The Use of Transfer Radiometers in Validating the Visible through Shortwave Infrared Calibrations of Radiance Sources Used by Instruments in NASA's Earth Observing System

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Abstract

The quantitative study of climate change over decadal time frames requires successive generations of satellite, airborne, and ground-based instrumentation carefully calibrated against a common radiance scale. In NASA's Earth Observing System (EOS) program, the most common sources used in the laboratory radiance calibration of satellite, ground-based, and airborne instruments operating in the reflective solar wavelength region of 400 nm to 2500 nm are integrating spheres and diffuse reflectance panels illuminated by irradiance standard lamps. Since 1995, the EOS Calibration Program operating within NASA's EOS Project Science Office (PSO) has enlisted the expertise of the National Institute of Standards and Technology (NIST), the University of Arizona Optical Sciences Center's Remote Sensing Group (UA), Japan's National Research Laboratory of Metrology (NRLM), and NASA's Goddard Space Flight Center (GSFC) in an effort to validate the radiance scales assigned to sources used in the pre-launch calibration of EOS instruments and to critically examine the operation, repeatability, and stability of those sources. Radiance scale validation is accomplished using stable, transfer radiometers operating at visible through shortwave infrared wavelengths and calibrated and

characterized by each institution using a variety of techniques. In the ten comparisons performed since February 1995, the agreement between the radiance measurements of these transfer radiometers is ±1.80% at 411 nm, ±1.31% at 552.5 nm, ±1.32% at 868.0 nm, ±2.54% at 1622nm, and ±2.81% at 2200nm ($\sigma = 1$).

1. Introduction

NASA's Earth Observing System (EOS), established in 1991 through a Presidential initiative, is an integrated, international, decadal, multi-platform, multi-satellite instrument program in Earth remote sensing. The primary goal of EOS is to advance the understanding of the Earth and its changes as a system through careful examination of the components of the system and their interactions. This goal is achieved by the acquisition and analysis of data from the numerous EOS satellite instruments located on the same and successive platforms. The correct interpretation of these satellite data requires the ability to distinguish between on-orbit instrumental changes and actual physical changes in the Earth processes being monitored. The ability to make this distinction depends on carefully calibrating the instruments against common physical standards pre-launch, successfully transferring those calibrations through launch, and correctly monitoring those calibrations on-orbit over the mission lifetime. On-orbit satellite instrument calibration is typically monitored using on-board calibration systems and ground-based and airborne vicarious calibration (VC) instruments deployed on or above spectrally and spatially featureless Earth sites at the times of satellite instrument over-passes.

In EOS, the pre-launch or pre-deployment radiometric calibrations of satellite and VC instruments are performed at the satellite instrument builders' facilities and at the VC instrument metrology laboratories, respectively. In the visible through shortwave infrared wavelength region, the uniform radiance sources of choice for these calibrations are internally and externally illuminated integrating spheres and diffuse reflectance panels illuminated by irradiance standard lamps. EOS instruments are required to trace their calibrations to either source-based or detector-based standards maintained by the national standards laboratory of the instruments' country of origin. For example, the pre-launch calibrations of the United States' Moderate Resolution Imaging Spectroradiometer (MODIS) and the Japanese Advanced Spaceborne Thermal and Emission Reflection Radiometer (ASTER) on the EOS Terra platform are traceable to standards maintained by the National Institute of Standards and Technology (NIST) and the National Research Laboratory of Metrology (NRLM), respectively.

In 1995, the EOS Calibration Program as part of NASA's EOS Project Science Office, enlisted NIST to help coordinate a Measurement Assurance Program (MAP) [1-3] to validate the radiance scales assigned to uniform sources by satellite instrument builders and VC laboratories. In this process, NIST has built, characterized, calibrated, and maintained stable radiometers operating in the visible/near infrared, shortwave infrared, and thermal infrared wavelength regions. These radiometers are designed to travel to EOS instrument builder and VC facilities and participate in radiometric measurement comparisons. In addition to the NIST radiometers, transfer radiometers from the University of Arizona Optical Sciences Center Remote Sensing Group (UA), NRLM, NASA's GSFC Sea-viewing Wide Field-of-View Sensor (SeaWiFS), NASA's GSFC Landsat Enhanced Thematic Mapper+ (ETM+), NASA's GSFC Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) projects, and NASA's GSFC Radiance Calibration Facility have participated in many of these comparisons. This paper presents and discusses the agreement between the transfer radiometer radiance measurements obtained from 10 radiometric comparisons on 14 radiance sources held from February 1995 to April 2001.

2. Radiometers

The radiometers which have participated in the EOS radiometric measurement comparisons are presented in Table 1. Included in Table 1 are the radiometer institutional affiliations, operating wavelengths, and bandwidths. A description and calibration of each radiometer is briefly described below.

