Validation of Spectral Radiance Assignments to Integrating Sphere Radiance Standards for the Advanced Baseline Imager

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**ABSTRACT**

The Advanced Baseline Imager (ABI) is the next-generation imaging sensor for the National Oceanic and Atmospheric Administration’s (NOAA’s) operational meteorological satellites in geostationary orbit. One pathway for traceability to reference standards of the visible and near-infrared radiometric response for ABI is to a 1.65 m diameter integrating sphere source standard of spectral radiance. This source illuminates the full entrance pupil via the ABI Earth-view port, thus determining the absolute spectral radiance responsivity in the visible and shortwave infrared. The spectral radiance values of the large sphere are assigned by Exelis using a double monochromator and a 15.24 cm diameter integrating sphere source standard that is calibrated by NIST. As part of the ABI program, Exelis was required by NASA to have the spectral radiance values assigned by Exelis to the large sphere be validated by NIST. Here we report the results of that activity, which took place in April, 2013. During the week of April 8, Exelis calibrated the 1.65 m diameter sphere at all 24 levels that correspond to the ABI calibration protocol. During the week of April 15, the NIST validation exercise for five selected levels took place. NIST deployed a portable spectral radiance source, a filter radiometer restricted to the visible and near-infrared, and two spectroradiometers that covered from 350 nm to 2500 nm. The NIST sphere source served as the validation standard. The comparison results, which are reported at the ABI bands, agreed to within the combined uncertainties. We describe the methodology, results, and uncertainty estimates related to this effort.

**Keywords**: Calibration, integrating sphere sources, spectral radiance scales, uncertainty estimates, validation

# INTRODUCTION

The Advanced Baseline Image (ABI) is the next generation imaging sensor for the National Oceanic and Atmospheric Administration’s (NOAA’s) operational meteorological satellites in geostationary orbit [[1](#_ENREF_1)]. One pathway for traceability to reference standards of the visible and near infrared radiometric response for the ABI instrument is to a laboratory standard of spectral radiance, as provided by the Exelis 1.65 m (65″) integrating sphere source (a.k.a “large sphere”). This source illuminates the full entrance pupil via the Earth-view port, thus determining the ABI spectral radiance responsivity in the visible and near infrared (VNIR) and shortwave infrared (SWIR). The spectral radiance values of the large sphere are assigned by Exelis using a Gooch & Housego (Optronic Laboratories, Inc.) double monochromator (model OL 750 M‑D)# and an Exelis 15.24 cm integrating sphere source (calibrated by NIST in November 2011) and termed the “small sphere”.

As part of the validation of ABI, the National Aeronautics and Space Administration (NASA) and the National Institute of Standards and Technology (NIST) developed a work plan that included measurements of the radiance values assigned to the large sphere by Exelis be validated by NIST. This report is a brief description of that activity, which took place in April, 2013. During the week of April 8, Exelis calibrated the large sphere at all 24 levels that correspond to the ABI Vis/NIR calibration protocol, with repeats at the five levels selected for the NIST validation exercise. During the week of April 15, the NIST validation exercise took place.

# PROCEDURE

The validation activities were developed by NIST in collaboration with Exelis, NASA, and NOAA. The primary test involved determinations of the large sphere’s spectral radiance at a pre-selected set of lamp levels using NIST equipment, personnel, and procedures. Table 1 gives a description of the NIST equipment. A NIST-calibrated portable integrating sphere radiance standard, the NIST Portable Radiance (NPR), served as the radiometric standard source, and all results reported here are referenced to the NPR. As described in [[2](#_ENREF_2)], the NPR is a 30.5 cm (12”) diameter, 10.2 cm (4”) diameter exit aperture, Spectralon® sphere with four internal lamps and two internal monitor detectors. The NPR is operated at constant current utilizing an Agilent 6644A power supply. Housekeeping data, including the lamp current as monitored with a shunt resistor, is recorded using an Agilent 34970A data acquisition unit. The NPR is housed in two shipping containers, one housing the sphere source and the other housing the electronics. Three radiometers were used as transfer radiometers: the Visible Transfer Radiometer (VXR) [[3](#_ENREF_3)], a six channel filter radiometer similar in design to the SeaWiFS Transfer Radiometer described in [[4](#_ENREF_4)], covered the range from 412 nm to 870 nm. Two commercial spectroradiometers were used; model SR-3500 from Spectral Evolution, Inc. (SEI), and model FieldSpec 3 from ASD, Inc. Both are fiber-coupled, portable instruments covering the spectral range from 350 nm to 2500 nm.

**Table 1**. NIST radiometric equipment for the validation exercise. In the fourth column the bandpass is stated along with the wavelength increment, shown in parenthesis.

