Metrology for remote sensing radiometry

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ABSTRACT: Metrology, the science of measurement, is discussed in terms of measurements of radiant flux and associated quantities. Radiometric measurements are naturally *remote*, that is, they are non-contact. A broad application is Earth science, as global measurements using satellites are spatially and temporally efficient and sufficiently long term to provide information on climate and global warming. Accurate radiometry requires a thorough understanding of the measurement problem, a complete description and understanding of the instruments, and mechanisms for comparing and assessing results. Here, we give an introduction to useful terminology and review some of the NIST activities in support of remote sensing.

1 INTRODUCTION

Measurements of the radiant flux from the Earth, Sun, Moon, or planets using optical instruments deployed remotely are used to determine a wide range of physical parameters. For the Earth-Sun system, a critical long-term goal is to acquire an accurate and detailed understanding of processes affecting global climate change, in particular the role of human activities. From radiometric data, it is possible to study and quantify the Earth's temperature distribution, energy budget, properties and dynamics of the atmosphere and oceans, land use, carbon cycle, and other systems that relate to climate. The accuracy of these data depends on the radiometric calibration and characterization of the instruments involved. Recognizing the stringent requirements for radiometric stability and accuracy, and the difficulty of radiometric measurements, verification activities involving experts in metrology are often performed.

This paper is a brief description of radiometric metrology with emphasis on remote sensing for the spectral interval from the ultraviolet (UV) to the thermal infrared (TIR). First, we provide some background on metrology and then introduce terminology and definitions. Then we give some examples relating to characterization, calibration, traceability, and validation, followed by a brief summary.

2 NATIONAL METROLOGY INSTITUTES

The International System of Units (SI) is the metric system of measurement for scientific, technical, and commercial endeavors. Adopted internationally, the SI defines base and derived units and an associated system of physical quantities (BIPM 1998). National metrology institutes (NMIs), with an eye towards public safety, science, technology, and the global marketplace, realize these quantities, perform research to improve their experimental and theoretical foundations, establish methods to disseminate their values to users, participate in international comparisons and related activities, and carry out specialized activities such as measurement assurance programs. In summary, NMIs represent the expertise in metrology. International interactions among these organizations (such as through the Treaty of the Meter) help ensure the robustness of global measurement science. This is necessary for international activities in science such as climate change monitoring.

The NMI for the USA is the National Institute of Standards and Technology (NIST), a non-regulatory agency in the Department of Commerce's Technology Administration (www.nist.gov). The measurement and standards laboratories within NIST interact with users through various established mechanisms, such as 1) calibration services; 2) standard reference materials; 3) reference information; 4) databases; 5) special publications; 6) training courses; 7) workshops and conferences; 8) cooperative research and development programs; and 9) special tests that are typically an extension of an established calibration service. In addition, collaborative efforts between various USA federal agencies and NIST are undertaken in areas of national interest or broad scope, such as defense, health, or, for the case here, global climate change. Similar NMI functions and activities exist in other countries, but in this paper we limit the discussion to the USA.

Several agencies involved with remote sensing for environmental applications have started or expanded radiometric collaborative efforts with the Optical Technology Division (OTD) in the Physics Laboratory at NIST over the past decades. The advantage to these programs includes independent validation of their methods by direct measurement and access to metrology programs that are permanent. NIST benefits because the often difficult measurement problems faced by users lead to incorporation of improved technologies, which are then available for all to use, as well as increased sophistication in the NIST expertise.

The spectral interval discussed in this paper (UV to TIR or from about 0.3 μm to 20 μm) covers, in terms of radiant flux from the Earth, much of the reflected solar and a portion of the emitted thermal radiation. This spectral region overlaps with the measurement programs in the OTD. The needs of the remote sensing community in other regions of the electromagnetic spectrum are also served at NIST, but not discussed here. For example, the NIST Synchrotron Ultraviolet Radiation Facility (SURF III) is used to calibrate sensors for solar physics (Woods et al. 1993). In the microwave region, NIST is developing a calibration/validation program with the National Polar-orbiting Operational Environmental Satellite System (NPOESS) (Randa, pers. comm.).

3 METROLOGY OF RADIOMETRY

A brief introduction to this topic is presented here. For additional descriptions of the NIST activities in remote sensing, see Rice & Johnson (2001) and Brown & Johnson (2003).

