1 / 3

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International Space Station Utilization for Radiometric Calibration Support to Earth Remote Sensing Programs

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Abstract. The idea of utilizing the International Space Station (ISS) to provide a platform for manned and maintained NIST/SI traceable standard sensors in the visible, infrared, and microwave spectral regions to augment the spectral calibration of other remote sensing sensors is being well received in the calibration community. Review of the current state of the art in solar monitoring as evidenced by intercomparison between different satellite sensors for total solar irradiance, solar spectral irradiance and measured spectral irradiance versus reference spectra very much proves this point. Analysis of the Microwave Sounding Unit (MSU) radiometer data to deduce global temperature trends also shows the dire need for a better calibration of these instruments flown on sequential satellites to a very high degree of accuracy. In this regard possible radiometric calibration missions on ISS as envisioned by NIST will be discussed. Also the current plan for a feasibility study for these missions on ISS that address issues such as ISS platform dynamics and contamination levels and effects will be discussed.

BACKGROUND

Concern over proposed anthropomorphic climate change has prompted national space agencies to plan more than 70 missions carrying over 200 different instruments over the next 15 years. The United State's major contributions to this effort are the Polar-orbiting Operational Environmental Satellites (POES) and Geostationary Operational Environmental Satellites (GOES) operated by the National Oceanic and Atmospheric Administration (NOAA), the series of satellites in the Earth Science Enterprise (ESE) of the National Aeronautical and Space Administration (NASA), and the next generation meteorological satellites under development as the National Polar-orbiting Operational Environmental Satellite System (NPOESS). These overlapping missions and instruments, covering a wide range of the electromagnetic spectrum, will provide measurements of many parameters of interest to those studying the Earth's environment. These instruments will be of different designs, placing a premium on the pre-launch instrument calibration and post-launch calibration of the in-orbit performance of satellite sensors for intercomparability and continuity of accurate long-term records of geophysical parameters across instrument platforms. Traceability to System International (SI) units is critical for the multi-instrument long term data intercomparability. A major problem in remote sensing is the change in the instrument calibration factors from the earth laboratory to space and the degradation of the sensor performance in the space environment.

Remote Sensing Measurement Requirements

A Spaced Based Radiometry Colloquium was held at the National Institute of Standards and Technology (NIST) on November 12, 1997, which lead to a document entitled "High Accuracy Space-Based Remote Sensing Calibration Requirements" (Murdock,1998). These requirements are summarized in Table 1. The uncertainty requirements for the total solar irradiance and solar spectral irradiance are on the order of 0.01 % since the solar flux (the energy input to the earth system) is known to vary in the 11 year solar cycle by approximately 0.1 %. The quantification of the long-term variability of the solar constant cannot be resolved until the effects of the slow, periodic variations in the measured quantities are characterized and incorporated into solar models so that the natural variability can be quantified and removed (IPCC, 1995). Measurements of the total solar irradiance with uncertainties of 0.01 % are the key to the successful completion of this modeling process. In summary, the uncertainty recommendations of the

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attendees was that the total solar flux and solar spectral irradiance needed to be 0.01%, traceable to SI units, in order to accurately track the known solar variability of 0.1 % per 11 year solar cycle. The requirement for earth scene spectral radiance of 0.2 % are driven by radiometric measurements in the thermal infrared that support earth scene radiance temperature assignments with in 0.1 K, necessary for the detection of global warming. The requirements on lunar and stellar fluxes are driven by the need to develop extraterrestrial sources as secondary standards at the desired uncertainties for earth observing sensors.

TABLE 1. Remote Sensing Measurement Requirements

Remote Sensing Measurement	Required Uncertainty (%)
Total Solar Irradiance	0.01
Solar Spectral Irradiance	0.01
Lunar Spectral Irradiance	0.10
Lunar Spectral Radiance/Phase Model	0.12
Earth Spectral Radiance	0.2
Stellar Irradiance	2.0

The Radiometric Measurement Challenge of Remote Sensing

The assignment of a absolute SI traceable quantity to the electrical signals of a remote sensing sensor is a complicated multistep process from fabrication to calibration through transfer to orbit after launch and long term degradation corrections with operation. The detailed characterization (field of view, linearity spectral properties, polarization, etc.) and calibration (response to a known stimulus) of a sensor are carried out in the laboratory versus SI traceable standards. After launch of the sensor, typically the response of the sensor has changed from the laboratory calibration and the post-launch calibration and characterization of the performance of satellite sensor. is carried out. The post-launch calibration and characterization is typically called the transfer to orbit calibration and is performed after out gassing events are over and the sensor is stabilized. There are two general methods used for the transfer to orbit calibration - the sensor can contain an onboard calibration unit to derive a new sensor calibration, and by a number of vicarious calibration techniques.

