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Best Practice for Pre-Launch Characterization and Calibration of Instruments for Remote Sensing

Summary of the Working Paper

This paper was requested by the GSICS Executive Panel for presentation to CGMS.

The pre-launch characterization and calibration of remote sensing instruments should be planned and carried out in conjunction with their design and development to meet the mission requirements. In the case of infrared instruments, the onboard calibrators such as blackbodies and the sensors such as spectral radiometers should be characterized and calibrated using SI traceable standards. In the case of earth remote sensing, this allows intercomparison and intercalibration of different sensors in space to create global time series of climate records of high accuracy where some inevitable data gaps can be easily bridged. In the case of ballistic missile defense, this provides sensor quality assurance based on SI traceable measurements. The recommended best practice for this pre-launch effort is presented based on experience gained at National Institute of Standards and technology (NIST) working with National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA) and Department of Defense (DoD) programs in the past two decades. Examples of infrared standards and calibration facilities at NIST in light of lessons learned from past in serving the remote sensing community will be discussed.

Best Practice for Pre-Launch Characterization and Calibration of Instruments for Remote Sensing

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1. INTRODUCTION

Satellite remote sensing provides continuous global coverage and has the potential to allow observation of climate variables through long time series. Climate modelers require such data to test their models and predict global climate variability. However, such data has to be accurate to be of value to the modelers. Two workshops were held to identify the accuracy requirements for radiometric measurements and identify ways to achieve those goals [1, 2]. In this article, measurements and calibrations refer to the radiometric quantities radiance, irradiance, and reflectance (such as Bidirectional Reflectance Distribution Function (BRDF)). Table 1 shows the required accuracies and stabilities for climate variable data sets and Table 2 shows the corresponding radiometric accuracies and stabilities of satellite instruments to meet those requirements, based upon the workshops [1]. The requirements are very demanding and the golden rule for achieving the needed accuracy is to make measurements traceable to international standards (SI) [2]. In order to make SI traceable measurements the satellite sensors are to be well calibrated and the uncertainty budgets are to be evaluated and documented following the International Organization for Standardization (ISO) Guide to expression of uncertainty in measurement [3]. This process allows uniformity and intercomparability of measurements on different satellite platforms in space simultaneously as well as in different times spanning decades as needed for climate observations. In Section 2, we will discuss further SI traceability and best practice for pre-launch characterization and calibration of sensors for achieving the measurement accuracy goals on-orbit. In Section 3, the infrared standards and transfer radiometers at NIST for SI traceability are discussed. In Section 4, the intercomparison of blackbody targets in a workshop at Miami for radiometers measuring sea surface temperature and the characterization of blackbody used for the GOES Imager calibration at ITT, Fort Wayne, Indiana are described as illustrations of best practice. Concluding remarks are given in Section 5.

Table 1. Required accuracies and stabilities for climate variable data sets. Column labeled signal indicates the type of climate signal used to determine the measurement requirements.

	Signal	**Accuracy**	**Stability(per decade)**
SOLAR IRRADIANCE, EARTH RADIATION BUDGET, AND CLOUD VARIABLES			
Solar irradiance	Forcing	1.5 W/m^2	0.3 W/m^2
Surface albedo	Forcing	0.01	0.002
Downward longwave flux: Surface	Feedback	1 W/m^2	0.2 W/m^2
Downward shortwave radiation: Surface	Feedback	1 W/m^2	0.3 W/m^2
Net solar radiation: Top of atmosphere	Feedback	1 W/m^2	0.3 W/m^2
Outgoing longwave radiation: Top of atmosphere	Feedback	1 W/m^2	0.2 W/m^2
Cloud base height	Feedback	0.5 km	0.1 km
Cloud cover (Fraction of sky covered)	Feedback	0.01	0.003
Cloud particle size distribution	Feedback	TBD*	TBD*
Cloud effective particle size	Forcing: Water Feedback: Ice	Water: 10 % Ice: 20 %	Water: 2 % Ice: 4 %
Cloud ice water path	Feedback	25 %	5 %
Cloud liquid water path	Feedback	0.025 mm	0.005 mm
Cloud optical thickness	Feedback	10 %	2 %
Cloud top height	Feedback	150 m	30 m
Cloud top pressure	Feedback	15 hPa	3 hPa
Cloud top temperature	Feedback	1 K/cloud emissivity	0.2 K/cloud emissivity
Spectrally resolved thermal radiance	Forcing/ climate change	0.1 K	0.04 K
ATMOSPHERIC VARIABLES			
Temperature			
Troposphere	Climate change	0.5 K	0.04 K
Stratosphere	Climate change	0.5 K	0.08 K
Water-vapor	Climate change	5 %	0.26 %
Ozone			
Total column	Expected trend	3 %	0.2 %
Stratosphere	Expected trend	5 %	0.6 %
Troposphere	Expected trend	10 %	1.0 %
Aerosols			
Optical depth (troposphere/ stratosphere)	Forcing	0.01/0.01	0.005/ 0.005
Single scatter albedo (troposphere)	Forcing	0.03	0.015
Effective radius (troposphere /stratosphere)	Forcing	greater of 0.1 μm or 10 % of particle size / 0.1 μm	greater of 0.05 μm or 5 % of particle size / 0.05 μm
Precipitation		0.125 mm/h	0.003 mm/h

Carbon dioxide	Forcing/ Sources-sinks	0.001 % by volume /0.001 % by volume	0.00028 % by volume/0.0001 % by volume
SURFACE VARIABLES			
Ocean color		5 %	1 %
Sea surface temperature	Climate change	0.1 K	0.04 K
Sea ice area	Forcing	5 %	4 %
Snow cover	Forcing	5 %	4 %
Vegetation	Past trend	3 %	1 %

* To be determined

Table 2. Required accuracies and stabilities of satellite instruments to meet requirements of Table 1. The instrument column indicates the type of instrument used to make the measurement.

	Instrument	**Accuracy**	**Stability (per decade)**
SOLAR IRRADIANCE, EARTH RADIATION BUDGET, AND CLOUD VARIABLES			
Solar irradiance	Radiometer	1.5 W/m^2	0.3 W/m^2
Surface albedo	Vis radiometer	5 %	1 %
Downward longwave flux: Surface	IR spectrometer and Vis/IR radiometer	See tropospheric temperature, water-vapor, cloud base height, and cloud cover	See tropospheric temperature, water-vapor, cloud base height, and cloud cover
Downward shortwave radiation: Surface	Broad band solar and Vis/IR radiometer	See net solar radiation: TOA, cloud particle effective size, cloud optical depth, cloud top height, and water-vapor	See net solar radiation: TOA, cloud particle effective size, cloud optical depth, cloud top height, and water-vapor
Net solar radiation: Top of atmosphere	Broad band solar	1 W/m^2	0.3 W/m^2
Outgoing longwave radiation: Top of atmosphere	Broad band IR	1 W/m^2	0.2 W/m^2
Cloud base height	Vis/IR radiometer	1 K	0.2 K
Cloud cover (Fraction of sky covered)	Vis/IR radiometer	See cloud optical thickness and cloud to temperature	See cloud optical thickness and cloud to temperature
Cloud particle size distribution	Vis/IR radiometer	TBD*	TBD*
Cloud effective particle size	Vis/IR radiometer	3.7 μm: Water, 5 %; Ice, 10 % 1.6μm: Water, 2.5 %; Ice, 5 %	3.7 μm: Water, 1 %; Ice, 2 % 1.6μm: Water, 0.5 %; Ice, 1 %
Cloud ice water path	Vis/IR radiometer	TBD*	TBD*
Cloud liquid water path	Microwave and Vis/IR radiometer	Microwave: 0.3 K Vis/IR: see cloud optical thickness and cloud top height	Microwave: 0.1 K Vis/IR: see cloud optical thickness and cloud top height
Cloud optical thickness	Vis radiometer	5 %	1 %
Cloud top height	IR radiometer	1 K	0.2 K
Cloud top pressure	IR radiometer	1 K	0.2 K
Cloud top temperature	IR radiometer	1 K	0.2 K