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| --- | --- | --- | --- |
|  **Item**  | **Sub-systems** | **Spectral coverage [nm]** | **Bandpass (sampling) [nm]** |
| Spectral radiance standard (NPR) | 4 lamps, 2 internal filtered photodiodes | 250 to 2500 | 10 |
| Filter radiometer (VXR) | 6 channels | 412 to 870 | 10 |
| SR-3500 spectroradiometer | VNIRSWIR1SWIR2 | 342 to 1000980 to 18941860 to 2505 | 3.5 (0.8 to 1.5)10 @ 1500 (3.3 to 4)7 @ 2100 (2.1 to 2.9) |
| FieldSpec 3 spectroradiometer | VNIRSWIR1SWIR2 | 350 to 10001001 to 18001801 to 2500 | 3 @ 700 (1.3)10 @ 1400 (2)10 @ 2100 (2) |

To execute the validation measurements, NIST designed and built a portable radiance bench utilizing the series of X95 structural rails and carrier platforms from Newport Corporation. NIST also designed and built a portable and adjustable structural frame for the sphere crate of the NPR from 80/20® hardware. Starting at the source end of the 1.5‑m long rail, the components were: a removable, on-axis, 7.62 cm diameter obscuration (a.k.a. the “on‑axis disk”), a two-way alignment laser, the FieldSpec 3 or the SR-3500, the VXR, and a second, rear, alignment laser. An alignment target was also utilized. Except for the VXR, all the components could be removed and replaced on the rail using kinematic mounts. The purpose of the on-axis disk was to block the central, geometrically-defined target area of the radiometers while not affecting the radiance in the sphere’s exit aperture in the concentric region observed by the radiometers between the disk edge and the edge of the sphere aperture, thus determining the size-of-source contribution to the radiometer’s signals. This source of bias is due to the out-of-field response, especially significant in the VXR at 870 nm, combined with the effect of observing different exit diameters: 50.8 cm for the large sphere and 10.2 cm for the NPR. We term the measurements with the on-axis disk in place “ambient,” those with it removed “light,” and those with the lens cap in place for the VXR “background.” The SR‑3500 and the FieldSpec 3 have automated internal shutters for background measurements. Lastly, NIST used a Fluke 1620A thermo-hygrometer to record ambient temperature and relative humidity. All testing was done in the Remote Sensing Laboratory (RSL) at NIST, Gaithersburg, MD, and the validation exercise took place in the Test and Integration Cleanroom at Exelis, Ft. Wayne, IN.

For the measurements, the VXR was located 105 cm from the either sphere’s exit aperture, measured from its faceplate. The lens focus setting was 0.85 m at f/1.4 and the temperature of the bandpass filters and silicon photodiode detectors was held at 26 °C using thermoelectric cooling, controlled to ±0.1 °C by an ILX Lightwave 5910B unit. The gain for the VXR internal voltage amplifier was set to unity for all sphere levels. The SR‑3500, which was fitted with the 2° foreoptic, and the FieldSpec 3, which was fitted with a 5° full field-of-view (FOV) Gershun tube, were located about 30 cm from the sphere’s exit apertures. Both the FieldSpec 3 and the SR-3500 are actually three systems; a silicon photodiode array spectrograph for the Vis/NIR and either two scanning monochromators with single thermoelectrically cooled InGaAs detectors (FieldSpec 3) or two thermoelectrically cooled InGaAs photodiode array spectrographs (SR‑3500) for the SWIR. The silicon detectors are not temperature stabilized.

The Exelis large sphere has 20 internal, baffled lamps, one InGaAs monitor detector and one Si monitor detector (both temperature stabilized). The rated lamp power ranged from 50 W to 600 W, see Table 2. The Si and InGaAs monitor detectors each have a six-position filter wheel, but only three positions are populated using witness filters from the ABI instrument; the nominal center wavelengths are at 470 nm, 640 nm, and 860 nm (Si monitor) and 1.378 µm, 1.61 µm, and 2.25 µm (InGaAs monitor), to coincide with the ABI channels 1 to 6 [[1](#_ENREF_1)]. The original manufactured configuration had 22 positions equally spaced around the exit aperture, e.g., separated by 16.36° in azimuth, with the 20 lamps and two internal monitors populating the 22 positions. Later, the monitor detectors were mounted outside the sphere, just below the exit aperture and aligned to view the back wall. In the numbering system from 1 to 22 (when facing the sphere, we define position 1 as the top and the azimuth angle ϕ as positive clockwise), the monitors were at positions 12 and 15. Later, the monitors were removed and the openings closed using polytetrafluoroethylene (PTFE) ports, leaving a gap in azimuth between lamp positions 11 to 12 and 13 to 14. The interior of the sphere is coated with Optowhite™, which utilizes BaSO4. Lamp position 9 has a variable attenuator for final adjustment of radiance levels. The maximum exit aperture diameter is 76.2 cm (30”) but for the April 2013 validation all measurements were made with a 50.8 cm reducing aperture. The large sphere is water-cooled and operated in constant current mode using separate power supplies for each lamp. More details can be found in the Exelis reference documents [[5](#_ENREF_5), [6](#_ENREF_6)].

**Table 2**. Exelis equipment for the validation exercise.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Item | Diam.[cm] | Aper. Diam. [cm] | Coating | No. of Lamps | Wattage | Calibration Date | Issuer |
| **Large Sphere** | 165.1 | 50.8 | BaSO4 | 112115 | 5075150300600 | Apr 8 to 12, 2013 | Exelis |
| **Small Sphere** | 15.24 | 3.81 | Spectralon® | 1 | 30 | Nov 2011 | NIST |

The Exelis 15.24 cm (6”) small sphere has one 30 W external lamp, see Table 2. The diameter of the exit aperture is 3.81 cm (1.5”) and the interior is made from Spectralon®. It was calibrated at the NIST Facility for Spectroradiometric Calibrations (FASCAL) in November, 2011 from 300 nm to 2400 nm in steps of 25 nm [[7](#_ENREF_7)]. Prior to the start of the April 8, 2013 calibration of the large sphere, the small sphere had 21.5 lamp hours since the FASCAL calibration.