In the thermal infrared spectral regions earth observing sounders and imagers have a flat plate internal blackbody calibrator for reference observations. An example of a visible and near infrared sensor with an on board calibrator is the polar orbiting sensor Along-Track Scanning Radiometer (ATSR-2) operated by the European Space Agency (ESA). The ATSR-2 calibration assembly uses the sun as a calibration source and the sensor views the sunlight illuminated Russian opal diffuser for the responsivity (Smith, 1997). In the case of on-board calibration assemblies it is difficult to determine if changes in the instrument response upon transfer to orbit are due to changes in the calibrator or changes in the sensor, or both. This ambiguity necessitates the verification of calibrator performance by vicarious calibration techniques.

There are a number of vicarious calibration methods of sensors in the visible and near infrared spectral region; most of these techniques have been developed for the long running series of sensors in NOAA's POES program (Rao et. al., 1993, 1995, 1996) and NASA's LANDSAT satellite (Slater et. al.,1987). Through long term observation NOAA has determined a number of radiometrically stable desert sites for vicarious calibration activities. From measurements at these sites of surface reflectance, atmospheric optical depth and aerosols, a top of the atmosphere radiance can be calculated with a radiative transfer model (Teillet, et. al., 1990). A second vicarious calibration technique uses the measurement of congruent path radiance (Abel et. al., 1993) of a radiometrically stable site by a high altitude absolutely calibrated sensor. This technique places constraints on the colocation and common viewing geometry of the satellite and the aircraft sensors and requires a small correction to extrapolate to a top of the atmosphere radiance. A third vicarious calibration technique employed is an inter-sensor comparison, where in the case of the NOAA POES satellites two to three of the same type of sensor may be operable, and the same radiometrically stable desert sites are used to cross calibrate similar sensors (Rao et. al., 1995). The cross calibration of sensors with dissimilar spectral and spatial characteristics is more problematic, where current experience has not developed robust procedures to correct for these differences but considerable work is ongoing. The experience of NOAA and NASA in vicarious calibration of sensors indicates that the current level of attainable uncertainty is on the order of 3 - 5 %. A large part of this uncertainty is due to the difference between the modeled atmosphere transmission and surface reflectance and the true parameters. Recent remote sensing earth target field experiments (Thome et. al., 1998) have indicated differences in the standard extraterrestrial solar irradiance, which is the input for the radiative transfer code. SI traceability of the extraterrestrial solar irradiance used in these radiative transfer models is largely unknown. It has been proposed (Kieffer and Wildey, 1996) to use the reflective radiance of the moon as a stable calibration standard for earth observing sensors, but as yet no SI traceable calibration of lunar radiance as a function of lunar libration and phase angle has been completed

There has been a concerted effort (Spencer and Christy, 1990, Prabhakara et. al, 1998, Christy et. al., 1998) to deduce global temperature trends using data from the Microwave Sounding Unit (MSU) on the POES operational satellites. It has been established by (1990) that the MSU data near 53.74 GHz can be used to deduce the global temperature trends because of its weak sensitivity to hydrometeors in the atmosphere and strong sensitivity to the thermal state of the midtroposphere, which closely relates to the earth surface air temperature. The Spencer and Christy analysis estimated the global temperature trend to be near zero (~ 0.03 K) for the time period of 1979 to 1990. However, other conventional methods of tracking temperature trends showed a warming of 0.1 K during the same period. This disagreement led to many critical studies of the data and the analysis (Jones, 1994, Hansen, et. al., 1995, Hurrell and Trenberth, 1998). It is shown by Prabhakara et. al. (1998) that although the basic method of using microwave sounding at 53.74 GHz for global temperature trend determination is valid, there are calibration problems in using the MSU satellite data. In addition, Prabhakara analysis show a warming trend of 0.1 K for that time period, when the data is corrected properly. This disagreement with Christy et. al. (1998) reanalysis is yet to be resolved.