2.1 NIST Visible Transfer Radiometer

The NIST Visible Transfer Radiometer (VXR), built in 1996 by NIST for the EOS Project Science Office, is a six-channel filter radiometer similar in design to the SeaWiFS transfer radiometer (SXR) [4]. The VXR filters were chosen to coincide with several visible and near infrared bands of the MODIS, ASTER, and Multispectral Imaging SpecroRadiometer (MISR) instruments on the EOS Terra platform. Prior to December 1999, the VXR was calibrated for radiance using an Optronic Laboratory Incorporated OL420 integrating sphere source located in NIST's Facility for Automated Spectroradiometric CALibrations (FASCAL) [5]. Before December 1999, the measurement uncertainties for the VXR were estimated to be 2% (k=1) for all but the 870 nm channel. For that channel, the uncertainty was estimated to be 3% (k=1) [6]. From December 1999 to December 2001, revised calibration coefficients were applied to the VXR radiance measurements [7]. In December 2001, the VXR was calibrated for spectral radiance responsivity in NIST's Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) facility [8]. The measurement uncertainties resulting from the SIRCUS calibration improved to 0.7% at 411nm and 0.5% at 870nm (k=1).

2.2 NIST ShortWave Infrared Transfer Radiometer

The NIST ShortWave Infrared Transfer Radiometer (SWIXR) [9] is a scanning spectroradiometer employing a double monochromator and using all-reflective input optics and a liquid nitrogen cooled indium antimonide (InSb) detector. The operating wavelengths for the SWIXR range from 800 nm to 2500 nm, with a variable bandwidth depending on the slit widths. In June 1998, the SWIXR was calibrated at NIST against an OL450 integrating sphere source calibrated for spectral radiance using a variable temperature blackbody located in the NIST Radiance Temperature Laboratory [10]. In the 1998 calibration, the radiance measurement uncertainty of the SWIXR was 4.5% (k=1). Subsequent calibrations of the SWIXR were performed using the NIST Portable Radiance (NPR) source [11] calibrated in the NIST Radiance Temperature Laboratory, resulting in the measurement uncertainties of 1.7% (k=1). The SWIXR is calibrated for wavelength before, during, and after all comparisons using atomic pen-lamps.

2.3 University of Arizona Visible/Near Infrared Radiometer

The University of Arizona Visible/Near Infrared Radiometer (UA VNIR) [12,13] is a simple, single channel radiometer with a manually rotated filter wheel containing seven filters. The optical design is based on two precision apertures spaced at a known distance by invar rods. The filters are placed in front of the first aperture and a trap detector is placed immediately behind the second aperture. The seven UA VNIR channels correspond to several of the MODIS, ASTER, and MISR bands. The laboratory calibration of the UA VNIR is traceable to NIST primary standards via a standard of spectral irradiance purchased from NIST and one obtained from a secondary standards laboratory. In its principal calibration mode, the instrument views the irradiance standard with the front aperture removed. This calibration is followed by a second in which the instrument views a Spectralon panel with known bi-directional reflectance distribution function (BRDF) illuminated by the irradiance standard. This radiance-mode measurement is made with both apertures in place. The measurement uncertainty of the UA VNIR radiometer is 2.1% at 412.8 nm and 2.2% at 666.5 nm (k=1).

2.4 The University of Arizona ShortWave Infrared Radiometer

The University of Arizona ShortWave Infrared Radiometer (UA SWIR) [14] is a nine-channel filter radiometer employing a liquid nitrogen cooled InSb detector. Like the UA VNIR, the Arizona shortwave transfer radiometer uses two precision apertures to define the solid angle of its field-of-view. The UA SWIR channels are chosen to have center wavelengths corresponding with those in the MODIS and ASTER satellite instruments. The UA SWIR is calibrated for spectral radiance responsivity in the laboratory using the same standard irradiance lamps, diffusely reflecting Spectralon panel, and calibration procedures used in the calibration of the UA VNIR radiometer. The measurement uncertainty of the UA SWIR radiometer is 3.3% at 1243.5 nm, 3.3% at 1646.0 nm, and 3.9% at 2402.9 nm (k=1).

2.5 National Laboratory of Metrology ASTER and OCTS/POLDER Radiometers

The NRLM ASTER radiometers are three single-filter radiometers built for the Japan Observation System Organization (JAROS) with center wavelengths designed to correspond to the visible and near infrared operating wavelengths of the ASTER satellite instrument [15]. The NRLM OCTS/POLDER (Ocean Color Temperature

Scanner/Polarization and Directionality of Earth's Reflectances) radiometers are six single-filter radiometers built for the National Space Development Agency (Japan) (NASDA) with center wavelengths and bandwidths close to those of the OCTS instrument [16]. These radiometers were calibrated using an NRLM copper point blackbody source. The relative spectral responsivities of the radiometers were determined by comparison to a thermopile detector using a lamp/monochromator narrow band source. The measurement uncertainty of the NRLM radiometers is 1.6% at 446.4 nm and 1.4% at 653.4 nm. The calibration uncertainty of the NRLM radiometers at 1600 nm and 2200 nm is 0.5% and 1.0% (k=1), respectively, with the measurement uncertainty of these shortwave infrared radiometers being slightly larger.