Spectrally resolved thermal radiance	IR spectroradiometer	0.1 K	0.04 K
ATMOSPHERIC VARIABLES			
Temperature			
Troposphere	MW or IR radiometer	0.5 K	0.04 K
Stratosphere	MW or IR radiometer	1 K	0.08 K
Water-vapor	MW radiometer IR radiometer	1.0 K 1.0 K	0.08 K 0.03 K
Ozone			
Total column	UV/VIS spectrometer	2 % (λ independent), 1 % (λ dependent)	0.2 %
Stratosphere	UV/VIS spectrometer	3 %	0.6 %
Troposphere	UV/VIS spectrometer	3 %	0.1 %
Aerosols	VIS polarimeter	Radiometric: 3 % Polarimetric: 0.5 %	Radiometric: 1.5 % Polarimetric: 0.25 %
Precipitation	MW radiometer	1.25 K	0.03 K
Carbon dioxide	IR radiometer	3 %	Forcing: 1 %; Sources/ sinks: 0.25 %
SURFACE VARIABLES			
Ocean color	VIS radiometer	5 %	1 %
Sea surface temperature	IR radiometer	0.1 K	0.01 K
	MW radiometer	0.03 K	0.01 K
Sea ice area	VIS radiometer	12 %	10 %
Snow cover	VIS radiometer	12 %	10 %
Vegetation	VIS radiometer	2 %	0.80 %

* To be determined

2. SI TRACEABILITY AND BEST PRACTICE

The question often raised is, what is the difference between having SI traceability as a requirement versus not having that stated in the requirements? The difference is such a requirement specifically mandates that the characterizations and calibrations are to be performed against standards traceable to the SI. Also, the uncertainties are to be carefully evaluated, tabulated component by component, and the total uncertainty budget is to be made transparent for peer review and independent critical analysis. There are two kinds of uncertainties to be evaluated according to the ISO Guide [3] called Type A and Type B. Type A uncertainties are basically the random type and represent the uncertainty in the repeatability of measurements. In general, because of good environmental control on the instrumentation and computer acquisition and analysis of the data at a fast rate, the random uncertainties can be made very small in the pre-launch phase. However, these uncertainties have to be re-characterized post launch and periodically re-assessed on orbit using space view of the sensor. While on orbit there may be good repeatability on a short time interval of measurements, in a long time series of measurements the sensor may have a drift due to its degradation in the space environment. This is a systematic effect which could be corrected if it could be measured or scientifically estimated. Such an effect or its correction will have an uncertainty that must be estimated based on the ISO guide. Such systematic uncertainties evaluated in the characterization of various parts of the sensor system are called Type B uncertainties and they are also to be evaluated in the pre-launch and post-launch phases. The square root of sum of squares (RSS) of these two types of uncertainties gives the combined standard uncertainty, u_c and an expanded uncertainty $U_p = k_p u_c$ where k_p is called the coverage factor. For a normal distribution, the level of confidence p for $k_p = 1$ corresponds to 68.27 %. In the remote sensing terminology the ability of the sensor to maintain its repeatability over a period of time is called the stability of the sensor and the accuracy is a measure of the standard uncertainty of the combined result. Accuracy is dominated by the systematic uncertainties and especially by the bias, that is, the difference between the measured value and the true value [1, 2]. These concepts are further elaborated and discussed in the rest of the paper.

The best practice to achieve the stability and accuracy requirements are presented in two parts. The first part deals with pre-launch sensor characterization and calibration. The second part deals with pre-launch preparation for post launch activity for achieving on-orbit SI traceability.

2.1 Pre-launch Characterization/Calibration of Instruments

Figure 1 shows the three step process for the pre-launch effort. The first step is to determine the mission and calibration requirements. It is ideal to have radiometric experts from National Metrology Institutes (NMIs) such as NIST involved in the deliberations on radiometric accuracy requirements and availability of SI standards for calibrations. For example, the variables in Tables 1 and 2 are linked in their role in the energetics of the climate system.

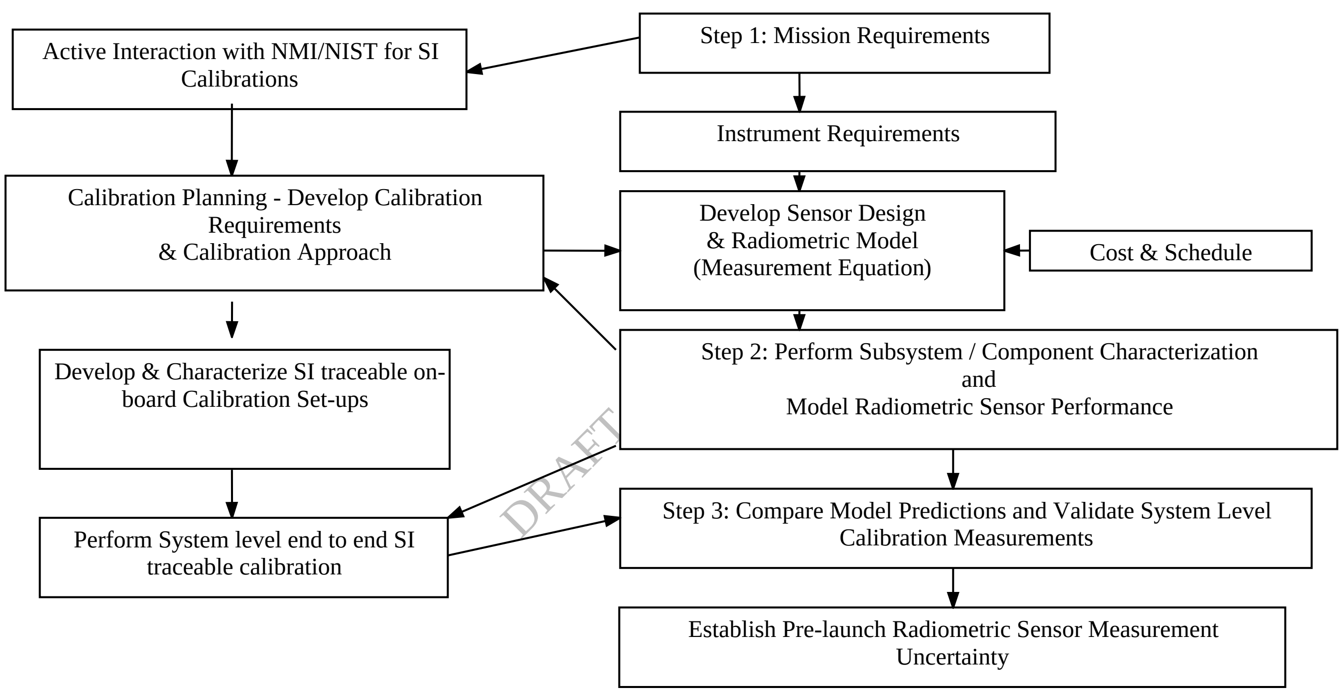


Fig. 1. Summary Steps of Best Practice in Pre-Launch Calibration.

