM	Polar Ozone and Aerosol Measurements
POES	Polar Operational Environmental Satellite
POLDER	POLarization and Directionality of the Earth’s Reflectances
PR	Precipitation Radar
PRT	Platinum Resistance Thermometer
PTFE	Poly-tetrafluoroethylene
R2O	Research to Operations
R2O2R	Research to Operations to Research
RAP	Rotating Azimuth Plane
RF	Radio Frequency
RFI	Radio Frequency Interference
ROLO	Robotic Lunar Observatory
RSR	Relative Spectral Response
RVS	Response Versus Scan-Angle
SAA	South Atlantic Anomaly

SAGE	Stratospheric Aerosol and Gas Experiment
SBRS	Santa Barbara Remote Sensing
SBUV	Solar Backscattered Ultraviolet instrument
ScaRaB	Scanner for Radiation Budget
SCIAMACHY	SCanning Imaging Absorption spetroMeter for Atmospheric CHartographY
SCO	Simultaneous Conical Overpass
SDR	Sensor Data Record
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SOHO	Solar and Heliospheric Observatory
SGP	Southern Great Plains
SI	International System (of units)
SIM	Spectral Irradiance Monitor
SIMBIOS	Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies
SIRCUS	Spectral Irradiance and Radiance Calibration with Uniform Sources
SIRN	Solar Irradiance Research Network
SIS	Spherical Integrating Source
SNO	Simultaneous Nadir Overpass
SNR	Signal to Noise Ratio
SOLSTICE	SOLar STellar InterComparison Experiment
SoRCE	Solar Radiation and Climate Experiment
SPARC	Stratospheric Processes and their Role in Climate
SRB	Surface Radiation Budget
SRF	Spectral Response Function
SSBUV	Space shuttle SBUV
SSM/I	Special Sensor Microwave/Imager
SSM/T	Special Sensor Microwave/Temperature sounder
SSM/T-2	Special Sensor Microwave/Water Vapor sounder
SSMIS	Special Sensor Microwave Imager Sounder
SST	Sea Surface Temperature
STAR	Center for Satellite Applications and Research
STSI	Space Telescope Science Institute
SURFRAD	Surface Radiation Budget Network
SW	Shortwave
SWIR	Shortwave Infrared
TES	Tropospheric Emissions Spectrometer
TIM	Total Irradiance Monitor
TMI	TRMM Microwave Instrument
TOA	Top of Atmosphere
TOAR	Top-Of-Atmosphere Reflectivity
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TOZ	Total column Ozone
TRMM	Tropical Rainfall Measuring Mission
TSI	Total Solar Irradiance
TXR	Thermal Transfer Radiometer
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTH	Upper Troposphere Humidity
UV	UltraViolet
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIRGO	Variability of Irradiance and Gravity Oscillations
VIRS	Visible and Infrared Scanner
VIS	Visible
VLBI	Very Long Baseline Interferometer
WMO	World Meteorological Organization
WOUDC	World Ozone and Ultraviolet Data Center

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