2.6 NASA's GSFC Landsat Transfer Radiometer

The Landsat Transfer Radiometer (LXR) [17,18] is a six-filter radiometer of similar optical design as the SXR, VXR, and SXR II. The LXR was built by NIST for the Landsat Project Science Office. The relative spectral responses for the first four LXR channels were configured to correspond to those for the Landsat ETM+ instrument. For those comparisons before the year 2000, the laboratory calibration of the LXR radiometer was traceable to NIST standards through NIST's OL420 source calibrated in NIST's FASCAL. The uncertainty in the transfer of the calibration from the FASCAL to the LXR was 0.5% to 1% (k=1), depending on the channel; and the overall measurement uncertainty of the LXR was 2 to 3% (k=1), also depending on the channel. In 2000, the LXR was calibrated for spectral radiance responsivity in the NIST SIRCUS facility. The radiance measurement uncertainties following the SIRCUS calibration improved to 1.2% at 440.0 nm and 0.9% at 827.0 nm (k=1).

2.7 NASA's GSFC SeaWiFS Transfer Radiometer

The SeaWiFS Transfer Radiometer (SXR) is a six-filter radiometer built by NIST for the SeaWiFS Project Science Office at NASA's GSFC [4]. The SXR was deployed in several measurement comparisons between 1995 and 1997. For those comparisons, the SXR was calibrated for radiance against the OL420 integrating sphere source in NIST's FASCAL. The measurement uncertainties of the SXR were 1.6% at 411.2 nm and 1.5% at 774.8 nm (k=1).

2.8 NASA's GSFC SeaWiFS Transfer Radiometer II

The SeaWiFS Transfer Radiometer II (SXR II) is a six-filter radiometer built by NASA's GSFC SIMBIOS project [19]. The SXR II participated in the April 2001 comparison at GSFC. For this comparison, the SXR II was calibrated for spectral radiance responsivity in the NIST SIRCUS facility. The measurement uncertainty of the SXR II is 1.2% at 411 nm and 0.9% at 776.7 nm (k=1).

2.9 NASA's GSFC 746/Integrating Sphere Irradiance Collector

The 746/ISIC [20] employs a scanning single grating monochromator whose entrance port is fitted with a 10.2 cm diameter integrating sphere collector. The 746/ISIC uses a silicon photodiode detector for operation from 400 nm to 1100 nm and a lead sulfide (PbS) detector from 900 nm to 2400 nm. The irradiance responsivity of the 746/ISIC is determined by scanning a 1000W quartz tungsten halogen irradiance standard lamp with calibration traceable to NIST. The 746/ISIC then scans the integrating sphere under test. The sphere radiance is calculated from the sphere irradiance data with knowledge of the diameter of the exit aperture of the sphere under test, the diameter of the aperture of the entrance port integrating sphere, and the distance between those apertures. From 1995 to

1999, the measurement uncertainty of the 746/ISIC was 6.5% at 412 nm, 2.5% at 443 nm, 1.6% at 565 nm, and 1.5% at 665nm (k=1) [21]. At that time, the large uncertainty at 412 nm was attributed to a combination of inadequate out-of-band stray light rejection and differences in the relative spectral shapes of the lamp and OCTS sphere. Since 1999, the measurement uncertainty of the 746 at 412 nm has been found to be attributable not only to stray light but also to non-linearities in the high gain ranges of the 746/ISIC and, to a lesser extent, wavelength uncertainties. This is discussed in the results section of this paper. Current measurement uncertainties of the 746/ISIC are 1.94% at 400 nm, 1.56% at 1000 nm, and 2.22% at 2200 nm (k=1).

3. Radiometric Measurement Comparisons

The 10 EOS radiometric measurement comparisons, 14 radiance sources, and participating radiometers are presented in Table 2. Participation a particular comparison is indicated by an "X" next to the radiometer's name.

4. Results

As seen in Table 1, the filter radiometers made radiance measurements of the 14 radiance sources using filters with different center wavelengths and different relative spectral responses. However, the filter radiometers share several bands nearly coincident in wavelength. These common bands are located at the following averaged center wavelengths: 411.3, 441.5, 552.5, 662.9, 868.0, 1636.0, and 2197.2 nm. In order to compare radiance measurements made by the radiometers at these wavelengths, the band averaged spectral radiances for the filter radiometers were computed according to (1) using a reference radiance spectrum covering the wavelengths and bandwidths of these filter radiometer bands and the relative spectral response functions for each radiometer band.

$$L_c(i,j) = \frac{\int_{\lambda_1}^{\lambda_2} L_{ref}(\lambda) R(i,j,\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} R(i,j,\lambda) d\lambda} \tag{1}$$

In (1), $L_c(i,j)$ is the computed band averaged spectral radiance for band j of radiometer i, $L_{ref}(\lambda)$ is the reference spectral radiance at wavelength λ, $R(i,j,\lambda)$ is the relative spectral response of the radiometer i, band j, and λ_1 and λ_2 are the lower and upper limits of integration, respectively. Table 3 presents the reference radiance spectrum, L_{ref}, used for each measurement comparison. The percent difference, P(i,j), of each radiometer measurement, $L_m(i,j)$, to the computed band averaged spectral radiance, $L_c(i,j)$, is calculated using (2).