Accurate measurements of solar irradiance are key to defining climate radiative forcing, and its accuracy requirements are specified in that context. Deliberations at the workshop in November 2002 [1] between climate modelers, calibration experts, and principal investigators of various satellite missions resulted in development of those requirements. Such stringent requirements for climate demand improvement of capabilities at the NMIs to provide SI traceable standards to meet those requirements for pre-launch calibrations. The mission requirements are generally specified at the product level, and the development of instrument design and radiometric models with predictions of uncertainties are left to the contractors who compete to fulfill the requirements of the mission. Again, the involvement of experts from NMIs in the calibration planning with mission scientists will help to specify calibration requirements and approaches for testing SI traceability, in the requisition for proposals. Such an interaction between NIST radiometric experts and NASA project scientists took place (although not as ideally as suggested here) for the Earth Observing System (EOS) instruments in various platforms and provided rich experience with lessons learned for dealing with future missions. Currently such an interaction is being actively pursued with the Visible/Infrared Imager Radiometer Suite (VIIRS) and Cross-track Infrared Sounder (CrIS) instruments for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP). Also, interaction with NIST for the Advanced Baseline Imager (ABI) instrument in the **Geostationary Operational Environmental Satellite-R Series (GOES-R) program** of NOAA and NASA is being established. An active interaction has just been initiated with NIST for the incubator projects for the Climate Absolute Radiance and Refractivity Observations (CLARREO) project at NASA.

The selection of SI traceable transfer radiometers from NIST depends upon the accuracy requirements of the mission and radiometric experts can help define the specifications well. Sometimes the specifications are very vague like "absolute radiance accuracy < 5 % required". It doesn't state the desired level of confidence. In other words, is this 5 % at coverage factor, k_p=1, k_p=2 or k_p=3 level? For example, Table 3 shows the uncertainty requirement for the sensor and corresponding requirement for the SI traceable transfer standard to meet such an accuracy requirement assuming a normal probability distribution. The transfer standard needed to meet the requirement will be different based on the interpretation. Generally transfer standards having uncertainties below the 1 % level require careful planning since the calibrations will involve uncertainties close to those attainable by NMI SI standards.

Table 3. Required Level of Confidence vs Instrument and Transfer Standard Uncertainties. (k_p is the coverage factor.)

Required Level of Confidence	Instrument Calibration Goal	Instrument Uncertainty (u_I)	Transfer Standard Uncertainty (u_T)
68.26 % (k_p =1)	u_c (5 %)	u_I (4.33 %)	u_T (2.5 %)
95.44 % (k_p =2)	u_c (2.5 %)	u_I (2.29 %)	u_T (1 %)
99.74 % (k_p =3)	u_c (1.67 %)	u_I (1.33 %)	u_T (1 %)

Step 2 shown in Fig. 1, is component and subsystem characterization and modeling the sensor performance. As discussed in Ref.4, characterization involves determining the component, sub-system, and system level instrumentation responses for various operating and viewing conditions on orbit emulated in the laboratory. The sensor performance is modeled based on the sensor measurement equation. It describes all the influencing parameters on the sensor responsivity. The influencing parameters are of broadly radiometric, spectral and spatial categories. The radiometric detector characteristics, like linearity, stability, and cross talk, spectral characteristics such as responsivity, stability and accuracy, and spatial characteristics such as pointing, spatial and angular responsivity etc. are to be characterized. It is best to follow the axiom "Test as you fly". That means it is important to have these characterizations performed at the environmental conditions such as temperature and vacuum as will be on orbit. However, cost and schedule are to be evaluated and characterizations are to be planned accordingly to meet the requirements. Often NMIs like NIST are well equipped to perform critical component evaluations and subsystem testing independently to confirm the sensor model, corrections and uncertainties. It is highly recommended to take advantage of such capabilities and expertise to get critical measurements done and gain high degree of confidence in building the sensor model. There are standard measurement equations that are given in Ref. 4 for the measurement of radiance, irradiance, or BRDF. As an example the output of a sensor measuring radiance in digital units can be written in a simplified equation

$$DN_{i,j} = G \cdot A_{i,j} \cdot \Omega \cdot L(\lambda) \cdot \Delta\lambda \cdot \eta \cdot \tau \cdot t, \qquad (1)$$

where $DN_{i,j}$ is the digital number output by instrument detector i in band j, G is the instrument detector plus digitization gain, $L(\lambda)$ is the spectral radiance at the instrument entrance aperture, $A_{i,j}$ is the area of detector i in band j, Ω is the instrument acceptance solid angle, $\Delta\lambda$ is the bandwidth, η is the detector quantum efficiency in electrons per incident photon, t is the integration time, τ is the instrument optical transmission. Instrument response non-linearity, background, focal plane temperature effects, and response versus scan angle effects are not shown in Eq. 1. These quantities are determined in pre-launch instrument characterization tests and are incorporated in instrument radiometric models and in the production of measured radiances.

Eq. 1. can be re-written as

$$L(\lambda) = DN_{i,j} \cdot m, \qquad (2)$$

where

$$m = \frac{1}{G \cdot A_{i,j} \cdot \Omega \cdot \Delta\lambda \cdot \eta \cdot \tau \cdot t} \qquad (3)$$

is the inverse of the product of the instrument responsivity and gain. For Step 3 shown in Fig. 1, *m* is determined pre-launch for an end-to-end remote sensing instrument by viewing uniform sources of known radiance, such as well-characterized and calibrated integrating sphere sources and blackbodies. The characterization of integrating spheres and blackbodies using SI traceable standards at NIST has been the hallmark of interaction between NIST and NASA for many of the EOS instruments such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) pre-launch sensor level calibrations. Such interactions also took place between NIST and NOAA in the past and lessons learned will be discussed in later sections of this report.

The quantity, *m*, can also be determined pre-launch through component and subsystem characterization measurements of quantities such as mirror reflectance, polarization responsivity, spectral radiance responsivity. These subsystem level characterization measurements are used as input to instrument radiometric sensor models used to validate the system level pre-launch calibration and in the calculation of instrument measurement uncertainty as shown as the final result of Part 1 of the best practice.

The quantity, *m*, in Eq. 3 is monitored on-orbit using stable, uniform on-board sources of known radiance. Again, on-board blackbody sources or artifacts like solar diffusers for BRDF measurements are to be developed and characterized as SI traceable standards using the expertise at NMIs like NIST as identified in Fig. 1 in Steps 2 and 3 of the best practice.

2.2 Pre-launch Preparation for Post-Launch Sensor Performance Assessments

Preparation for post launch assessments of measurements and uncertainties is Part 2 of the best practice that is to be simultaneously undertaken during pre-launch preparations.