At NIST, for testing the X95 radiometric bench setup, it was supported on a 1.52 m by 3.05 m laser table with a surface 0.99 m from the floor; at Exelis the rail was supported on a 1.22 m by 1.83 m laser table with a surface 0.62 m from the floor. In either case, the bench was parallel to the long dimension of the table. At NIST the NPR sphere containing the integrating sphere source was raised to the correct height using the 80/20 frame and placed at the edge of the laser table so the bench was aligned perpendicular to the exit aperture. At Exelis, the NPR sphere crate and the Exelis small sphere were placed at one end of the laser table and the large sphere at the other, so the spheres faced each other. In order to change spheres, the transfer radiometers on the rail were rotated 180° and realigned to the sphere under test.

Prior to any radiometric measurements, the radiometric bench was aligned to the sphere under study. First, the X95 rail was leveled, and the optical axis defined using a self-leveling, two-way (beams 180° apart) alignment laser. The height of the laser and the rotation about the vertical axis were adjusted so the laser was centered on the large sphere’s exit aperture and the optical axis was parallel and centered on the radiometric bench. The 80/20 NPR frame was assembled and adjusted to locate the center of the NPR’s exit aperture onto the optical axis. Using glass slides held against the integrating sphere’s aperture cover plates to retroreflect the alignment laser, the large sphere and the NPR were made normal to the optical axis. A second alignment laser was mounted at the back of the bench, and co‑aligned to the two-way laser. The obscuration disk and the spectroradiometer foreoptics, without the optical fibers connected were aligned to the optical axis using the back alignment laser. Using the lasers, it was verified that the disk, SR‑3500, or FieldSpec 3 could be removed and replaced onto the bench without affecting the results. Finally, the VXR was mounted and aligned using both the visual, on-axis sighting with the eyepiece and by removing the eyepiece and using the back alignment laser to reverse-illuminate the VXR with co-alignment to the front, two-way laser. Figure 1 is a photograph of the SR-3500 aligned to measure the large sphere, with the on-axis disk in place (not visible due to camera saturation).

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| Figure 1. Making adjustments of the SR-3500 when viewing the large sphere. |

The overall approach was to calibrate the three NIST radiometers using the NPR, measure the large sphere at five predetermined levels, and assess the stability and repeatability of the three radiometers by repeating the measurements of the NPR. The test plan was formulated prior to the validation exercise, see [[8](#_ENREF_8)]. In addition, the Exelis small sphere was measured using the SR‑3500 and the FieldSpec 3 (its exit aperture is too small for the VXR’s FOV). The NPR, and a non-travelling version of this source named NPR‑II, are measured routinely in the RSL, and data acquired before and after the deployment to Ft. Wayne are used to assess stability for the Ft. Wayne deployment. To independently assess the wavelength stability, we also performed wavelength validations of the SR‑3500 and FieldSpec 3 using Hg(Ar), Kr, and Xe pen lamps, as well as transmitting samples with known spectral absorption features – a polyester film (Mylar) and a NIST Standard Reference Material (SRM) 2065. The general procedures followed at Exelis for these tests on the NIST bench was as follows (after the initial set up and alignment): 1) set the sphere level and allow it to stabilize; 2) record the lamp voltages manually and acquire a set of sphere monitor readings; 3) background, ambient, and light with the VXR; 4) ambient, light, and background with the SR‑3500 or the FieldSpec 3; 5) ambient, light, and background with the FieldSpec 3 or the SR‑3500; 6) repeat background, ambient, and light with the VXR; 7) run the large sphere housekeeping program that recorded the monitor signals; and 8) change levels and repeat steps (1) to (7).

Five of the possible 24 ABI levels on the large sphere were selected for validation, termed Level 1, 5, 8, 14, and 24. Level 24 was the lowest possible setting, and the SNR of the FieldSpec 3 was insufficient in the SWIR to make a measurement at the required precision. Consequently, we added Level 22 to the measurement schedule on the second day (April 17, 2013). The configuration of the large sphere levels is given in Table 3. For all levels studied, the sphere is not illuminated symmetrically, which would be expected to impact the uniformity of the radiance in the exit aperture. The sphere uniformity was not quantified in this study. The most asymmetrically-illuminated level were Level 22 and 24, where only lamps in the upper right quadrant were on. Note the range in total lamp rated power varied by more than two orders of magnitude for Level 1 to Level 24.

**Table 3**. Lamp configurations for the large sphere at the six validation levels. When facing the sphere, position 1 is at the top and the azimuth angle ϕ is positive clockwise.

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| Position | ϕ [°] | Rating [W] | LevelRated Power [kW] |
|  |  |  | **1****7.325** | **5****4.200** | **8****2.025** | **14****0.900** | **22****0.225** | **24****0.075** |
| **1** | 0 | 75 | x |  | x |  | x | x |
| **2** | 16.36 | 600 | x |  |  |  |  |  |
| **3** | 32.73 | 600 | x |  |  |  |  |  |
| **4** | 49.09 | 600 | x | x |  |  |  |  |
| **5** | 65.45 | 150 | x | x | x |  | x |  |
| **6** | 81.82 | 600 | x | x |  |  |  |  |
| **7** | 98.18 | 300 | x | x |  | x |  |  |
| **8** | 114.6 | 150 | x | x |  |  |  |  |
| **9** | 130.9 | 600 |  |  |  |  |  |  |
| **10** | 147.3 | 600 | x | x |  |  |  |  |
| **11** | 163.6 | 600 |  |  | x |  |  |  |
| **12** | 196.4 | 600 | x |  |  |  |  |  |
| **13** | 212.7 | 600 | x |  |  |  |  |  |
| **14** | 245.5 | 600 |  | x | x |  |  |  |
| **15** | 261.8 | 600 | x |  |  |  |  |  |
| **16** | 278.2 | 600 | x | x |  |  |  |  |
| **17** | 294.6 | 50 | x |  |  |  |  |  |
| **18** | 310.9 | 600 | x | x |  |  |  |  |
| **19** | 327.3 | 600 | x |  | x |  |  |  |
| **20** | 343.6 | 600 |  |  |  | x |  |  |