3.1 *General terminology*

It is necessary to begin with terminology. A frequently-uttered phrase is "NIST-traceable." But what does this mean? The definition recommended by NIST and other NMIs is from the *International Vocabulary of Basic and General Terms in Metrology*, known as the VIM (ISO 1993b). Traceability is defined as the "property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties." It is NIST policy that, for claims of traceability of measurement results or values of standards, the provider is responsible for documenting support of the claim, and the user is responsible for assessing the validity of the provider's claim. These *verification steps* may not involve NIST, but if they do, the procedures can be selected from existing tools or made specific, e.g. a joint radiometric calibration program.

Proper assessment and statement of uncertainties is required for the measurements used to establish claims of traceability. Evaluation and expression of uncertainty is often an area of confusion, and it is not unusual to have incomplete information on this topic stated by the provider or reported by the user. Fortunately, again we can turn to international documents, in this case the *Guide to the Expression of Uncertainty in Measurement*, known as the GUM (ISO 1993a). Other useful documents are available from NCSL International (NCSL 1998 & 1995) and NIST (Taylor and Kuyatt 1994).

The VIM, GUM, and related documents provide clear definitions and recommendations of usage for common metrological and statistical terms typically encountered when describing the results of measurements; examples include error, uncertainty, accuracy, and repeatability. For example, the term "combined standard uncertainty" refers to the combination of the uncertainty components with consideration of their interdependence, or correlation. Uncertainty components can be distinguished as Type A or Type B. Type A uncertainties are evaluated using statistical methods and Type B uncertainties are evaluated using models or other external information. The term "standard uncertainty" refers to an estimated standard deviation. Type B components of standard uncertainty are evaluated to be equivalent to one standard deviation. The expanded uncertainty is the product of the combined standard uncertainty and the coverage factor k, where the value of k is chosen based on the desired level of confidence (typically $k = 2$). In reporting the uncertainty for a measurement, the components of standard uncertainty should be listed and their designation stated (A or B). It should be clear if the final result corresponds to a combined standard or expanded uncertainty, and, if the latter, the value of the coverage factor.

For more information on terminology, including how to acquire the reference documents, see the NIST Technology Services Division website (http://ts.nist.gov/).

3.2 *Radiometric quantities*

3.2.1 *Radiant energy quantities*

We discuss three radiant energy quantities that are significant to remote sensing radiometry. Other quantities exist; for a more complete discussion see, for example, Hengstberger (1989), DeCusatis (1998), or McCluney (1994). The distinguishing features for the quantities are with respect to the geometry of the measurement situation. The first, radiant flux or radiant power, is simply the total amount of power in a defined optical beam, measured in watts. When measuring optical power with a simple radiometer consisting of an aperture in front of a detector, the optical beam must be well-defined, such as from a laser, and it must underfill the aperture.

More generally, the optical beam of radiant flux at the detector is constrained by the geometry of the source and the radiometer, and this leads to the second and third radiant energy quantities—irradiance and radiance. Irradiance is radiant flux per unit area, with the reference area located with respect to the radiometer. For the simple radiometer described above, let radiant flux, such as from a distant point source, overfill the aperture. If the spatial distribution of the irradiance is uniform across the aperture (for this case it should be), then the irradiance from the source at the location of the aperture is the radiant flux measured by the detector divided by the area of the aperture. An example from remote sensing is determination of the solar irradiance at the top of the Earth's atmosphere (e.g., Lawrence et al. 2003 & Frohlich et al. 1995).

Radiance is radiant flux per unit area per unit solid angle. Fundamentally, radiance is a differential optical beam concept, and the direction of the beam is part of the definition. For radiance, the area of interest is the projected source area in the viewing direction. The solid angle (unit steradian) is an example of a SI dimensionless derived unit. Typically in radiometry, a pair of apertures separated by some distance defines the solid angle. If both apertures are filled by the source, radiance is measured, as both the cross-sectional area and angular extent of the beam have been defined. An example from remote sensing is the radiance of the Earth in the TIR, from which the thermodynamic temperature can be determined using Planck's Law, if the emittance is known (e.g., Moeller et al. 2003 & Minnett et al. 2001).

3.2.2 *Material properties*

Quantities describing the optical properties of materials are also of interest to remote sensing radiometry; examples are reflectance, transmittance, and emittance. Quantification of material properties is necessary for the realization of radiometric quantities. In addition, prior to final sensor assembly, it is often important to determine the optical performance of critical components such as filters, mirrors, beamsplitters, or lenses.