2.2.1. Plan for component performance reassessments.

One of the lessons learned at NIST in previous interactions with NASA and NOAA is that some of the sensor data problems on orbit could not be isolated fully because no duplicates or even samples of components were available for reexamination. Duplicates of filters, apertures, mirror samples, diffusers etc. are very valuable to have for reexamination at the metrology laboratories where high accuracy data can be obtained simulating the space environment and conditions of on-orbit operation to sort out data discrepancies. For example, the band edge wavelength of filter transmission is temperature dependent and it could be re-measured to understand on-orbit data. At NOAA, in the case of both GOES sounder on GOES – N and High Resolution Infrared Sounder (HIRS) on Polar Operational Environmental Satellites (POES) NOAA –N programs, a large discrepancy as high as 6K was observed between measured radiance of on-orbit blackbody and that calculated using the pre-launch vendor supplied spectral response function (SRF) of the sensor. This affected the on-orbit product retrieval and assimilation of Numerical Weather Prediction Models because the atmospheric quantity of interest is determined by varying it to make calculated radiances match with observed atmospheric radiances. The calculated radiance is essentially a convolution of the SRF with the monochromatic radiances from radiative transfer computation. Therefore, as a first step NOAA employed NIST to make independent measurements of SRFs of witness samples of filters of on-orbit GOES sounders. In the affected channels of GOES -8 and GOES-10 sounders, NIST measurements done at the on-orbit operational temperature conditions disagreed with SRFs in use by NOAA and also were found to be more consistent with on-orbit radiance observations at known blackbody temperatures, thus explaining the possible discrepancy. However, the NIST measurements on witness filters were so different compared to those used at NOAA, the vendor expressed doubts on the witness samples as being authentic. A similar investigation was carried out on HIRS filters to compare vendor measurements and NIST measurements. Again, there were noticeable discrepancies and NOAA analysis showed such discrepancies affect product retrievals and their inferences on weather prediction models. As a lesson learned from this interaction, it is essential to have SRFs measured at simulated on-orbit operating conditions and they should be independently verified with authentic witness samples. In another program at NASA, the only best representative apertures of a sensor on orbit were lost in the shipment to NIST, compromising the results of a comparison of aperture area determinations among similar sensors on orbit. So one simple best practice based on all these lessons learned is that each satellite mission at least should require duplicates of critical components of their radiometric instruments for future on-orbit data reassessments.

2.2.2. Pre-launch and post launch validation and SI traceability.

The best plan for validation of sensor performance includes the algorithms for product retrieval from radiance data. It is becoming possible to project scenes that are radiometrically calibrated [5]. It is achieved by using a light source and a Digital Micromirror Device (DMD) to project a scene of interest as shown in Fig. 2.

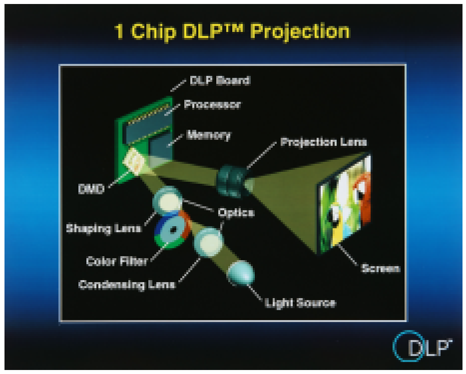


Fig. 2. Digital Light Processor (DLP) projector technology to project appropriate scenes that are radiometrically calibrated using NIST standards.

Such image data could be projected to the sensor and thus preflight validation could be emulated with on-orbit sensor data samples. As the accuracies of validation equipment improve, such an exercise could help evaluate the sensor accuracy more realistically. Also, post launch validation should be planned using land sites of known radiometric characterization. For satellites like the Advanced Very High Resolution Radiometer (AVHRR) such sites essentially provide what is called vicarious calibration. The Working Group on Calibration and Validation (WGCV) of the Committee on Earth Observing Satellites (CEOS) is identifying suitable SI traceable sites and their characteristics for on orbit sensor validations and vicarious calibrations for sensors across the world [6]. CEOS WGCV members are working with NMIs like NIST in U.S.A. and National Physical Laboratory (NPL) in Britain in this effort. One of such sites selected is the moon as an on-orbit stability monitor for the Visible and near IR spectral region up to 2.5 micrometers. The SeaWIfs and MODIS sensors currently on-orbit have been successfully viewing the moon as a stability monitor. One of the recommendations of the ASIC3 workshop is that necessary lunar observations are to be carried out to make the moon an SI traceable absolute source for on-orbit satellite calibrations [2].

There are programs at NASA and NOAA to provide high altitude aerial platforms with radiometrically calibrated sensors for validation of satellite sensor data by simultaneously observing the satellite footprint of earth's atmosphere [7]. The University of Wisconsin Scanning Hyperspectral Imaging Spectrometer (HIS) is an example. Recently, the SI traceability of the Scanning HIS has been verified by utilizing the NIST Thermal-infrared Transfer Radiometer (TXR) to view the scanning HIS laboratory standard blackbody source.

2.2.3. On-orbit Inter-comparisons and SI traceability.

It is best to have inter-comparisons of similar sensors on orbit to assess consistency in data and sensor performance. Such inter-comparisons are possible when both sensors being intercompared are SI traceable on orbit. Intercomparison of on-orbit sensors has become possible with the technique of Simultaneous Nadir Observations (SNO) when both satellites observe the same foot print at the time they cross each other in their orbits [8]. In order to bring self consistency and intercalibration of sensors across the world, a group called Global Satellite Inter-Comparison System (GSICS) formed and is actively pursuing SI traceability for intercalibrations working with NMIs like NIST. Intercomparisons may show good agreement or disagreement between sensors in their radiance measurements. In either case lessons will be learned on possible systematic effects that are ignored or neglected. As the true value of the measurand on orbit will always be an unknown quantity the accuracy of the measurement can best be assessed by combining the results from different SI traceable sensors and calculating the uncertainty of that Combined Reference Value (CRV) based on the individual sensor data [9]. The CRV and the estimate of its uncertainty in the time series will allow scientists to look into methods to minimize uncertainties and achieve the stated accuracy requirements by using the lessons learned through intercomparisons.

3. IR STANDARDS AT NIST FOR SI TRACEABILITY

The optical radiation measurements are generally referenced to one of two SI scales: optical power in watts or thermodynamic temperature in kelvin. The radiance or irradiance scale is derived from the measurement of optical watt in terms of an equivalent electrical watt achieved by the use of cryogenic radiometers. The temperature scale is derived from the triple point of water. The SI unit kelvin is defined as 1/273.16 of the thermodynamic temperature of the triple point of water. The temperature at that point is defined as 0.01 ^{0}C in the commonly used Celsius scale.

At NIST, the Optical Technology Division realizes and maintains the unit of optical power (watt) using a custom built state of the art electrical substitution radiometer, called the Primary Optical Watt Radiometer (POWR), as shown schematically in Fig. 3. It is operated at 2 K or 4.2 K to minimize background effects. Its dynamic range is 1 µW to 1 mW in measuring optical power from intensity stabilized lasers. The standard uncertainty achieved in POWR measurements is at 0.02 % level [10]. Silicon trap detectors which have absolute quantum efficiency close to unity are used to transfer the power scale from POWR to other cryogenic radiometers or detectors. The standard uncertainty for such transfers is 0.02 % to 0.04 % [10].