# ANALYSIS AND RESULTS

## Data sets

The data set for each VXR measurement condition (which sphere and level; background, ambient, or light mode) consist of two files, one with the multiple readings and the other with the average and standard deviation. The timestamp, viewing mode (ambient, background, signal), gain, and number of readings are recorded. For each set of ambient, background, or light, data were acquired for 5 minutes, corresponding to 5 sets of 11 readings for each of the 6 VXR channels. For Level 1 on April 16 and Levels 5, 8, 14, 22, and 24 on April 17, the VXR measured twice – once before the two NIST spectroradiometers and once after.

The data set for each SR‑3500 measurement condition (which sphere level; ambient or light mode) consists of 11 or 12 sequential files in which header information is followed by the output counts (digital numbers, DN) as a function of wavelength from 341.8 nm to 2505.4 nm. The SR-3500 output data in DN correspond to the readings from the 1024 individual detector pixels. The header contains instrument identifier, timestamp, internal temperatures, integration times, and other housekeeping data. In the SEI files, the regions of overlap (974 nm to 1000 nm and 1859 nm to 1894 nm) are useful as a validation tool. For each condition, the data sets were normalized by integration time and averaged and a Type-A uncertainty was determined. Then the net, normalized results (now in DN/ms) were found by subtracting the mean ambient signal from the mean light signal.

The data set for each FieldSpec 3 measurement condition (which sphere level; ambient or light mode) consists of 20 sequential scans, stored in one file, in which header information is followed by the output counts (DN) as a function of wavelength from 350 nm to 2500 nm. The data area acquired using NIST custom software. The scans are taken alternately with the internal shutter closed (dark) and the internal shutter open (light) so that there are 10 scans of each. The header information contains detailed housekeeping data and the timestamp or internal gain for each of the scans. There are three spectral regions reported that correspond to the three FieldSpec 3 spectrographs, but no overlap data are supplied. Also, the FieldSpec 3 output data in DN have been resampled onto a 1 nm grid. For each file, the 10 dark and light scans were subtracted (for the VNIR array only), normalized by the integration time or gain, then averaged and a Type-A uncertainty was determined. Then the net, normalized results were found by subtracting the mean ambient signal from the mean light signal.

The control program for the NPR records the voltage across the shunt resistor, the output of the two monitor photodiodes, and the voltage drop across each of the four lamps at the lamp connector. Measurements are made every 10 s, with the time recorded along with every reading.

There are three data sources for the large ABI sphere. First, the output of the internal monitor detectors is displayed as a function of time during operation for operator examination, in particular to determine if the system has stabilized and is ready for measurements. Second, during some point of measuring a particular level, and after the sphere had stabilized for that level, the lamp voltages were recorded manually in the comparison notebook. Third, at the beginning and end of the measurement sequence for each level, the sphere control program was directed to issue a “Radiance Report.” This produced a timestamped file, with averages and standard deviations for each of the three filter configurations for each of the two detectors. At the time of the validation, the ABI calibration plan called for utilizing the Radiance Report data to adjust the spectral radiance calibration values at the ABI bands and in this way hold the radiance scale. As such, evaluation of their veracity was a part of the validation exercise.

## System stability – Exelis

During the validation exercise on April 16 and 17, the manually-recorded lamp voltages at each lamp position were repeatable to ±0.3 % except for the 75 W lamp in position 1, used in Level 1, 8, 22, and 24, where the repeatability was +0.5 % and -0.3 %. The maximum change in voltage was 0.7 V for lamp position 15 on the repeat of Level 1. The typical maximum change in lamp voltage was 0.1 V to 0.2 V.

The normalized sphere monitor signals recorded using the “Radiance Reports” during the calibration and validation of the large sphere are plotted as a function of time in Fig. 2a and as a function of wavelength in Fig. 2b. The time interval includes the week of the Exelis calibration and the week of the NIST validation. The normalization is to the average for the same channel and level. The majority of the results are within ±1.0 %. The exceptions are two instances with the 470 nm monitor channel (crosses in Fig. 2a) that are at Level 1, and values for Level 24 and all three channels in the InGaAs monitor that appear as outliers – as low as 0.957 and as high as 1.114 in Fig. 2a. The 470 nm channel data are more variable than the other two Si monitor channels. Note if Level 24 is excluded, even the cirrus band at 1.378 µm is repeatable to within ±1.0 %.

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| Figure 2. a) left graph, illustrates the temporal history of the large sphere monitor detectors during the calibration and validation exercises; b) right graph, illustrates this variability as a function of wavelength. The normalization was to the average monitor signal for each channel and level, and all levels are illustrated. |

We compared the average monitor signals, for all levels, during the calibration (*S*c) to those during the validation (*S*v). For the 640 nm, 860 nm, 1.61 µm, and 2.25 µm channels, the agreement was better than 0.3 %, comparable to the standard deviation over level. The average ratio *S*c/*S*v for the 1.378 µm channel was 1.011 with a standard deviation over level of 0.018; if Level 24 is excluded the average ratio is 1.0038 with a standard deviation of 0.003. The average ratio for the 470 nm channel is 0.99 with a standard deviation of 0.004, indicating that overall the monitor readings at 470 nm during the validation were greater than those during the calibration.