The elementary reflectance quantity is the bidirectional reflectance distribution function (BRDF), which is defined as the ratio of radiance leaving a target to the irradiance incident on the target (Barnes et al. 1998). Samples subjected to BRDF studies are typically "diffuse," that is, flux incident from one direction is scattered into the entire hemisphere. The reflectance of mirrors, which are highly specular, does not have to be measured for all exitant angles in the full hemisphere at each incident angle, although in some critical applications this is necessary. In general, reflectance depends on polarization and wavelength.

The transmittance of a sample is the ratio of the incident to transmitted flux. Scattering within the sample and sensitivity to temperature, beam divergence, humidity, and air pressure must be considered in addition to the factors mentioned above, especially for optical elements coated with thin film multilayers.

Finally, the emittance of a sample is the ratio of its radiance to the radiance emitted from an ideal blackbody at the same thermodynamic temperature of the sample.

3.3 *Methods of traceability*

The realization of values for radiant quantities is usually based on either electrical and dimensional metrology or on temperature metrology. The former utilizes electrical substitution radiometry (ESR) and the latter blackbody physics.

3.3.1 *ESR*

The basic principle of ESR is that an optical watt is the same as an electrical watt (Hengstberger 1989). Optical power is compared to electrical power in an absorbing receiver by direct substitution using a shutter and external electrical heating of the receiver. Since the scale is realized on an optical detector, this is often termed detector-based radiometry.

One ESR method utilizes intensity-stabilized lasers and cryogenic receivers to determine values of radiant flux very accurately. A scale of radiant flux responsivity is then realized on transportable, stable radiometers by direct substitution; the units are amps per watt (Gentile et al. 1996). Here, the radiometers are as described in Sec. 3.2.1—an aperture in front of a detector. However, use of a single detector element has several disadvantages when one recognizes the primary objective is to realize values for other radiant energy quantities. Instead, for the spectral range corresponding to silicon photodiodes, multiple photodiodes are arranged in a light-trapping configuration; this is termed a "trap" detector.

The disadvantages of the single detector are related to the "like-to-like" rule in radiometry: to avoid introducing bias in the measurement result from systematic effects, the measurement conditions in the traceability "chain of comparisons" should be as similar as possible. However, this is not always achievable. For example, for general detector spectral responsivity realizations, radiometers are calibrated with the laser beams and then used as the reference standards in a system where the source is the exit slit of a lamp-illuminated monochromator (Larason et al. 1998). Hence the radiometer is used with sources that differ in terms of their coherence, polarization, degree of monochromaticity, f/#, flux level, and spatial uniformity. Compared to a single photodiode, the trap detector is less sensitive to these source parameters (Eppeldauer & Lynch 2000).

3.3.2 *Blackbody physics*

The basic principle here is Planck's Radiation Law, which predicts the spectral radiance from an ideal blackbody in terms of its thermodynamic temperature and the measurement wavelength. Since the scale is realized with an optical source, this is often termed source-based radiometry. In "fixed-point" blackbodies, the temperature is set by surrounding the blackbody cavity by a pure, molten metal that is undergoing a freeze. With the temperature at a constant value during this phase transition, the spectral radiance is calculable. Values for the relevant freezing temperatures of the metals are given in The International Temperature Scale of 1990 (ITS-90) (Preston-Thomas 1990).

Fixed-point blackbodies are expensive, tedious to operate, and exhibit substantial temperature gaps in their coverage. Instead, variable temperature blackbody standards are constructed with various materials and instrumented with calibrated contact thermometers, such as Platinum Resistance Thermometers (PRTs). Thus the traceability of spectral radiance values is established using temperature standards that are calibrated according to ITS-90 (http://www.cstl.nist.gov). Of course, this procedure will not work at higher temperatures where contact thermometers cannot function.

If a cavity is black (unity emittance) and its temperature is uniform, the uncertainty of the radiance is determined only by the uncertainty of the temperature and associated fundamental constants. Real blackbodies are only an approximation of this ideal, and therefore they must be characterized to determine the emittance, spatial uniformity, stability, and so forth. For large-area blackbodies typically used in the TIR to calibrate Earth-observing sensors, it is difficult to achieve unity emittance. If the background environment is not cooled to low temperatures, the reflection of the background radiance from the blackbody must be considered.

3.4 *Scale realization at NIST*

The previous section gave examples of detector-based radiometry for realization of radiant-flux and spectral-flux responsivity and source-based radiometry for realization of spectral radiance. Using these concepts, we describe various other methods at NIST used to realize spectral irradiance and radiance. For both irradiance and radiance, limiting apertures play a critical role. At NIST, these areas are determined using optical metrology in a dedicated facility (Fowler & Litorja 2003).