Radiometric Measurement Strategy for Remote Sensing

A solution to problems of lack of SI traceability in the transfer to orbit calibration of sensors and the uncertainties in atmospheric corrections is to deploy a highly calibrated returnable sensor system to cross calibrate orbiting sensors directly. This is a variant of the inter-sensor vicarious calibration strategy discussed earlier. This reference sensor would be calibrated at the lowest achievable uncertainty before and after launch and have on-board calibration stability monitors. This highly calibrated sensor could determine solar irradiance, lunar radiance, or top of the atmosphere radiance directly, and deploy briefly to minimize calibration degradation, providing direct SI traceability for operational sensors over the course of time. This sensor could have near identical spectral characteristics with a sensor in orbit or be hyperspectral in order to calibrate a broad range of similar spectral region sensors. The essence of this concept was the Shuttle Solar Backscatter Ultraviolet (SSBUV) program which underwent eight missions between 1989 and 1996 to verify the calibration of a number of polar orbiting ozone and solar irradiance sensors (Cebula et. al., 1998). Considerable understanding of the performance of the SSBUV was learned by these repeat missions, resulting in the modeling of the instrument performance to achieve an estimated flight to flight calibration uncertainty of 1 %.

A schematic diagram of how such a strategy would work is shown in Fig. 1. The NIST calibrated sensor in Fig. 1 is shown transitioning between NIST and the ISS with a number of possible deployment missions, direct measurements of quantities from extraterrestrial sources such as the sun, moon and stars, or the determination of top of the atmosphere radiance in the observation of earth targets. The schematic depicts the calibrated sensor on the ISS flying in formation with a satellite sensor and concurrent with aircraft observations and surface field observations. In the case of measurements of extraterrestrial sources continuously observing sensors on satellites could use the values of the ISS calibrated radiometer as one point calibration values with degradation functions determined by continuous recalibrations on the extraterrestrial source and repeat missions to ISS would yield repeatability of these determinations. In the case of observations of top of the atmosphere radiance of earth targets, ISS values can be used for calibration of on-orbit sensors and for verification of vicarious calibration methodologies

The Role of NIST

The role of NIST in the ISS deployable sensor strategy is to work with the remote sensing agencies on the design of the sensor to be deployed, and the design and development of the sensor ground calibration facility to transfer to the sensor SI traceability with the lowest achievable uncertainty. NIST scientists would also participate in the design and verification of sensor calibration assemblies to be deployed as calibration stability monitors on ISS sensors. There is strong international interest by other National Measurement Institutes (NMI), such as the Russian

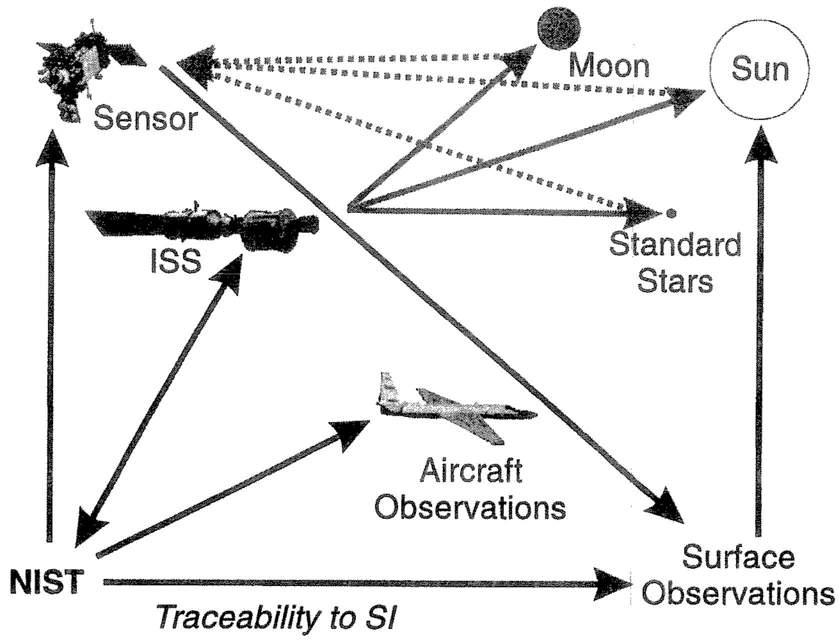

FIGURE 1. Radiometric measurement strategy using returnable highly calibrated radiometers on the ISS for calibration of on orbit sensors.

GOSTANDART agency working with the Russian Space Agency to participate with NIST and U. S. remote sensing space agencies in a sensor calibration program on ISS.

POSSIBLE ISS MISSION OPPORTUNITIES

There are a number of important ISS mission opportunities. High accuracy electrical substitution radiometers measuring the total solar irradiance have been flown in space for more than 20 years. Frolich and Lean (1998) have reviewed this record and the spread in the results from the different radiometers is greater than 0.45 %, compared to an observed solar variation from maxima to minima of 0.1 % over a 11 year solar cycle. The current estimate for the uncertainty of total solar irradiance is 0.3 % over the 20 year period and must be improved to 0.01% to truly detect the natural solar variability (Foukal, 1994). This is a state-of-the-art radiometric measurement, as high accuracy cryogenic radiometers in NMI laboratories typically achieve uncertainties on the order of 0.01 % in mW laser power measurements. A cryogenic radiometer for ISS should be tested against a ground-based reference instrument and deployed on the ISS for short periods of operation and retested upon return to achieve 0.01 % uncertainty. Repeat checks of the ISS radiometer against continuously monitoring redundant radiometers would permit the assessment of degradation functions and SI traceability.