## System stability – NIST

To quantify the drift in the combined system of NIST radiometers and the NPR, the VXR, SR-3500, and FieldSpec 3 measured the NPR before, during, and after the deployment. The spectroradiometer net signals have been band-averaged as described below. The results, normalized by the channel averages, are plotted in Figs. 3a and 3b. The VXR/NPR system was repeatable to +0.3 %, -0.4 % from March 26 to May 2, 2013. The SR-3500 and FieldSpec 3 results were taken from April 10 to May 2. The majority of the SR-3500 results fall within ±0.5 %, with the exception of the water-vapor band at 1378 nm, which was repeatable to ±1.5 %. At the water-vapor band, the repeatability of the FieldSpec 3 was comparable to the SR-3500, but elsewhere the FieldSpec 3 was more variable than the SR‑3500.

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| Figure 3. a) left graph, illustrates the temporal history of the NPR before and after the deployment for the three NIST radiometers; b) right graph, illustrates this variability as a function of wavelength. The normalization was to the average signal for each channel. |

To quantify the repeatability of the ABI levels, the NIST radiometers measured the 6 levels of the large sphere on the separate operations on April 16 and April 17. In addition, the VXR was used to assess the stability of a level during continuous operation by acquiring a second set of measurements. The VXR results are shown in Fig. 4. These duplicate measurements indicate for the majority of the levels in the VNIR region, the stability of the large sphere (LS) spectral radiance at a particular level is 0.05 % or better over the approximately 20 min interval between VXR measurements. The exceptions are at Level 1, where the VXR signals changed by 0.1 % at 412 nm and 0.2 % at 440 nm, and Levels 5 and 8, where the VXR signals changed by 0.08 % at 412 nm. The repeatability of the levels on the two measurement days was within ±0.4 % at 412 nm to ±0.1 % at 870 nm, see Fig. 4b.

Comparisons of Figs. 2, 3, and 4 lead to these conclusions in the blue spectral region (412 nm to 470 nm): 1) at 412 nm and 440 nm, the VXR is stable to ±0.2 % or less, see Fig. 3a; 2) at 412 nm and 440 nm with the VXR, the 6 levels of the large sphere are less repeatable (at ±0.4 %) than the NPR (at ±0.2 %), see Fig. 3b and Fig. 4b; and 3) the large sphere monitor at 470 nm is less stable, at ±1.5 %, than the other ABI sphere VNIR monitor channels or the VXR at all channels, see Fig. 2b.

The wavelength calibration data of the SR-3500 and FieldSpec 3 was analyzed according to the type of source. For the scans of atomic emission lines, the observed wavelength was determined from a moment analysis. For the scans of the Mylar or 2065 filter, the absorption features were fitted to a cubic polynomial and the minimum value determined. The three spectral regions were analyzed separately for each spectroradiometer. The differences were fitted to a straight line to determine the average offset, and the uncertainty in these means was taken as the spectroradiometer’s wavelength uncertainty. In the final analysis, the resolution and accuracy of these methods for evaluating the stability of the wavelength calibration of the SR‑3500 and the FieldSpec 3 made it difficult to quantify any change, and any effects of changes in the wavelength calibration were accounted for implicitly by observing the long term drift in measurements of the NPR.

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| Figure 4. a) left graph, illustrates the temporal history of the LS during the validation deployment for the VXR; b) right graph, illustrates this variability as a function of wavelength. The normalization was to the average signal for each channel and level. |

## NIST validation analysis

The measurement equations are based upon band averaging. For the VXR, the necessary information is the spectral responsivity for each channel, $r\_{V}(λ)$ and the spectral radiance *L*(λ) of the observed source. When the calibration values supplied by Exelis are used, *L*E(λ), we derive a predicted signal, *S*p,E for each VXR channel according to

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Similarly, for a spectral radiance $L\_{N}\left(λ\right)$ of the radiometric reference standard, the NIST NPR, the predicted signal is

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When the spectral radiance responsivities values are absolute, the units of *S*p,E are volts and the values can be compared directly to the signals measured during the validation. However, using NPR as a source standard allows the use of ratios between signals so relative units for spectral responsivity can be substituted because the absolute magnitudes cancel. With the measured signals indicated by the subscript “m,” the validation measurement equation for the VXR is

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If we define the left hand (predicted) ratio to be $R\_{p}$ and the right hand (measured) ratio to be $R\_{m}$we see we have cast the validation exercise into the question, “does $R\_{p}$ = $R\_{m}$?”

For the spectroradiometers, a similar approach was followed, where the spectral responsivities used were the six VXR channels the six ABI LS monitor channels, with relative responsivity data provided by Exelis. The widths of the ABI monitor channels were 17 nm at 1380 nm, 35 nm at 470 nm and 640 nm, 45 nm at 1610 nm and 2250 nm, and 88 nm at 640 nm. As before, for each responsivity data set we have

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where the subscript V/ABI indicates the channel is either one of the VXR or ABI sphere monitors. A similar expression holds for measurements of NPR (subscript N). The spectroradiometers report a set of values $S\_{m,{E}/{N}}(λ)$, which are then used in conjuction with the known radiance of the NPR sphere to report a measurement of the sphere under observation:

 

Note that due to the use of the NPR to calibrate the spectroradiometers, $S\_{m,N}=S\_{p,N}$, and Eqns. (1.4) and (1.5) can be used as with the VXR in Eqn. (1.3). In all cases, the measured signals were corrected for spatial out-of-field using the on-axis obscuration disk. The correction factors for this size-of-source effect (SSE) are given in Table 4. The correction factors are the ratio of the net signal using the ambient mode for the offset to the net signal using the background mode for the offset. As expected the bias, in relative terms, was independent of level and so the average was used; we report the means and the standard deviations for each instrument in Table 4.