3.4.1 *Radiance*

The Low Background Infrared (LBIR) facility at NIST has a vacuum chamber with 20 K cryoshrouds; the radiance temperature of blackbodies is determined using a cryogenic ESR (Carter et al. 2003). Radiant flux from the aperture of the blackbody overfills the aperture on the radiometer. The area of the apertures and the distance between them is measured. The radiometer is designed to absorb equally at all wavelengths, so the measured flux is proportional to the blackbody exitance (Stefan-Boltzmann Law); consideration of the geometric factors allows determination of the radiance temperature. For small blackbody apertures diffraction effects must be considered. From the LBIR measurements, it is possible to assess the accuracy of the user's source-based radiance scale that is based on the temperature standards.

In the Medium Background Infrared (MBIR) and Ambient Background Infrared (ABIR) facilities at NIST, large area (10 cm diameter apertures) blackbodies serve as standard sources of spectral radiance. The cryoshrouds in the MBIR vacuum chamber are operated at 80 K or room temperature (ambient). With 80 K cryoshrouds, the MBIR cryogenic blackbody operates over the temperature range 200 K to 350 K (Fowler et al. 1998). In the ABIR facility, which is a standard laboratory environment, water- and oil-bath based blackbodies cover the temperature range 288 K to 460 K. The blackbody temperatures are traceable to ITS-90 by use of calibrated PRTs.

In the Facility for Automated Spectroradiometric Calibrations (FASCAL), a gold-point blackbody (1337.33 K) is the source standard for spectral radiance (Walker et al. 1987). A prism-grating spectroradiometer is used to measure, at 654.6 nm, spectral radiance ratios of the gold-point blackbody to higher temperature sources (tungsten filament lamps or high temperature graphite blackbodies). The spectral radiance values of lamp-illuminated integrating sphere sources are then determined by comparison to the high temperature blackbody. Calibrated integrating sphere sources are used as spectral radiance standards in the remote sensing community.

The Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) facility is detector-based and designed for determination of absolute spectral irradiance or radiance responsivity of complete radiometers (Brown et al. 2000 & Eppeldauer et al. 2000). The output of tunable lasers is input into an integrating sphere. The irradiance of the laser-illuminated sphere is determined using a standard radiometer such as the aperture/trap detector radiometer described in Sec. 3.3.1. As in the LBIR facility, the sphere is fitted with a known aperture, and the distance between the source and detector apertures is measured. This allows determination of the radiance of the laser-illuminated sphere.

Integrating spheres with large exit aperture diameters that overfill the field-of-view of the radiometer under test are used for radiance responsivity, and smaller ones that underfill the field-of-view of the radiometer under test are used for irradiance responsivity. Currently, the laser systems in SIRCUS are continuously tunable from 350 nm to about 5 μm, with discrete output at CO and CO_2 laser wavelengths (5 μm to 7 μm and 10 μm to 11 μm, respectively). Several methods are under development for operation to 20 μm. For the longer wavelengths, the reference radiometers utilize InGaAs photodiodes or an electrically substituted bolometer. In addition, the interior of the sphere is coated with diffuse gold, instead of the polytetrafluoroethylene (PTFE)-based material used in the visible.

3.4.2 *Irradiance*

NIST has recently modified the procedure for realizing spectral irradiance. In the past, spectral irradiance values were traceable to the gold-point blackbody spectral radiance at 654.6 nm using multiple comparison steps: spectral radiance values were assigned to a small integrating sphere source as described in Sec. 3.4.1, then the prism-grating spectroradiometer was configured with irradiance fore-optics (an small integrating sphere with a circular input aperture) and, using the integrating sphere source as a standard, the spectral irradiance responsivity of the spectroradiometer was determined. Using the calibrated spectroradiometer, spectral irradiance values were assigned to 1000 W quartz-tungsten standard irradiance lamps, type FEL (not an acronym).

In 2000 a new NIST irradiance scale was introduced (Yoon et al. 2000). It is detector-based, not source-based. The spectral irradiance values of the NIST FEL working standard lamps are determined by comparison to a high temperature (3000 K) blackbody using a spectroradiometer. The temperature of the blackbody is determined using filter radiometers calibrated for absolute spectral irradiance responsivity by separate determination of the aperture area and the filter/detector spectral flux responsivity. The great benefit is a factor of between 2 and 10 times reduction in uncertainty for the assigned spectral irradiance values, with the greatest improvement in the short-wave infrared (SWIR).