$$P(i,j) = 100 \frac{L_m(i,j) - L_c(i,j)}{L_c(i,j)} \tag{2}$$

The deviation of each radiometer % difference, D(i,j), from the average % difference of all the radiometers is then calculated using (3).

$$D(i,j) = P(i,j) - \frac{\sum_{i=1}^{N} P(i,j)}{N} \tag{3}$$

In (3), N is the total number of radiometers compared at common radiometer band j. D(i,j) is plotted in panels a through g of Fig. 1 versus comparison date for each of the common radiometer bands.

5. Discussion

The data of Fig. 1 show the agreement of the transfer radiometer measurements over a wide range of comparison source radiance levels. At each comparison, radiance levels were measured by the radiometers over a dynamic range representative of the range of radiances used in the calibration of the EOS instruments. In order to accurately validate radiance scales, the uniform radiance sources were operated in a manner identical to that used in the calibration of the EOS instruments.

The deviation of the % difference of each radiometer's measurements from the average % difference of all the radiometers shown in Fig.1 provides an upper level measure of the long-term level of agreement of the transfer radiometers. This agreement is an upper limit to the true agreement of the radiometers due to a number of factors, not attributable to the radiometers, contributing to the scatter in the plotted data. Two major contributors to the scatter are instability and irreproducibility in the radiance output from the spheres. A minor contributor to the scatter of the data is relative error as a function of wavelength in the reference spectra used as the bases for the comparison. This is a minor contributor due to the narrow bandwidths of the radiometer channels in the comparison.

In the comparison at 411.3nm presented in Fig.1a, the 746/ISIC instrument was not included for three reasons. Being a single grating instrument, the 746/ISIC is affected by spectral stray light effects from longer wavelengths when operating in the blue. In addition, the 746/ISIC suffers from a non-linearity between the high gain ranges used at 411.3nm. This problem was compensated at the 2001 GSFC measurement comparison by constraining the 746/ISIC to operate on one gain range in this wavelength region. Finally, the cosine collector (i.e. integrating sphere) on the entrance of the 746/ISIC is susceptible to scattered room light. Beginning in 1996, this effect was determined by measuring the scattered light using a beam block and then correcting the 746/ISIC sphere measurement data. The net effect of accounting for gain non-linearities and scattered light improved the 746/ISIC measurement uncertainties from 6.5% to 1.94% (k=1) near 400 nm.

From the data of Fig. 1, the agreement of the transfer radiometers is ±1.80% at 411.3 nm, ±1.25% at 441.5 nm, ±1.31% at 552.5 nm, ±1.28% at 662.9 nm, ±1.32% at 868.0 nm, ±2.54% at 1636.0 nm, and ±2.82% at 2197.2 nm (σ =1). This agreement is within the combined uncertainties of the radiometers compared at each wavelength. Typical radiance calibration specifications for uniform sources used in the pre-launch calibration of EOS satellite instruments are typically ±3% (k=1) for visible through shortwave infrared wavelengths. For visible and near infrared wavelengths, the transfer radiometers are capable of validating the radiance scale of those sources well within the calibration specification. For shortwave infrared wavelengths outside water vapor absorption regions, the transfer radiometers marginally meet the source calibration specifications.

Considering that the transfer radiometers are calibrated at their home institutions using a variety of techniques and then shipped to comparison sites world-wide, the level of agreement of the radiometers is exceptional. The recent realization of a detector-based irradiance scale at NIST [22] will decrease future calibration uncertainties of the radiometers calibrated using standard irradiance lamps. Those radiometers include the UA VNIR, UA SWIR, and 746/ISIC instruments. The detector-based irradiance scale will also improve future agreement between the radiance measurements from these radiometers and those from the NIST and NRLM radiometers and the GSFC LXR. A more accurate determination of the level of agreement of the radiometers can be realized through the application of sphere monitor data to account for sphere drift during the radiometer measurements. Unfortunately, of the 14 radiance sources measured in the EOS comparisons, only 6 sources were monitored; and not all monitors produced useful data. Lastly, the best agreement between the radiometers can be achieved by having each radiometer view a well calibrated, fully characterized uniform radiance source before and after measurements on the comparison sources. In the August 1999 and April 2001 comparisons at NASA's Ames and GSFC, respectively, and in future comparisons, the NIST NPR source will be used in such an evaluation.

6.0 Summary

From February 1995 to April 2001, a total of ten transfer radiometers participated in a radiometric measurement comparisons with the goal of validating the radiance scales assigned to 14 uniform radiance sources used in the calibration of EOS satellite, ground-based, and airborne instruments. The transfer radiometers were independently calibrated in their home institutions using a variety of techniques. The agreement between the radiance measurements made by these radiometers was ±1.80% at 411 nm, ±1.31% at 552.5 nm, ±1.32% at 868.0 nm, ±2.54% at 1622nm, and ±2.81% at 2200nm ($\sigma = 1$), within the combined uncertainties of the radiometer measurements. This level of agreement is sufficient to validate the radiance scales of EOS sources with typical radiance calibration specifications of ±3.0% (k=1).