**Table 4**. Size-of-source correction factors from averaging over all levels, reported as mean (standard deviation).

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| --- | --- | --- | --- |
| Wavelength [nm] | VXR | SR-3500 | FieldSpec 3 |
| 411.81 | 0.9950 (0.0006) | 0.99637 (0.00011) | 0.9952 (0.0020) |
| 440.98 | 0.9976 (0.0004) | 0.99664 (0.00005) | 0.9959 (0.0008) |
| 478.34 |  | 0.99687 (0.00003) | 0.9952 (0.0001) |
| 548.23 | 0.9983 (0.0001) | 0.99704 (0.00002) | 0.9949 (0.0002) |
| 650.50 |  | 0.99706 (0.00001) | 0.9942 (0.0000) |
| 661.37 | 0.9983 (0.0001) | 0.99719 (0.00001) | 0.9942 (0.0000) |
| 775.19 | 0.9899 (0.0001) | 0.98960 (0.00003) | 0.9859 (0.0001) |
| 869.68 | 0.9573 (0.0002) | 0.98829 (0.00007) | 0.9828 (0.0001) |
| 872.04 |  | 0.98823 (0.00006) | 0.9828 (0.0002) |
| 1387.02 |  | 0.98305 (0.00006) | 0.9840 (0.0031) |
| 1620.25 |  | 0.98264 (0.00006) | 0.9839 (0.0028) |
| 2270.70 |  | 0.98152 (0.00206) | 0.9845 (0.0029) |

# UNCERTAINTIES

The uncertainty estimates follow the Expression of Uncertainty in Measurement (GUM) [[9](#_ENREF_9)]. We report the validation uncertainties at the VXR and ABI wavelengths. Common to all three instruments are the uncertainties in the spectral radiances of the sphere sources. For the NPR and the small sphere, these were determined from the FASCAL calibration reports by linear interpolation and converted to standard uncertainties. They are Type B uncertainties. For the large sphere, linear interpolation in the reported values from the Exelis calibration report was performed. For the validation, all of these components are Type B. There is uncertainty associated with the interpolation of the input spectral radiance and spectral responsivity data, as well as the numerical integrations of Eqns. (1.1), (1.3), (1.4) and (1.5). The results reported in Tables 5 – 8, termed *u*i, are based on previous comparisons and experience. They are Type B components. The alignment of the radiometers to the spheres was within 0.5 mm in position within the large sphere exit aperture and within 0.1 mr (0.057°) in tilt. These are sufficient in our estimate to reduce the alignment uncertainty to negligible values.

The uncertainties of the averaged SR-3500 and FieldSpec 3 measurements of the small sphere are given in Table 5. The measurement uncertainty for each run, *u*m, is negligible in almost all cases. The system stability term, *u*s, refers to the repeatability of the SR-3500 and FieldSpec 3 – NPR systems. It was estimated from the uncertainties in the means of a 6-month long time series in 2012 at the 12 wavelengths (VXR and ABI). Ten of the 12 channels showed strong correlation between the SR-3500 and the FieldSpec 3, and we use the average rather than the root-mean-square to estimate *u*s. The ABI channels at 1610 nm and 2250 nm were uncorrelated between the two instruments and the root-mean-square was calculated to give *u*s. The measurement uncertainty, *u*m, is the uncertainty in the mean for the sequential scans of a particular level. The linearity of the SR-3500 or the FieldSpec 3 has not been determined. For the small sphere, this uncertainty component is negligible as this sphere is similar in radiance to the NPR. Also, since its exit aperture diameter is small, the uncertainty due to spatial out of field is negligible. The wavelength uncertainty of the SR‑3500 and FieldSpec 3 was also found to have negligible impact on the uncertainty budget. The combined standard uncertainties from the residual sum of squares (RSS) are between 0.63 % and 4.89 %.

**Table 5.** Uncertainty components for the measurement of the small sphere using the SR‑3500 and the FieldSpec 3. These standard uncertainties are reported in percent. SS stands for small sphere.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **λ [nm]** | 412 | 441 | 478 | 548 | 650 | 661 | 775 | 870 | 872 | 1387 | 1620 | 2271 |
|  | VXR | VXR | ABI | VXR | ABI | VXR | VXR | VXR | ABI | ABI | ABI | ABI |
| **Radiance Scale** |
| NPR | 0.57 | 0.52 | 0.47 | 0.40 | 0.33 | 0.33 | 0.30 | 0.25 | 0.25 | 0.59 | 0.61 | 0.77 |
| SS | 0.57 | 0.52 | 0.46 | 0.41 | 0.34 | 0.33 | 0.32 | 0.26 | 0.26 | 1.88 | 0.59 | 0.73 |
| **Instruments & NPR** |
| *u*m | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.08 |
| *u*i | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Instruments and Small Sphere** |
| *u*m | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.08 |
| *u*i | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Common** |
| *u*s | 0.43 | 0.45 | 0.50 | 0.58 | 0.51 | 0.51 | 0.51 | 0.49 | 0.49 | 4.47 | 1.07 | 1.13 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| **RSS**  | 0.95 | 0.88 | 0.84 | 0.83 | 0.71 | 0.71 | 0.69 | 0.63 | 0.63 | 4.89 | 1.37 | 1.56 |