It is possible to realize spectral radiance using the FEL spectral irradiance standards to illuminate a diffuse reflectance standard. If the BRDF of this target is known (see Sec. 3.2.2), then the spectral radiance is calculable (Mueller & Austin 2003). Therefore, there are two methods to establish traceability to NIST spectral radiance standards—via a calibrated integrating sphere source or by use of an irradiance and diffuse reflectance standard. In an ideal world, one would utilize both methods and then intercompare the results routinely. In the practical world, the choice between the two methods should involve discussion of issues such as size limitations, operating environment, planned frequency of calibration schedule, methods in place to monitor the stability in spectral radiance, and sensitivity to uniformity, scattered flux, and so forth.

4 CHARACTERIZATION

We have described how traceability of values can be established for detector responsivity, irradiance, and radiance. Although not described here, determination of reflectance, transmittance, or emittance values also utilize sources and radiometers (see for example Barnes et al. 1998 & Hanssen 2001). We have seen how as measurements progress through the "chain of comparisons" required for traceability, it is possible to violate the "like-to-like" rule. For proper assessment of uncertainties, the sources and radiometers must be characterized.

4.1 *Measurement equation*

A measurement equation is a mathematical expression that describes the role and effect of all of the influencing parameters (Nicodemus et al. 1976). By influencing parameters, we mean, for example, the wavelength, polarization, direction, beam size, and flux level of the radiant quantity. The responsivity of a radiometer depends on, and the specifications of a source involve, these parameters. Time is also an essential variable, as it relates to both the measurement precision (short term stability) and drift or degradation (long term stability). Temperature of the environment, intervening medium, or instrument components can be a significant influencing parameter.

One usually starts by assuming that the parameters can be treated independently, which allows for separate characterization measurements for each parameter. This assumption should either be confirmed or the experiments designed to minimize possible systematic effects. An example of testing would be to perform the measurements that verify the linearity of the radiometer output with flux level is independent of integration time. An example of reducing sensitivity to systematic effects would be to fill the entire entrance pupil of the radiometer with monochromatic flux during spectral responsivity characterizations, taking care to match the f/# of the beam to final measurement configuration. For cases where correlations must be considered, see the recent work by Gardner that discusses the effect of correlations on the expression of uncertainty (Gardner 2000 & Gardner 2003). Below, we discuss the problem of spectral responsivity in more detail.

4.2 *Spectral responsivities*

Determination of radiometer spectral responsivity is critical for the correct interpretation of measurements of natural sources. For filter radiometers or spectroradiometers at a particular wavelength setting, both the in-band and out-of-band spectral responsivites are of interest. The measurement equation with all of the other influencing parameters neglected (or at some reference values) is

$$i = \int L(l)\, R(l)\, dl \qquad (1)$$

where i is the measured output current, $L(l)$ is the source spectral radiance, l is the wavelength, and $R(l)$ is the absolute radiance responsivity at wavelength l. Note Equation 1 could have been written in terms of source irradiance and absolute irradiance responsivity.

One way of determining the function $R(l)$ is in two steps—by measuring the relative spectral responsivity and then performing a calibration measurement using a source standard. The relative spectral responsivity values are typically determined using dispersive or interferometric systems that are illuminated with continuum sources. The determination of the relative spectral responsivity is sometimes done at the component level, with the relative spectral responsivity for the entire sensor calculated as the product of the individual values for transmittance, reflectance, etc. This can introduce bias from systematic effects such as interreflections and scatter that are present in the complete system but not for the individual components. Modeling of such effects is possible, and provides useful insight, but such estimations of bias may not have the required uncertainty.

A second way to determine $R(l)$ is to use the method employed in the SIRCUS facility. The absolute responsivity is determined in one step. Compared to methods that use filtering of continuum sources, it is straightforward to achieve the correct beam geometry, flux level, and bandwidth. The output of SIRCUS is continuously tunable and has a wide dynamic range in flux. In the TIR, the laser can be chopped as a means to eliminate thermal background radiation.

4.2.1 *In-band example*

Often it is convenient to refer to a measurement channel of a filter radiometer in terms of its measurement wavelength, l_{m}, and bandwidth, Dl:

$$l_{\mathrm{m}} = \frac{\int l\, R(l)\, dl}{\int R(l)\, dl} \qquad (2)$$

$$(\Delta l)^2 = 2.354 \frac{\int (l - l_{\mathrm{m}})^2 R(l)\, dl}{\int R(l)\, dl}\ . \qquad (3)$$

In general, the limits of integration in Equations 1-3 correspond to the entire region of finite detector responsivity. The in-band profile is defined by restricting the region around l_{m}, with the location of the upper and lower wavelength defined in various ways, for example where the responsivity is a certain percentage of the maximum responsivity.