7.0 References

1. Butler J.J., Johnson B.C., Organization and Implementation of Calibration in the EOS Project Part 1, *The Earth Observer*, 1996, **8**, 22-27.

2. Butler J.J., Johnson B.C., Calibration in the EOS Project Part 2: Implementation, *The Earth Observer*, 1996, **8**, 26-31.

3. Simmons J.D., NIST Calibration Services Users Guide, *NIST Special Publication 250*, U.S. Department of Commerce, Gaithersburg, Maryland, 220pp.

4. Johnson B.C. Fowler J.B., and Cromer C.L., The SeaWiFS Transfer Radiometer, SeaWiFS Postlaunch Technical Report Series, NASA Technical Memorandum, **1**, S.B. Hooker and E.R. Firestone, eds. NASA Goddard Space Flight Center, Greenbelt, Maryland.

5. Walker J.H., Saunders R.D. Hattenberg A.T., Spectral Radiance Calibrations, NBS Special Publication 250-1, U.S. Department of Commerce, National Bureau of Standards, Washington, D.C., 1987, 26pp., appendices.

6. Brown S.W., Johnson B.C., Yoon H.W., Butler J.J., Barnes R.A., Biggar S.F., Spyak P.R., Thome K., Zalewski E., Helmlinger M., Bruegge C.J., Schiller S., Fedosejevs G., Gauthier R., Tsuchida S., Machida S., Matsunaga T., Radiometric Calibration of Field Radiometers in Support of the 1997 Lunar Lake Experiment to Determine Surface Reflectance and Top-of-the-atmosphere Radiance, *Remote Sens. Environ.*, 2001, **77**, 367.

7. Johnson B.C., S.W. Brown, and Yoon H.W., Radiometric Calibration History of Visible and Near-infrared Portable Radiometers, *Metrologia*, 2000, **37**, 423.

8. Brown S.W., Eppeldauer G.P., Lykke K.R., NIST Facility for Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources, *Metrologia*, 2000, **37**, 579.

9. Brown S.W., Johnson, B.C., Yoon H.W., Description of a Portable Spectroradiometer to Verify EOS Radiance Scales in the Short-wave Infrared, *The Earth Observer*, 1998, **10**, 43.

10. Gibson C.E., Tsai B.K., Parr A.C., Radiance Temperature Calibrations, *NIST Special Publication 250-43*, U.S. Department of Commerce, Gaithersburg, MD, 1998, 53pp., appendices.

11. Brown S.W., Johnson B.C., A Portable Integrating Sphere Source for Radiometric Calibrations from the Visible to Shortwave Infrared, *The Earth Observer*, 1999, **11**, 14.

12. Biggar S.F., Calibration of a Visible and Near-infrared Portable Transfer Radiometer, *Metrologia*, 1998, **35**, 701.

13. Biggar S.F., Slater P.N., Preflight Cross-calibration Radiometer for EOS AM-1 Platform Visible and Near-infrared Sources, *Proc. SPIE*, 1993, **1939**, 243.

14. Spyak P.R., Smith D.S., Thiry J., Burkhart C., Short-wave Infrared Transfer Radiometer for the Calibration of the Moderate-resolution Imaging Spectrometer and the Advanced Spaceborne Thermal Emission and Reflection Radiometer, *App. Opt.*, 2000, **39**, 5694.

15. Sakuma F., Kobayashi M, Ono A., ASTER Round-robin Radiometers for the Preflight Cross-calibration of EOS AM-1 Instruments, *Proc. IGARSS*, 1994, 1995.

16. Sakuma F., Bret-Dibat T., Sakate H., Ono A., Perbos J., Martinuzzi J.M., Imako K., Oaku H., Moriyama T., Miyachi Y., Tange Y., POLDER-OCTS Preflight Cross-calibration Experiment Using Round-robin Radiometers, *Proc. SPIE*, 1995, **2553**, 232.

17. Markham B.L., Bomcyk W.C., Helder D.L., Barker, J.L., Landsat-7 Enhanced Thematic Mapper Plus Radiometric Calibration, *Can. J. Remote Sens.*, 1997, **23**, 318.

18. Markham, B.L., Schafer J.S., Wood F.M., Dabney P.W. Barker J.L., Monitoring Large-aperture Spherical Integrating Sources with a Portable Radiometer During Satellite Instrument Calibration, *Metrologia*, 1998, **35**, 643.

19. Meister G.P., Abel P., Barnes R., Cooper J., Davis C., Godin M., Goebel D., Fargion G., Frouin R., Korwan D., Maffione R., McClain C., McLean S., Menzies D., Poteau A., Robertson J., Sherman J., The First SIMBIOS Radiometric Intercomparison (SIMRIC-1), NASA Technical Memorandum 210006, 2002.