The spectral distribution of the solar irradiance is another key measurement for the determination of global change. While the total solar irradiance appears to be stable with in 0.1 %, different regions of the spectrum are more highly variable than others, primarily the ultraviolet. The ultraviolet region is the driving force for photochemistry in the upper atmosphere while the visible and infrared regions are the primary energy inputs to the earth system. In addition there is considerable question about the extraterrestrial irradiance spectrum used for the model input for determination of top of the atmosphere spectral radiance in the vicarious calibration of sensors. What is the relationship and uncertainty of the model extraterrestrial solar spectral irradiance to the current SI scales of spectral irradiance? A high accuracy campaign should be mounted to determine the extraterrestrial solar flux from ISS in a program similar to SSBUV but throughout the solar reflective band important to earth observing sensors. This program would provide calibration verification to long term observation sensors and help provide data for the definition of a SI traceable reference solar irradiance spectrum.

In the measurement of other extraterrestrial sources, such as the moon and the stars, a number of sensors are using these sources to correct for sensor calibration degradation. The Sea-viewing Wide Field-of-View Sensor (SeaWiFS) is using monthly lunar observations as a relative correction for sensor responsivity changes. Kieffer and Widley (1995) have proposed to develop a model of the lunar spectral radiance as a function of phase angle and libration, these observations are ongoing. The SOLar STellar Irradiance Comparison Experiment (SOLSTICE) on the Upper Atmosphere Research Satellite has been tracking the calibration degradation by using an ensemble average of observations of eighteen blue stars. The SeaWiFS lunar observations have been ongoing since 1997 and the SOLSTICE stellar measurements since 1991. Stellar irradiance has been used as a secondary irradiance standard for a number of Department of Defense programs. The ideal advantage to using ISS for lunar and stellar mission is that it is exoatmospheric, requiring little or no atmospheric correction. High accuracy lunar observations from ISS would be used to augment Kieffer's ongoing work to develop a lunar spectral radiance model, the observations for which are made through the atmosphere. Since the lunar reflectance is basically stable, previous satellite sensor observations can be retrospectively calibrated with these values.

Highly calibrated radiometers can be used on the ISS for the vicarious calibration of earth observing sensors. In this case top-of-the-atmosphere radiance can be determined directly, cross calibrating on-orbit sensors directly and confirming vicarious calibration strategies of airborne sensors and ground calibrations. This sensor could have near identical spectral characteristics with a sensor in orbit or be hyperspectral in order to calibrate a broad range of similar spectral region sensors. The different highly calibrated sensors on ISS can cover each of the earth observing spectral regions solar reflective, thermal infrared or passive microwave. In the case of passive microwave temperature measurements, a highly calibrated sensor could resolve the current analysis differences and be used for inter-sensor calibrations of MSU on POES and future passive microwave instrumentation.

In all missions existing sensor designs could be flown on ISS optimized for short term stability, with calibration assemblies for stability monitoring. The uncertainty requirements in Table 1 are state of the art requirements requiring unique ground calibration and characterization facilities to achieve mission uncertainty objectives.

ISS FEASIBILITY STUDY

Scientists from NIST are currently establishing and coordinating an interdisciplinary and interagency Ad Hoc Committee for ISS Radiometric Calibration Utilization from interested scientists. This committee will address and prioritize the key calibration missions of an ISS program should. The prioritization should be based upon examination of the current measurement uncertainties of existing programs and the importance of the measured quantity for national goals. The Ad Hoc committee should identify partner agencies for these missions and the possibility of leverage by using existing sensors or sensor designs for the mission. The committee should also consider whether the ISS is the best operational platform for this program and identify alternative platforms such as shuttle missions, etc. The study would also include which available ISS platform would be ideal for the program and what the platform dynamics are for observation relative to the orbits of operational sensors to be calibrated. The study should also assess the limiting factors of ISS utilization such as contamination and identify engineering solutions to those problems. In addition the study should include an assessment of the necessary ground calibration support infrastructure to achieve uncertainty goals of the program. The term of this Ad hoc Committee should be to issue a report within one year, that is by January 2001.

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