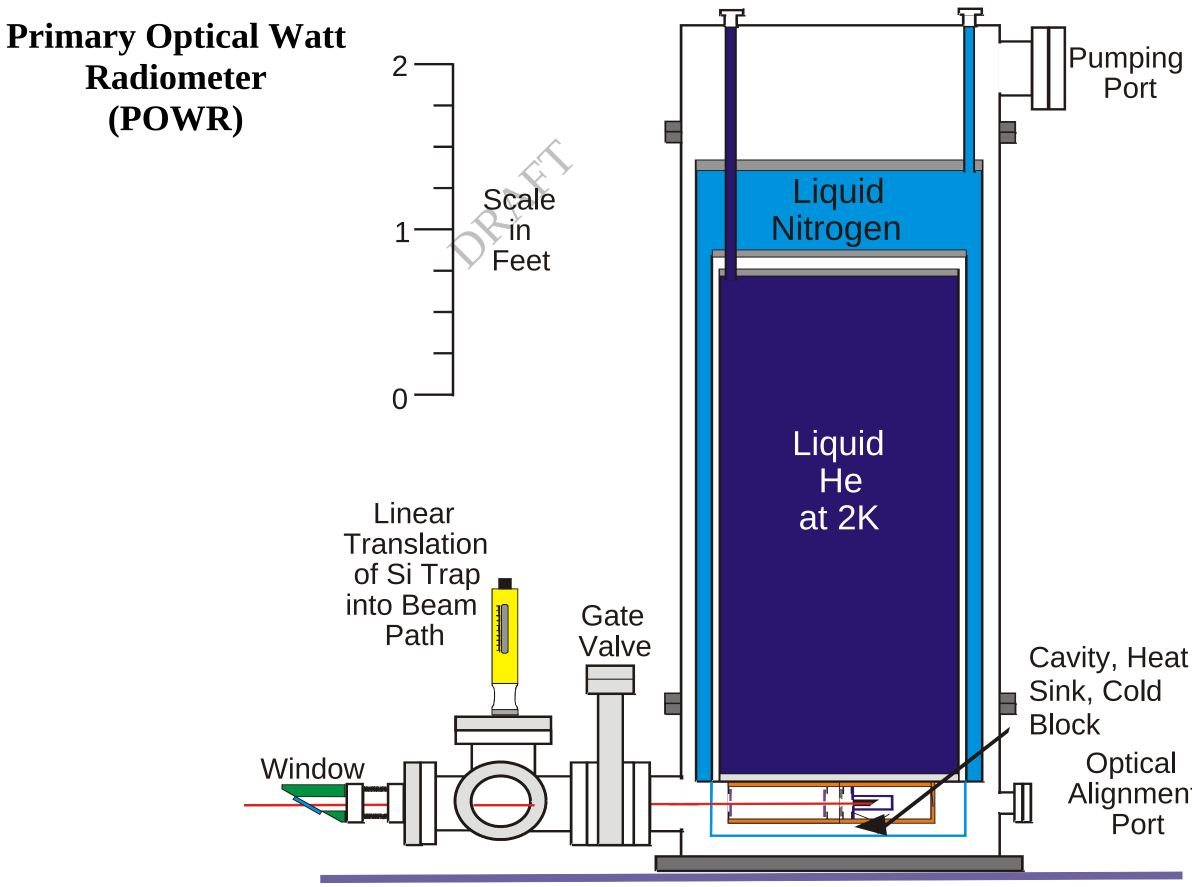


Fig. 3. NIST primary standard for optical power measurements, Primary Optical Watt Radiometer, POWR.

In order to calibrate detectors and radiometers for spectral irradiance responsivity and spectral radiance responsivity from the UV to the IR, a facility called SIRCUS is available at NIST and is shown in Fig. 4. SIRCUS stands for Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources. In this facility, tunable lasers covering the wavelength range from 210 nm to 5.3 µm are coupled to integrating spheres to produce either uniform irradiance at a reference plane or uniform radiance within the sphere exit port at high levels. Detectors are calibrated directly against reference standards such as the trap detectors referenced earlier. Lasers ultimately determine the spectral coverage available at SIRCUS, while the uncertainties achievable are in the 0.1 % level [11] for the visible and at few percent levels for the infrared detector calibrations [12]. There are two separate SIRCUS facilities, one to cover the UV-Vis-NIR spectral region, and the other to cover the IR from 700 nm to 5.3 µm, and discrete lasers extend the spectral coverage to 10 µm. A portable, table-top, tunable laser system, complete with integrating spheres and transfer standard detectors, called Traveling SIRCUS to cover UV-Vis-NIR region is available at NIST to visit customer facilities and provide on-site calibrations. It has been sent to NASA, NOAA, and United States Geological Survey (USGS) sites to characterize instruments.

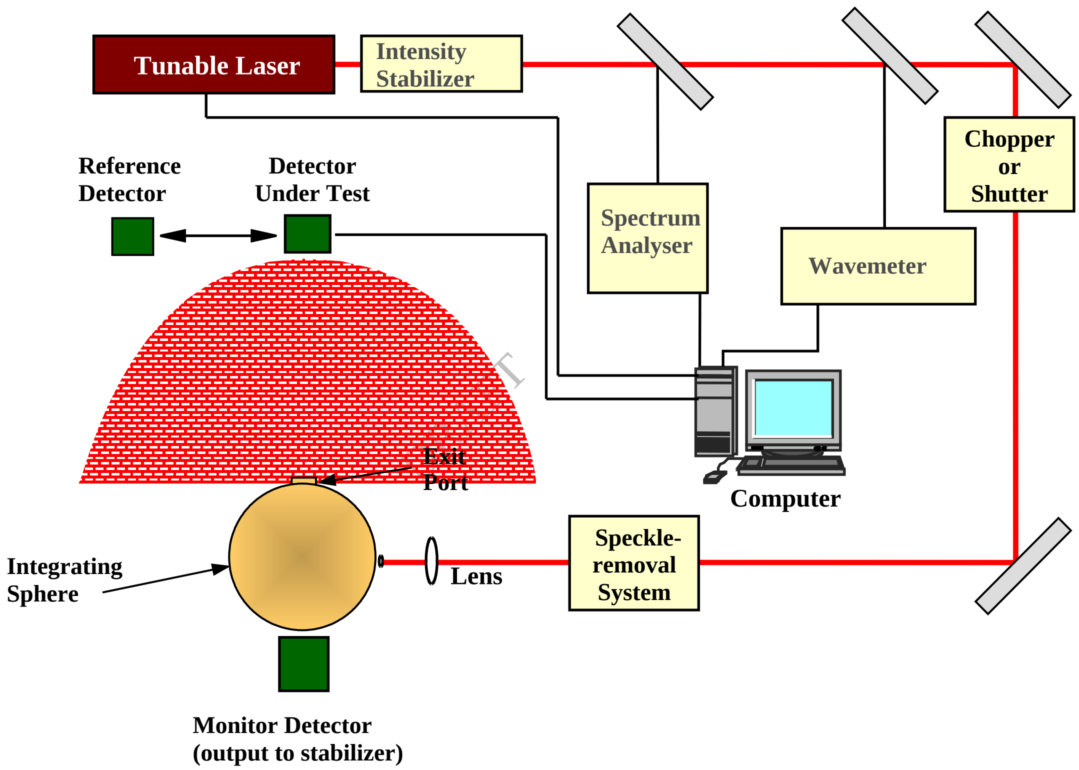
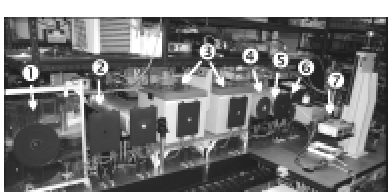