Table 6 reports the uncertainty components for the VXR validation measurements of the large sphere. The uncertainty in radiance scales is as described above. The Type A measurement uncertainty, *u*m, for the NPR was determined from the average of the uncertainties in the mean net signals (using background mode) for the each of the pre- through post-measurements; it is negligible, with values less than 0.001 %. For the large sphere, we did the same calculation, but averaged over all levels. The results were also negligible, with values less than 0.002 %. The system stability term, *u*s, refers to the repeatability of the VXR – NPR system. It was estimated from the uncertainty in the mean measurements of the NPR pre though post validation (see Fig. 4). The linearity of the VXR was measured during its initial characterization in the mid-90s, and from that we estimate the component associated with nonlinearity, *u*φ, to be 0.1 %. We take the uncertainty in the size-of-source correction using the on-axis disk, *u*d, to be 10 % of the correction. The wavelength scale of the VXR spectral responsivities is very accurate, being derived from laser-based sources, and we do not include an uncertainty component for this effect. The combined uncertainty is between 0.92 % and 1.23 %.

**Table 6.** Uncertainty components for the measurement of the large sphere using the VXR. These standard uncertainties are reported in percent.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **λ [nm]** | 412 | 441 | 548 | 661 | 775 | 870 |
|  | VXR | VXR | VXR | VXR | VXR | VXR |
| **Radiance Scales** |
| NPR | 0.57 | 0.52 | 0.40 | 0.33 | 0.30 | 0.25 |
| LS | 1.05 | 1.05 | 0.97 | 0.89 | 0.85 | 0.86 |
| **VXR & NPR** |
| *u*m | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *u*i | 0.20 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| **VXR & LS** |
| *u*m | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *u*i | 0.20 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| **Common** |
| *u*s | 0.03 | 0.05 | 0.04 | 0.03 | 0.06 | 0.09 |
| *u*φ | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| *u*d | 0.05 | 0.02 | 0.02 | 0.02 | 0.10 | 0.43 |
|  |  |  |  |  |  |  |
| **RSS** | 1.23 | 1.18 | 1.06 | 0.96 | 0.92 | 1.01 |

In Tables 7 and 8, we report the uncertainty components for the SR-3500 and FieldSpec 3 validation measurements of the large sphere. The uncertainty in radiance scales is as described above. The Type A measurement uncertainty, *u*m, was determined from the average of all levels excluding the ABI Band 6 values for Level 22 and 24. The system stability term, *u*s, was estimated from a 6 month time series of measurements of the NPR. As mentioned previously, the linearity and the dependence upon integration time for the SR‑3500 and FieldSpec 3 has not been measured and we assign this component a value of 1 % based on experience. As with the VXR, we take the uncertainty in the size-of-source correction using the on-axis disk, *u*d, to be 10 % of the correction. The combined standard uncertainties are between 1.48 % and 4.89 % for the SR‑3500 and between 1.40 % and 5.38 % for the FieldSpec 3.

**Table 7.** Uncertainty components for the measurement of the large sphere using the SR‑3500. These standard uncertainties are reported in percent.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **λ [nm]** | 412 | 441 | 478 | 548 | 650 | 661 | 775 | 870 | 872 | 1387 | 1620 | 2271 |
|  | VXR | VXR | ABI | VXR | ABI | VXR | VXR | VXR | ABI | ABI | ABI | ABI |
| **Radiance Scale** |
| NPR | 0.57 | 0.52 | 0.47 | 0.40 | 0.33 | 0.33 | 0.30 | 0.25 | 0.25 | 0.59 | 0.61 | 0.77 |
| LS | 1.05 | 1.05 | 1.05 | 0.97 | 0.89 | 0.89 | 0.85 | 0.86 | 0.86 | 2.23 | 1.00 | 1.09 |
| **SR-3500 & NPR** |
| *u*m | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 |
| *u*i | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **SR-3500 and Large Sphere** |
| *u*m\* | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| *u*i | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Common** |
| *u*s | 0.41 | 0.48 | 0.58 | 0.70 | 0.63 | 0.67 | 0.70 | 0.60 | 0.60 | 4.19 | 0.40 | 0.45 |
| *u*φ | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| *u*d | 0.10 | 0.12 | 0.04 | 0.12 | 0.03 | 0.17 | 0.17 | 0.18 | 0.03 | 0.03 | 0.03 | 0.03 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| **RSS** | 1.64 | 1.62 | 1.63 | 1.62 | 1.52 | 1.55 | 1.53 | 1.49 | 1.48 | 4.89 | 1.60 | 1.74 |

\* For ABI Band 6 and Level 22, *u*m = 0.36 %; for Level 24, *u*m = 0.13 %.