20. Johnson B.C., Bruce S.S., Houston J.M., O'Brian T.R., Thompson A., Hooker S.B., Mueller J.L., The Fourth SeaWiFS Intercalibration Round-robin Experiment (SIRREX-4), SeaWiFS Technical Report Series, NASA Technical Memorandum 104566, 1996, **37**, 65pp.

21. Johnson B.C., Sakuma F., Butler J.J., Biggar S.F., Cooper J.W., Ishida J., Suzuki K., Radiometric Measurement Comparison Using the Ocean Color Temperature Scanner (OCTS) Visible and Near Infrared Integrating Sphere, *J. Res. NIST*, 1997, **102**, 627.

22. Yoon H., Gibson C.E., Barnes P.Y., The Realization of the NIST Detector-based Spectral Irradiance Scale, submitted for publication in *Appl. Opt.*, 2002.

Table 1. Visible, Near Infrared, and ShortWave InfraRed Transfer Radiometers Participating in the EOS Radiometric Measurement Comparisons

Radiometer	Institutional Affiliation/Project or Program	Radiometer Wavelengths[1] (Bandwidths[2]) in nm
Visible Transfer Radiometer (VXR)	NIST/EOS Project	***411.8(10.8), 441.0(10.5), 548.4(10.2), 661.4(9.5),*** 775.5(11.1), ***870.0(13.4)***
ShortWave Infrared Transfer Radiometer (SWIXR)	NIST/EOS Project	***800 to 2400(16.5 to 12.5)***
SeaWiFS Transfer Radiometer (SXR)	NIST/NASA's SeaWiFS Project	***411.2(10.8), 441.5(10.3),*** 486.9(10.6), ***547.9(10.4), 661.7(9.57),*** 774.8(11.6)
SeaWiFS Transfer Radiometer II (SXR II)	NASA's SIMBIOS Project	***410.7(9.0), 441.5(9.7),*** 487.6(9.8), ***546.9(9.4), 661.9(10.9),*** 776.7(10.5)
NRLM ASTER Radiometers	NRLM/JAROS ASTER Project	***561(48), 650(56),*** 807(72), ***1608(150), 2181(170)***
NRLM OCTS/POLDER Radiometers	NRLM/NASDA OCTS Project	***445(19),*** 490(20), ***567(24), 670(18),*** 764(37), ***864(42)***
U. of Arizona Visible/Near Infrared Radiometer (UAVNIR)	U.of Arizona	***412.8(14.9), 441.8(11.8),*** 488.0(9.6), ***550.3(9.9), 666.5(9.8),*** 746.9(10.6), ***868.1(14.0)***
U. of Arizona ShortWave Infrared Radiometer (UA SWIR)	U.of Arizona	746.9(10.5), 868.7(12.1), 940.0(16.2), 1243.5(15.7), 1380.8(29.0), ***1646.0(23.4),*** 2133.5(55.1), 2164.2(40.8), ***2207.8(44.5),*** 2262.9(49.3), 2332.2(63.1), 2402.9(70.3)
Landsat Transfer Radiometer (LXR)	NASA's Landsat ETM+ Project	***440.0(10.4),*** 480.7(61.1), 560.7(76.5), ***661.1(9.4),*** 662.3(60.3), 827.0(109.4)
746 Integrating Sphere Irradiance Collector (746/ISIC)	NASA's GSFC	***400 to 1100(10)*** ***900 to 2400(20)***

[1]Comparison wavelengths are in bold italics.

[2]Bandwidths are reported as full width at half maximum (FWHM).

Table 2a. EOS Radiometric Measurement Comparisons: 1995 to 1997

Date	Feb-95		Aug-96		Aug-96	Nov-96	Nov-96	Jun-97		Nov-97
Host Institution	NEC, Japan		Raytheon SBRS, CA		JPL, CA	NEC, Japan	Melco Japan	U. of Arizona AZ		NASA's GSFC MD
Source(s) Measured	2m $BaSO_4$ Sphere	1m $BaSO_4$ Sphere	1m $BaSO_4$ Sphere	1.22m $BaSO_4$ Sphere	1.6m $BaSO_4$ Sphere	1m $BaSO_4$ Sphere	1m $BaSO_4$ Sphere	1m $BaSO_4$ Sphere	0.8m $BaSO_4$ Sphere	1.07m $BaSO_4$ Sphere
Instruments Calibrated by Source(s)	OCTS	ASTER	MODIS ETM+	ETM+	MISR	ASTER	ASTER	Val. Insts.[1]	Val. Insts.[1]	SeaWiFS & Val. Insts.[1]
NIST VXR			X	X	X	X			X	X
NIST SWIXR	X	X	X	X	X					X
UA VNIR	X	X	X	X	X	X			X	X
UA SWIR			X				X		X	X
NRLM/JAROS VNIR		X	X	X	X	X				
NRLM/JAROS SWIR			X				X			
NRLM/NASDA VNIR	X									
GSFC SXR	X	X	X	X	X					X
GSFC SXR II										
GSFC LXR			X	X						X
GSFC 746/ISIC	X	X	X	X	X	X	X			