Measurements to determine the in-band profile can be incorrect through improper assignment or understanding of the wavelength scale, inadequate spectral resolution or bandwidth, or mistreatment of interreflections, scattered light, and thermal effects. Although we used the example of a filter radiometer for Equations 2 and 3, similar issues exist in spectroradiometers.

The in-band example concerns the Robotic Lunar Observatory (ROLO), which is a pair of Ritchey-Chrétien telescopes, each fitted with a rotating filter wheel and an array detector (Anderson et al. 1999). Relative spectral responsivities were estimated from the transmittance traces provided by the filter vendor. However, the f/# for these measurements was not the same as for the illumination conditions in the ROLO telescopes. For interference filters, the wavelength scale depends on f/# because of the sensitivity to the angle of incidence, and errors of this type impact the ROLO atmospheric correction algorithm as well as the values determined for the lunar radiances.

The solution involved construction, by the ROLO team, of a collimator-source assembly with beam properties designed to simulate lunar illumination (Stone et al. 2003). A portable version of SIRCUS, "Traveling SIRCUS," was deployed to ROLO outside Flagstaff, Arizona. Using a tunable Ti:sapphire laser configured for intracavity doubling that was fiber-optic coupled to the collimator, the relative in-band profiles for eight channels were determined. Shifts of up to 2.5 nm were observed.

4.2.2 *Out-of-band example*

As seen from space, in the visible and near-infrared (VNIR), the total radiance when viewing the sunlit oceans is a function of the atmospheric contribution, reflection at the ocean surface, and flux scattered from the oceans. The latter component, the water-leaving radiance, depends on the optical properties of the oceans, which are a function of bio-physical parameters (e.g., chlorophyll concentration). The water-leaving radiance is a small component of the total radiance, and to achieve the desired accuracies for ocean products continuous in-situ measurements from optical sensors such as the in-water Marine Optical Buoy (MOBY) are used to revise the satellite calibration coefficients (Gordon 1998 & Barnes et al. 2000).

Typically, lamp-based sources are used for the pre-flight satellite sensor and the in-situ radiometer calibration. Lamp-based sources produce an overabundance of red and near-infrared flux compared to the natural ocean scenes. This is another example of unavoidable violation of the "like-to-like" rule, and results in bias if the sensors have significant spectral out-of-band that is not properly accounted for.

In the MOBY instrument, two CCD spectrographs are used to cover the interval from 360 nm to 940 nm. In the overlap region of the two spectrographs (560 nm to 640 nm), the derived radiant values did not agree. However, a simplified version of Equation 1 was in use, which assumed that the sensor output at a measurement wavelength was proportional to the product of spectral responsivity and spectral radiance at that wavelength. As Equation 1 demonstrates, the relative effect of spectral out-of-band on the total output depends on the spectral shape of the source; since the sources measured are quite different, the effect can be significant. It is most apparent in spectral regions where the system responsivity is small (e.g., where a dichroic beamsplitter is limiting the flux), as the fraction of measured signal from the spectral out-of-band effect is significant. In MOBY, a dichroic beamsplitter directs the incoming flux to the spectrographs, and spectral out-of-band (or "stray light") was suspected as the cause of the discrepancy in the region of overlap.

The size and deployment schedule of MOBY made it impossible to perform characterizations at NIST, so Traveling SIRCUS was deployed to the MOBY Operations Facility in Honolulu, Hawaii. A dye laser and several discrete lasers were included in addition to the Ti:sapphire laser. By fine-tuning the Traveling SIRCUS wavelength, the relative in-band profile at selected regions on each CCD for both spectrographs was determined.

The features observed in the images of monochromatic illumination were identified—they arose from the image of the slit, haze and diffuse reflections, and interreflections of higher-order diffraction. Using the laser characterization data along with the lamp-based calibration data, an iterative solution that results in "stray-light corrected" values for the MOBY spectral responsivities as well as the measured up-welling and water-leaving radiances was implemented. As anticipated, the magnitude of the discrepancy in the region of overlap was reduced with application of the stray-light correction. In the spectral region between 410 nm and 550 nm, the values for water-leaving radiance reported by MOBY were revised by several percent, with concomitant improvements in the uncertainties for water-leaving radiance (Brown et al. 2003).