Fig. 4. Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) Facility at NIST

The kelvin thermodynamic temperature scale is realized through melting points of various pure metals as defined in the International temperature Scale of 1990 (ITS-90) [13]. At NIST these blackbodies are used to calibrate standard platinum resistance thermometers (SPRT) to cover the temperature range from 15 ^{0}C to 170 ^{0}C and standard gold-platinum thermocouples to cover the range from 400 ^{0}C to 900 ^{0}C. These temperature sensors are used in the ideal blackbodies such as the water bath, cesium heat pipe, and others to provide SI traceable calibrations of radiance temperature and radiance using a transfer standard spectroradiometer. These heat pipe blackbodies and various fixed point blackbodies for radiance temperature measurements and radiometers and pyrometers at the Advanced Infrared Radiometry and Imaging (AIRI) Facility at NIST are shown in Figs. 5a. and 5b. The AIRI facility allows realization of uncertainties in the 50 mK range in the radiance temperature calibrations.



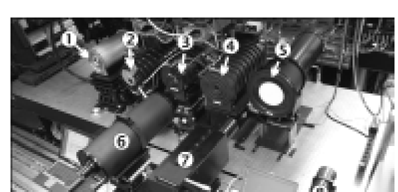


Fig. 5a **Fig. 5b**

Fig. 5a. Variable temperature heat pipe Blackbodies (BB) at the AIRI Facility: 1. Controlled Background Plate for Unit Under Test; 2. Ammonia BB (-50 °C to 50 °C), 3. Water Bath BB (15 °C to 75 °C), 4.water heat pipe BB (60 °C to 250 °C), 5.Cs heat pipe BB (300 °C to 650 °C) and 6. Na heat pipe BB (500 °C to 1100 °C), 7. spectral comparator (3µm to 14.8 µm)

Fig. 5b. Fixed Point Blackbody (BB) Bench of the AIRI Facility: 1.Ga BB; 2. High T Furnace #1 (Al, Ag and Au), 3. Low T Furnace (In, Sn and Zn), 4.High T Furnace #2 (Al and Ag), 5.Out-of-Field Scatter Tool, 6. NIST Transfer Standard Pyrometer RT1550L (150 °C to 1064 °C), 7. NIST Transfer Standard Pyrometer RT900 (600 °C and higher), 8. Transfer Standard Pyrometer TRT (- 50 °C to 300 °C)

3.1. IR Radiometers at NIST to provide SI traceability

Radiometers have been built at NIST and calibration protocols have been established for deployment at customer sites to provide SI traceable calibrations. Two such radiometers, the TXR and the radiometer built to support Ballistic Missile Defense programs (BXR) for infrared calibrations are described below.

3.1.1. TXR.

NIST developed the TXR in support of NASA's Earth Observing System (EOS) program and its deployment at the customer site is in line with the best practice advocated earlier in Section 2.1. The TXR measures radiance scales in the thermal-infrared spectral region for satellite sensors calibrated by extended area blackbody sources at customer sites [14]. The TXR is a portable two channel radiometer, with one channel at 5 µm using a photovoltaic InSb detector and the other at 10 µm using a photovoltaic MCT detector. It has a self-contained vacuum jacket and liquid nitrogen (LN_2) reservoir. It can be used for radiance scale verifications of blackbody sources either in cryogenic vacuum chambers or in ambient conditions. The standard uncertainty for radiance measurements using the TXR is of the order of 0.2 % (k=1) or better. In terms of radiance temperature deduced from TXR measurements for blackbodies operated between 200 K to 350 K, the uncertainty is in the 50 mK (k=1) range. The TXR can be used to measure emitted radiance as well as, with special setups, the reflected radiances from the blackbody. From such measurements the blackbody emissivity can be deduced. In a deployment at Raytheon Santa Barbara Remote Sensing, the TXR characterized the blackbody calibration source (BCS) that was used to calibrate NASA's MODIS sensor. The measurements verified the emissivity to the 0.001 % level and the emitted radiance scale was found to be in agreement with the NIST scale with no corrections needed. The TXR calibration at NIST is carried out by using several methods. One method uses at the system level the ambient background water bath blackbody or a Large Area Black Body (LABB) for the absolute calibration. Another method still under development is a system-level approach using a laser-illuminated integrating sphere at the NIST IR SIRCUS described in Section 3. The TXR has been successfully deployed about six times during the past several years to several different aerospace calibration facilities for in-situ measurements of various sources in space-simulating chambers. These measurements were used to verify the infrared radiance scales currently used by several NASA, NOAA, DOE, and DOD satellite programs. The results of a deployment of TXR to the GOES calibration chamber at the contractor (ITT) site in Ft. Wayne, IN in 2001is reviewed in Section 4 as an illustration of best practice.

3.1.2. FTXR and MDXR.

The Fourier-transform Thermal-infrared Transfer Radiometer (FTXR) is a spectroradiometer system designed to measure spectral radiance in the infrared. The original motivation for its use at NIST was to improve upon the spectral coverage of the TXR for comparisons of extended-area blackbodies such as those used to calibrate Earth-observing satellite and validation instruments. The spectral coverage of the FTXR for use in viewing such blackbodies is 800 cm-1 to 12000 cm-1 using both an MCT and an InSb detector. Both of these detectors are used at the same time, since the FTXR has two detector ports that share a common input port, and their spectra are concatenated to provide the full spectral range. It is based on a four port Michelson interferometer. It has corner cubes and flexture mounts, for a spectral resolution of about

1 cm/sec corresponding to a spectral resolution of roughly 1 cm-1. The scale of the FTXR can in principle be derived from the NIST Water Bath Blackbody (WBBB) rather than the on-board blackbodies. The FTXR is designed to operate in ambient environments, so it needs to look through a window to view blackbodies in vacuum chambers. In such an arrangement one has to limit observations to atmospheric transmission regions of the IR spectrum unless a very good purge arrangement is available. Also the window transmission, reflection, and stray light introduces extra systematic uncertainties. Therefore, a new radiometer called the Missile Defense Transfer Radiometer (MDXR) is under construction to mitigate these problems. The MDXR will have the capabilities of the TXR and also is equipped with a cryogenic Fourier transform spectrometer to cover the wavelength of interest, a cryogenic radiometer traceable to POWR, and a blackbody calibrated at the NIST Low Background Infrared (LBIR) facility. A vacuum compatible fluid bath blackbody is also under construction to provide kelvin scale calibration. The MDXR will also be self-contained to serve user facilities in both radiance and irradiance modes at the power levels that are of interest.