[1]Validation instruments

Table 2b. EOS Radiometric Measurement Comparisons: 1998 to 2001

Date	May-98	Aug-99			Apr-01		
Host Institution	Raytheon SBRS, CA	NASA's Ames, CA			NASA's GSFC, MD		
Source(s) Measured	1m $BaSO_4$ Sphere	0.76m $BaSO_4$ Sphere	Lamp + Spectralon Panel	0.3m Spectralon Sphere	1.8m $BaSO_4$ Sphere	0.5m $BaSO_4$ Sphere	0.3m Spectralon Sphere
Instruments Calibrated by Source(s)	MODIS ETM+	MAS[2] MASTER[3]	MAS[2] MASTER[3]		Cimels[4] & Val. Insts.[1]	SOLSE[5] LORE[6] TOMS[7] SBUV/2[8]	
NIST VXR	X	X	X	X	X	X	X
NIST SWIXR		X	X	X	X	X	X
UA VNIR	X	X	X	X	X	X	X
UA SWIR	X	X	X	X	X	X	X
NRLM/JAROS VNIR							
NRLM/JAROS SWIR							
NRLM/NASDA VNIR							
GSFC SXR							
GSFC SXR II					X	X	X
GSFC LXR					X	X	X
GSFC 746/ISIC	X	X		X	X	X	X

[1]Validation instruments
[2]MODIS Airborne Simulator
[3]MODIS/ASTER Airborne Simulator
[4]Cimel Sunphotometer
[5]Shuttle Ozone Limb Sounding Experiment
[6]Limb Ozone Retrieval Experiment
[7]Total Ozone Mapping Spectrometer
[8]Solar Backscatter UltraViolet/2 instrument

Table 3. Instruments Providing the Reference Radiance Spectra, L_{ref}, Used in the Comparison of the Radiometer Measurements.

Comparison Site-Date	Radiance Source	L_{ref} Instrument
NEC-February 1995	2 m $BaSO_4$ Sphere	NEC Scanning Spectroradiometer
	1 m $BaSO_4$ Sphere	NEC Scanning Spectroradiometer
Raytheon SBRS-August 1996	1 m $BaSO_4$ Sphere	NASA's GSFC 746/ISIC
	1.22 m $BaSO_4$ Sphere	Raytheon SBRS Cary 14 Spectrometer
JPL-August 1996	1.6 m $BaSO_4$ Sphere	NASA's GSFC 746/ISIC
NEC-November 1996	1 m $BaSO_4$ Sphere	NEC Scanning Spectroradiometer
Melco-November 1996	1 m $BaSO_4$ Sphere	Melco Spectroradiometer
U. of Arizona-June 1997	1 m $BaSO_4$ Sphere	U. of Arizona Analytical Spectral Devices Field Radiometer
	0.8 m $BaSO_4$ Sphere	Optronics Laboratories OL 750S Spectroradiometer
NASA's GSFC-November 1997	1.07 m $BaSO_4$ Sphere	NASA's GSFC 746/ISIC
Raytheon SBRS-May 1998	1 m $BaSO_4$ Sphere	Raytheon SBRS Cary 14 Spectrometer
NASA's Ames-August 1999	0.76 m $BaSO_4$ Sphere	NASA's Ames Analytical Spectral Devices Field Radiometer
	Lamp + Spectralon Panel	NASA's Ames Analytical Spectral Devices Field Radiometer
	0.3 m $BaSO_4$ Sphere	NIST FASCAL Cary 14 Spectroradiometer
NASA's GSFC-April 2001	1.8 m $BaSO_4$ Sphere	NASA's GSFC 746/ISIC
	0.5 m $BaSO_4$ Sphere	NASA's GSFC 746/ISIC
	0.3 m $BaSO_4$ Sphere	NIST FASCAL Cary 14 Spectroradiometer