5 CALIBRATION & VALIDATION

The results of the instrument characterization measurements are methods to describe sensor performance for all operating conditions, e.g., a system of equations and associated parameters, lookup data tables, results of thermal models, uncertainty budgets, etc. Calibration of a sensor involves measurement of a known source, with the roles reversed for calibration of a source. As a result, radiometric quantities are known in terms of measured quantities. In the case of a *primary* device, such as an ESR or blackbody, a calibration measurement is not performed. In either case, the uncertainty is based on the measurement equation and the characterization experiments.

Validation is the process of verifying radiometric performance by using an independent method. With values traceable to SI quantities, as is recommended for remote sensing (CCPR 1995), the results of intercomparison measurements should be consistent within the combined uncertainty because all values are traceable to the same system of measurement. Validation of an instrument can be performed by comparison of detector- and source-based calibration approaches. Primary instruments are intercompared, or used in specialized experiments that determine fundamental constants radiometrically. Here we mention results of validation programs with the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the Departments of Energy and Defense (DOE and DOD).

5.1 *VNIR*

The Earth Observing System (EOS) Project at NASA established a calibration/validation program with NIST in the mid-1990's (Butler & Barnes 2003). One part of the program involves validation of the spectral radiance of sources using NIST-designed, built, and deployed transfer radiometers. The sources are used to assign pre-flight calibration coefficients for EOS sensors, and they consist of lamp-illuminated integrating sphere sources (VNIR) or blackbodies (TIR).

The EOS/NIST Visible Transfer Radiometer (VXR) (Johnson et al. 2003) and the Shortwave Infrared Transfer Radiometer (SWIXR) (Brown et al. 1998) are filter- and grating-based instruments, respectively, that cover the spectral interval from 412 nm to 2.5 μm. They have been used in conjunction with transfer radiometers from other institutions to independently determine spectral radiance values of radiance standards (Butler & Barnes 2003). Because of resource constraints, it is generally not possible to perform validation tests during the calibration of flight hardware. Therefore, the measurement protocol is for the hosting institution, immediately prior to the comparison measurements, to assign spectral radiance values to the source using the same methods of establishing traceability that were used for the calibration of the EOS sensor. The VNIR results to date confirmed that the uncertainties in spectral radiance assigned the by the manufacturer (±3 %, $k = 1$) are valid.

As for radiometers, their calibration can be validated by using different methods and comparing the results. For example, the VXR was calibrated using SIRCUS and FASCAL and the results agreed within the combined uncertainties (Johnson et al. 2003). In the NOAA/MOBY project, a portable version of the optical system used in the buoy was characterized and calibrated using the SIRCUS facility at NIST, and also used to measure a lamp-illuminated radiance source that was calibrated on FASCAL. The stray-light corrected system responsivities derived from the source agreed with those from SIRCUS to within 2 % (Brown et al. 2003).

5.2 *TIR*

The NIST/EOS Thermal-infrared Transfer Radiometer (TXR) is a two-channel portable filter radiometer that operates in vacuum or ambient conditions (Rice & Johnson 1998). The detectors, filters, and reflective optics are built into a liquid-nitrogen cryostat with a ZnSe window. The two TXR channels are at 5 μm (photovoltaic InSb detector) and 10 μm (photovoltaic MCT detector). A variable-temperature, vacuum compatible blackbody that can rotate in front of the TXR window under computer control is used to monitor the stability of the TXR radiance responsivity during deployments.

The motivation for the TXR was as described above for the VNIR spectral regions: to validate the spectral radiance scale of standard sources using a portable, NIST-calibrated radiometer. There are differences worth noting, however. For the VNIR, the radiance values are traceable to NIST standards using a chain of measurement steps that involve radiometric artifacts—typically spectral irradiance standard lamps and diffuse reflectance standards. For the blackbodies used in thermal/vacuum chambers to calibrate infrared sensors, the spectral radiance values are traceable to NIST temperature standards. As pointed out in Sec. 3.3.2, there are uncertainties associated with the emittance of the blackbody source, and these are often difficult to evaluate. Finally, in the TIR spectral region, all "warm" structures (> 100 K) are an additional source of radiant flux. Reflection of this background flux from a non-ideal blackbody results in a calibration that is dependent on the temperature of the surrounding environment.