4. ILLUSTRATIONS OF BEST PRACTICE

Two examples of best practice where NIST was involved are described below. One was the laboratory intercomparison of infrared radiometers funded by NOAA/NESDIS, EMETSAT, ESA and NASA in 2001 at the University of Miami's Rosentiel School of Marine and Atmospheric Science (RSMAS). The other one is the TXR deployment for the calibration of the blackbody in the GOES imager test chamber at ITT, Ft. Wayne, Indiana in 2001.

4.1. Miami workshop 2001.

The intercomparison workshop that NIST participated in at the University of Miami in 2001 dealt with the intercomparison of blackbodies used to calibrate radiometers that are deployed on ships to measure sea surface temperature [15]. As NIST employed the TXR for this purpose, this process provided a independent experimental check of the SI traceability of sea surface temperature measurements. Such intercomparisons are highly recommended in this paper as a best practice for SI traceability.

The NIST TXR employed was an ultra-stable, well-characterized filter radiometer [16] in reasonably controlled laboratory conditions to view several cavity blackbodies and measure the brightness temperature of each. The laboratory blackbodies were five in total, one a reference blackbody, the NIST water bath blackbody (WBBB), and four other participating blackbodies (BB): The RSMAS BB, the Jet Propulsion Laboratory (JPL) BB, the Combined Action for the Study of the Ocean Thermal Skin (CASOTS) Rutherford Appleton Laboratory (RAL) BB, and the CASOTS Southampton Oceanography Centre (SOC) BB. All of these were operated independently of each other in the same laboratory at RSMAS during the workshop. Each BB consisted of a conical metal cavity with a black coating on the inside and each was surrounded on the outside by its own stirred fluid bath to improve temperature uniformity. They each had a calibrated thermometer located in the stirred bath, which was used to determine the temperature of the cavity. All cavity exit apertures were of the order of 10 cm to 11 cm in diameter, and all BBs were designed to be horizontally emitting. Beyond these general similarities, these five BBs can be classified into two groups depending on whether the bath temperature has active control or not. The NIST water bath blackbody (WBBB) and the RSMAS BB have active temperature control of the bath and essentially follow a design described previously [17]. The JPL BB, the CASOTS RAL BB, and the CASOTS SOC BB do not have active temperature control and follow another general design described previously [18]. The blackbodies intercompared were designed so that the emissivity is as high as possible even with a relatively large aperture diameter of about 10 cm to 11 cm. The TXR target spot diameter was about 3 cm, so it underviewed these apertures. The TXR was placed sufficiently close to each BB under test such that the TXR 30 mrad field of view was overfilled by the BB aperture.

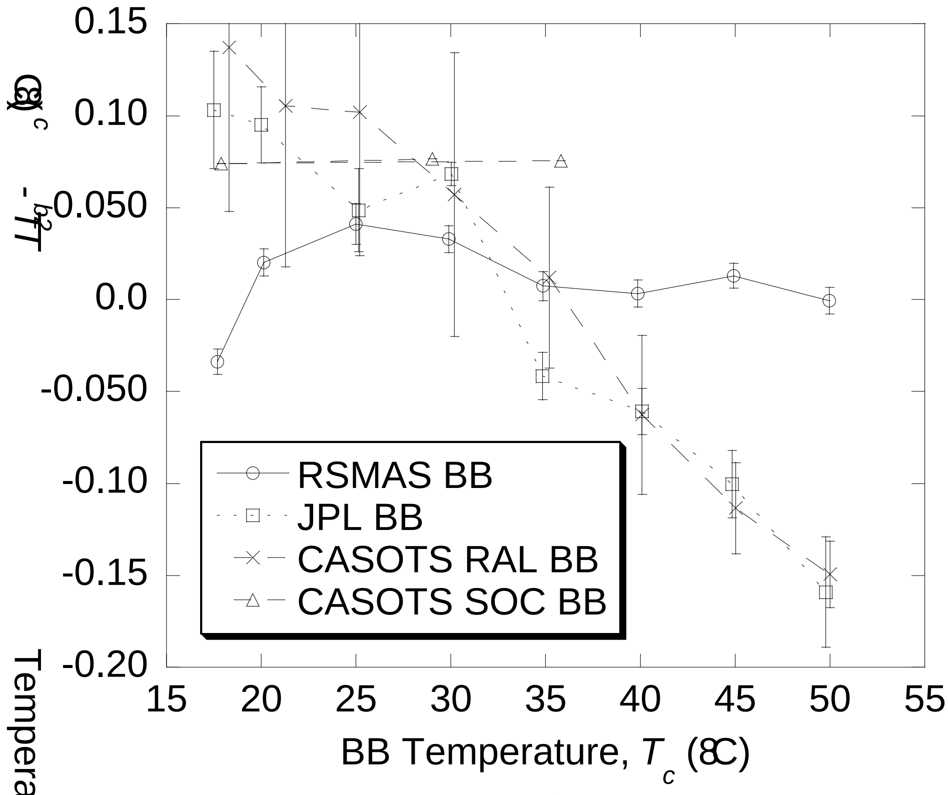


Fig. 6**.** Comparisons are brightness temperature. The symbols are from the mean values of data points averaged over the last 100 seconds of each plateau of the temperature setting for each blackbody. The error bars are the standard deviation of the values over this time interval.

The results of the intercomparison are shown in Fig. 6 in terms of 10- m TXR brightness temperature (T_{b2}) minus contact temperature (T_c) as function of BB temperature for all four participating blackbodies: RSMAS BB, JPL BB, CASOTS RAL BB, and CASOTS SOC BB. The T_c values for each BB are from the user's choice of thermometer placed in the BB water bath. Averages over the last 200 seconds of each plateau interval are reported for all but the CASOTS SOC comparison, and the error bars represent the standard deviation of the 100 readings of this last, most stable interval on the plateau. The RSMAS BB error bars are much lower, down at the stability level of the TXR, since the RSMAS BB was under active temperature control and so its plateaus were very flat with time. For the other blackbodies, the lack of active temperature control over the plateau caused temperature drift to dominate the uncertainty, hence the larger error bars. Plotting only instantaneous points, rather than interval averages, gives similar results.

Figure 6 also shows that the RSMAS BB 10- m brightness temperature agrees with that of the NIST WBBB over the entire range of temperatures studied, to within the 0.05 C (k=2) uncertainty of the TXR. It also shows that the JPL BB and the CASOTS RAL BB agree with the NIST WBBB this well only near 30 C, giving too high a value at lower temperatures and too low a value at higher temperatures. Given that the surrounding ambient temperature was near 30 C, this indicates that these blackbodies have effective emissivity significantly less than unity.

The agreement between the NIST water bath blackbody with a 4 cm aperture and the RSMAS blackbody at any aperture diameter as verified by the TXR 10- m channel is within the noise and fitting uncertainty (about 50 mK, k=2) of the data. The CASOTS RAL and JPL blackbodies did not agree at temperatures away from ambient, although they did agree to within 0.1 C as long as they were near ambient. Effective emissivity values relative to the NIST water bath blackbody were near 0.991 at 10 m for both of these blackbodies. The CASOTS SOC blackbody was not measured carefully enough to draw any definite conclusions. Careful use of these blackbody targets to calibrate ship-based radiometers used in the validation of satellite-derived skin sea-surface temperatures could therefore result in validation data sets that have uncertainties within 0.1 C. This intercomparison also demonstrated some of the verification capabilities that are now available to the environmental remote sensing community with the use of the NIST TXR, and another intercomparison such as this is being planned for 2009 at the University of Miami.