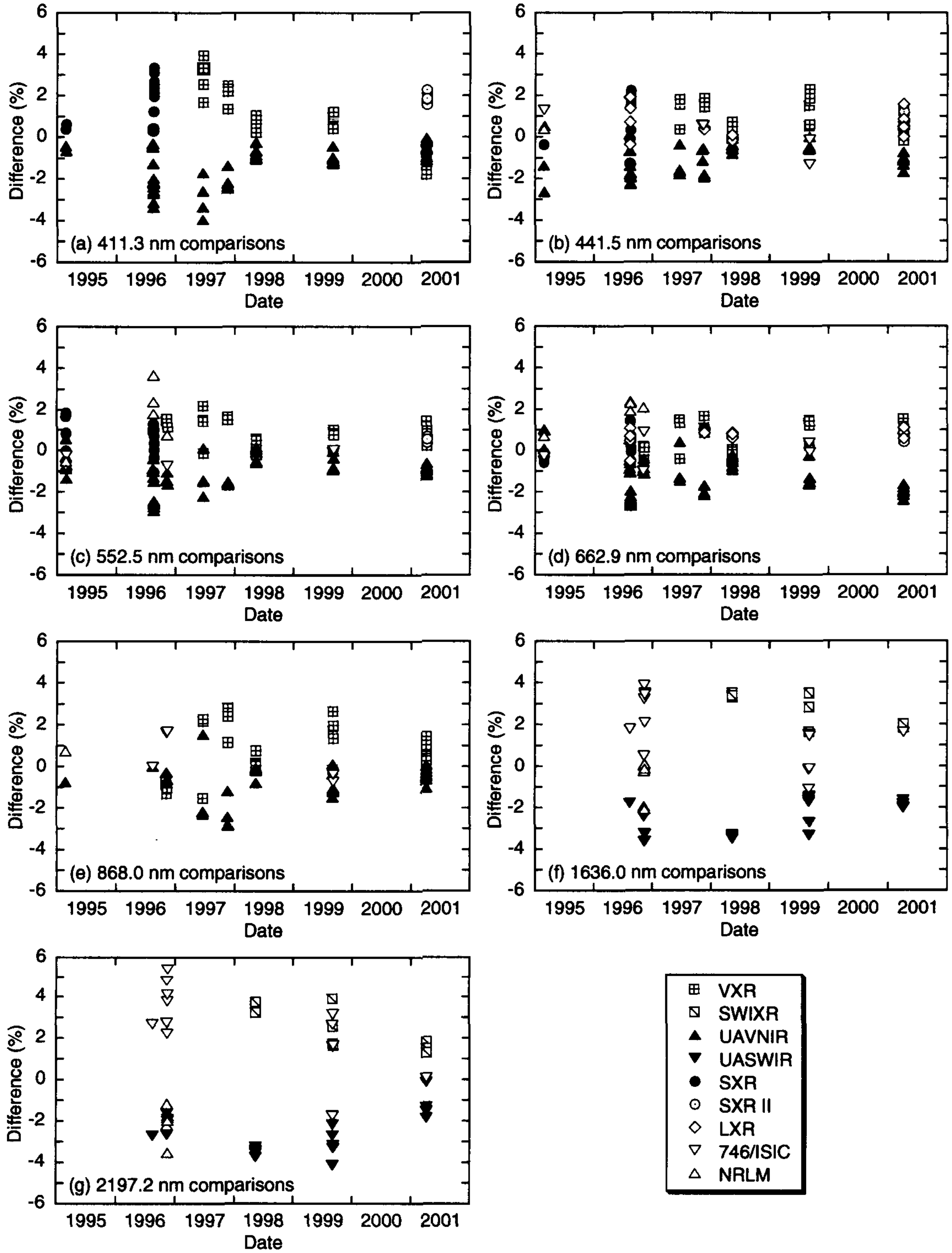
(a) 411.3 nm comparisons
(b) 441.5 nm comparisons
(c) 552.5 nm comparisons
(d) 662.9 nm comparisons
(e) 868.0 nm comparisons
(f) 1636.0 nm comparisons
(g) 2197.2 nm comparisons
Difference (%)
Date
1995 1996 1997 1998 1999 2000 2001
6 4 2 0 -2 -4 -6
VXR
SWIXR
UAVNIR
UASWIR
SXR
SXR II
LXR
746/ISIC
NRLM

Figure Caption

Figure 1. Plots of the % difference of each radiometer's measurements from the average % difference for all radiometers. The data are plotted as a function of measurement comparison date. Data are presented at the following common wavelengths: (a) 411.3 nm, (b) 441.5 nm, (c) 552.5 nm, (d) 662.9 nm, (e) 868.0 nm, (f) 1636.0 nm, and (g) 2197.2 nm.

Summary:

The Use of Transfer Radiometers in Validating the Visible through Shortwave Infrared Calibrations of Radiance Sources Used by Instruments in NASA's Earth Observing System by James J. Butler and Robert A. Barnes

Submitted for publication in ***Metrologia***

The detection and study of climate change over a time frame of decades requires successive generations of satellite, airborne, and ground-based instrumentation carefully calibrated against a common radiance scale. In NASA's Earth Observing System (EOS) program, the pre-launch radiometric calibration of these instruments in the wavelength region from 400 nm to 2500 nm is accomplished using internally illuminated integrating spheres and diffuse reflectance panels illuminated by irradiance standard lamps. Since 1995, the EOS Calibration Program operating within the EOS Project Science Office (PSO) has enlisted the expertise of national standards laboratories and government and university metrology laboratories in an effort to validate the radiance scales assigned to sphere and panel radiance sources by EOS instrument calibration facilities. This state-of-the-art program has been accomplished using ultra-stable transfer radiometers independently calibrated by the above participating institutions. In ten comparisons since February 1995, the agreement between the radiance measurements of the transfer radiometers is ±1.80% at 411 nm, ±1.31% at 552.5 nm, ±1.32% at 868.0 nm, ±2.54% at 1622nm, and ±2.81% at 2200nm ($\sigma = 1$).