Calibration of the TXR has been performed using multiple approaches. Initially, the NIST water-bath blackbody (Fowler 1995) was used (Rice & Johnson 1998). More recently, the TXR was calibrated in the MBIR chamber using its cryogenic blackbody. The blackbody was characterized and the emittance determined using the TXR with the MBIR thermal background at 300 K and 80 K. At the present time, the TXR uncertainty is <0.1 K at 300 K ($k = 2$). In the future, the TXR will be calibrated on SIRCUS and an ESR based on high-Tc superconducting temperature sensors will be used to determine the total irradiance from the MBIR blackbody, thus validating the calibration of the TXR and the blackbody using independent methods.

The TXR has been used on multiple occasions to verify TIR spectral radiance values. In July 1999 and August 2001, it was deployed to the remote sensing radiometric calibration facility at Los Alamos National Laboratory (LANL) in support of DOE programs. The LANL system has two chambers connected by a gate valve—one with a cold shroud at ≈ 80 K for the sensor, and one at room temperature for the standard blackbody, two cold blackbody sources, and a collimator for coupling radiant flux to the sensor. With the TXR located in the cold chamber at the location normally used by a remote sensing sensor, the measurements validated the LANL blackbody-collimator system. The 1999 results at 5 μm agreed in spectral radiance to within 0.16 %, or 50 mK at 300 K ($k = 2$) (Rice et al. 2003). At the time of the 1999 deployment, the 10 μm channel had offsets of up to 0.5 K with cryocycling. Measurements of a check-source were used to correct for this effect, and the resulting agreement with LANL was within 0.1 K (Rice et al. 2000).

In May 2001 the TXR was used in an EOS sea-surface temperature (SST) intercomparison at the University of Miami (UM) (Rice et al. 2004). Ship-based measurements of SST are used to validate satellite results using different types of infrared radiometers and field-deployable blackbody sources. Members of the international Committee on Earth Observing Satellites helped organize and support the 2001 comparison, which included ship-based measurements (Barton et al. 2004), and deployment of the TXR and the NIST water-bath blackbody source as part of the laboratory comparison. Five blackbody sources were measured using the TXR—the NIST source plus four sources used for field calibration of SST radiometers. The comparison was performed in a UM laboratory at ambient temperature. All blackbodies agreed to within 0.1 °C near ambient; measurements at other temperatures provided information on the emittance of the SST sources (Rice et al. 2004).

In July 2001 the TXR was deployed to the Geostationary Operational Environmental Satellite (GOES) Imager radiometric calibration chamber at ITT in Ft. Wayne, Indiana (Rice 2003). The chamber is not equipped with cryoshrouds. The GOES Imager is calibrated from measurements of the Earth Calibration Source (ECT) and a cold blackbody source. The ITT procedure involves correcting for temperature gradients in the ECT, which were believed to be driven by the thermal background of the chamber (Farthing 1993).

During the GOES TXR deployment, measurements were made at a range of temperatures of the ECT and the TXR check standard blackbody, as well as the cold blackbody source. An analysis procedure was developed that enabled parameterization of the results in terms of a non-unity emittance and a temperature gradient in the ECT. The results are in qualitative agreement with the existing GOES model, thus providing valuable confirmation to the project (Rice 2003).

More recently, in the fall of 2003 the TXR was used to measure a blackbody source at Santa Barbara Remote Sensing (SBRS) in Goleta, California in support of DOD research. Plans are in place for TXR measurements of a second blackbody source at SBRS in early 2004. This source was used to calibrate the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on the EOS satellites Terra and Aqua. Plans call for use of this blackbody for the calibration of the Visible/Infrared Imager/Radiometer Suite sensor that will be flown as part of NPOESS.

6 CONCLUSIONS

Metrology and radiometry are established fields and substantial reference material is available regarding standards, terminology, and protocols. International organizations and NMIs represent a valuable resource—they maintain and disseminate the SI, validate their own results through international comparisons, and engage with industry and the research community in specialized measurement assurance programs in broad efforts such as remote sensing.

Characterization and calibration of sources and radiometers, and validation of measurement results are all essential for reliable products such as that required for climate quality data. The expanded use of tunable laser facilities such as SIRCUS at commercial facilities appears possible and would benefit the remote sensing community. Calibration of radiometric artifacts should be in terms of the SI in order to produce long-term data sets on a common measurement system. Validation is the process of verifying a result with an independent approach and it should be performed whenever a technically feasible method with appropriate uncertainties is available. Examples include using a common instrument with multiples of its radiometric counterpart (e.g. the TXR and several blackbody sources); using source- and detector-based calibration methods with the same instrument; and investigating ways to validate model results.

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