4.2. TXR deployment to ITT for GOES Imager

The NIST thermal-infrared transfer radiometer (TXR) was deployed in the GOES Imager calibration chamber in July of 2001 and performed radiometric measurements of the calibration targets used to calibrate GOES Imager instruments. The GOES Imager emissive band pre-flight absolute calibration is generically similar to most radiometric calbration exercises in that it is based on measurements of the instrument response to two blackbodies held at different temperatures in a space-simulating cryogenic vacuum chamber. Traditionally, the radiance entering the sensor aperture is modeled, starting with the temperature sensors in the warm blackbody, here called the Earth Calibration Target (ECT). As the measurements are performed in a significant thermal-infrared background, correction for background-induced offsets is made by subtracting the response to a liquid-nitrogen temperature blackbody, here called the Space Clamp Target (SCT).

It is believed that the honeycomb surface of the ECT can support substantial temperature gradients, forced by the thermal-infrared background. The GOES calibration model makes a correction for the non-ideal behavior of the ECT. The TXR was deployed to provide independent quantitative verification of this model through careful radiance measurements from the ECT and the SCT.

Within the GOES Imager chamber, the TXR was mounted on a platform in a specially-constructed GOES instrument simulator. The instrument simulator was an aluminum frame structure which supported multilayer insulation. The simulator was designed by ITT to look from the outside as much like a GOES Imager instrument as possible, except that it had the TXR inside instead of an actual GOES instrument. The instrument simulator included an optical port baffle, just as the GOES imager does when in the chamber. This is normally run at one of three temperatures during GOES instrument testing: Mission Low (ML), Mission Nominal (MN), and Mission High (MH). For the TXR deployment, the optical port baffle was run at only the two lowest temperatures: ML and MN. The radiative cooler patch panels, used with a real GOES instrument to provide cooling for the GOES radiative coolers, were also adjusted between ML and MN conditions to the same temperatures that they are set at for real GOES instrument testing. This was all done so as to simulate the radiometric environment existing during a typical GOES instrument calibration. The photograph of the physical set up of TXR in the GOES Imager Test chamber is shown in Fig. 7.

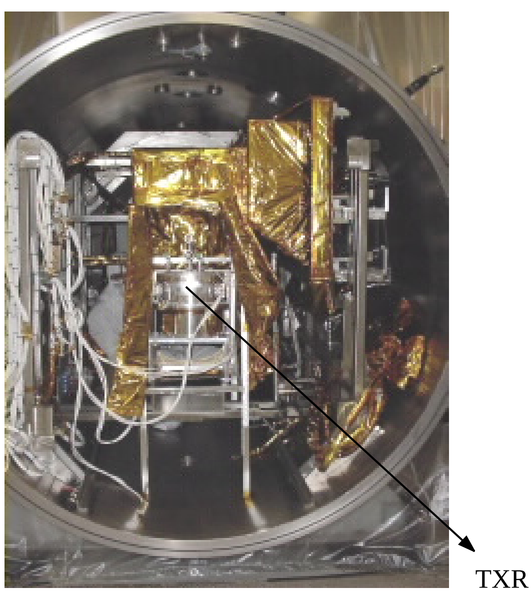


Fig. 7. The TXR in the GOES Imager simulator in the Imager Chamber at ITT. The view is from the back of the TXR. The ECT and SCT sources are located in front of the TXR and so are blocked by the simulator in this view (picture provided by ITT).

There were two main types of tests: TXR response measurements of its internal calibration source (CS), and TXR response measurements to the ECT (or SCT). The response data were collected and analyzed as band-integrated

radiances and compared to that expected for an ideal blackbody. An analysis procedure was developed that enabled parameterization of the results in terms of a non-unity emissivity and a temperature gradient in the GOES Earth Calibration Target (ECT). The model was used to compute the correction to be made to the ECT temperature sensor readings so that the measured results are in agreement with the NIST radiometric scale. Values for the true temperature and ECT emissivity at standard uncertainty levels below 0.1 K and below 0.2%, respectively, were obtained. Recommended values for ECT temperature correction as shown in Fig. 8, were computed based upon a fit of the model to the data. The data agreed qualitatively with the expectations. These data, in the form of an electronic text file, have been provided to ITT to enable the recommended ECT correction to be made. Use of this recommended correction curve will enable GOES calibration model to be more directly traceable to NIST.

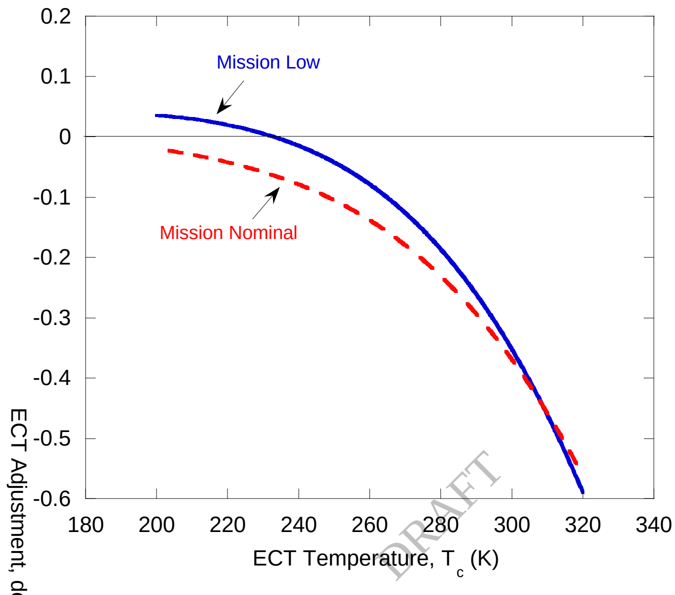


Fig. 8. The recommended ECT adjustment curves, delta *T'* (*T'*) vs. T_c. with T_c defined as the average of all 13 ECT sensors. Correction of the ECT to blackbody radiance requires only these curves and no emissivity adjustment. This is not to say that the emissivity of the ECT was unity. Rather, a value of unity has been historically used for the ECT in the GOES program, so these curves lump the combined effects of non-unity emissivity and temperature error into one temperature depended parameter in order to make the required corrections simpler to implement using the existing GOES calibration algorithms.

5. CONCLUDING REMARKS

Satellite remote sensing has the unique potential to deliver the high accuracy data required to identify the small signals of climate change in a long time series record. The hallmark for accuracy is pre- launch and post-launch SI traceable calibrations of sensor performance. The steps to be taken in pre-launch and post-launch as a best practice are to plan and implement calibration activity from the beginning of the mission, allocating resources as necessary to achieve SI traceability. In this regard it is best to have calibration experts from NMIs involved from the mission start and through the entire life of the mission in various steps as recommended in this paper.

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Certain commercial companies are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and technology (NIST), nor does it imply that they are the best available for the purpose. DMD and DLP are trademarks of Texas Instruments, Inc.

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