**Table 8.** Uncertainty components for the measurement of the large sphere using the FieldSpec 3. These standard uncertainties are reported in percent.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **λ [nm]** | 412 | 441 | 478 | 548 | 650 | 661 | 775 | 870 | 872 | 1387 | 1620 | 2271 |
|  | VXR | VXR | ABI | VXR | ABI | VXR | VXR | VXR | ABI | ABI | ABI | ABI |
| **Radiance Scale**  |
| NPR | 0.57 | 0.52 | 0.47 | 0.40 | 0.33 | 0.33 | 0.30 | 0.25 | 0.25 | 0.59 | 0.61 | 0.77 |
| LS | 1.05 | 1.05 | 1.05 | 0.97 | 0.89 | 0.89 | 0.85 | 0.86 | 0.86 | 2.23 | 1.00 | 1.09 |
| **FieldSpec 3 & NPR** |
| *u*m | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.15 |
| *u*i | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **FieldSpec 3 and Large Sphere** |
| *u*m\* | 0.15 | 0.09 | 0.04 | 0.02 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.25 | 0.28 | 0.18 |
| *u*i | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Common** |
| *u*s | 0.45 | 0.42 | 0.42 | 0.45 | 0.38 | 0.36 | 0.33 | 0.38 | 0.38 | 4.75 | 0.99 | 1.03 |
| *u*φ | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| *u*d | 0.14 | 0.17 | 0.05 | 0.17 | 0.04 | 0.16 | 0.16 | 0.16 | 0.05 | 0.05 | 0.06 | 0.06 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| **RSS** | 1.66 | 1.61 | 1.58 | 1.53 | 1.44 | 1.44 | 1.40 | 1.41 | 1.40 | 5.38 | 1.86 | 1.99 |

\* For ABI Band 6 and Level 22, *u*m = 2.52 %; for Level 24, *u*m = 8.15 %.

# RESULTS

The results are presented in Fig. 5a as the ratio for the small sphere (SS) with the SR‑3500 and FieldSpec 3 and in Fig. 5b for the LS with all three radiometers. The expanded uncertainties (*k* = 2) are shown as dashed lines, but the values are valid only at the stated wavelengths, see Tables 9 and 10. For the large sphere, the majority of the results at each wavelength are independent of level and lie within the expanded uncertainties. The exceptions are the FieldSpec 3 at 2250 nm for Levels 22 and 24. Based on the *u*m values, we exclude these two points from the final results, which are averaged over the levels for the large sphere in Table 10.

The results for the small sphere, stated in Table 9, agree within the comparison uncertainties. Note the result at 412 nm, which is 0.988, and the result at 1378 nm, which is 0.96. The former could be a change in the small sphere, the NPR, or both since their calibration in FASCAL. The latter is at the water vapor band and most likely reflects the differences in humidity between the cleanroom during the validation and the independent FASCAL calibrations of the small sphere and the NPR at NIST.

**Table 9.** Validation results for the small sphere at the ABI and VXR bands using the average SR‑3500 and FieldSpec 3 results, see Fig. 7. The expanded uncertainties at *k* = 2 for this test are also reported.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **λ [nm]** | 412 | 441 | 478 | 548 | 650 | 661 | 775 | 870 | 872 | 1387 | 1620 | 2271 |
| Band | VXR | VXR | ABI | VXR | ABI | VXR | VXR | VXR | ABI | ABI | ABI | ABI |
| $$R\_{p/}R\_{m}$$ |
|  | 0.988 | 1.004 | 1.004 | 1.002 | 1.000 | 1.000 | 0.999 | 1.005 | 1.004 | 0.960 | 0.990 | 0.992 |
| **Expanded Uncertainty (*k* = 2)** |
|  | 0.019 | 0.018 | 0.017 | 0.017 | 0.014 | 0.014 | 0.014 | 0.013 | 0.013 | 0.098 | 0.027 | 0.031 |

The results for the large sphere are stated in Table 10 and Fig. 5b. Excluding the FieldSpec 3 results at 2250 nm for Levels 22 and 24, results agree within the expanded uncertainties at *k* = 2. However, many of the results are greater than unity, independent of instrument. This is particularly evident in the Vis/NIR. Application of a two-tailed Student’s T‑test indicates there is a 90 % probability that the mean ratio of 1.0098 and a standard deviation of 0.008 for the large sphere is statistically different from the mean ratio of 0.999 and a standard deviation of 0.006 for the small sphere (here, we have excluded the small sphere results at 1380 nm, as well as the FieldSpec 3 outliers at ABI Band 6 for Levels 22 and 24).

|  |  |
| --- | --- |
|  |  |
| Figure 5. The validation results presented as the ratio *R*p/*R*m as a function of instrument and wavelength. a) the small sphere; b) the large sphere. Expanded uncertainties (*k* = 2 at each VXR or ABI wavelength are plotted using straight lines between the values for the purposes of illustration only. |

**Table 10.** Validation results for the large sphere using the VXR, SR‑3500 (SR), or FieldSpec 3 (FS), see Fig. 5. For each instrument, the average over all levels was determined; the FieldSpec 3 results at 2250 nm for Levels 22 and 24 were too noisy and not included. The expanded uncertainties at *k* = 2 for these test are also reported.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **λ [nm]** | 412 | 441 | 478 | 548 | 650 | 661 | 775 | 870 | 872 | 1387 | 1620 | 2271 |
|  | VXR | VXR | ABI | VXR | ABI | VXR | VXR | VXR | ABI | ABI | ABI | ABI |
| **Inst.** | $R\_{p/}R\_{m}$ |
| VXR | 0.996 | 1.014 |  | 1.013 |  | 1.010 | 1.009 | 1.010 |  |  |  |  |
| SR | 1.019 | 1.025 | 1.020 | 1.014 | 1.010 | 1.009 | 1.012 | 1.018 | 1.016 | 0.999 | 1.010 | 1.004 |
| FS | 0.993 | 1.011 | 1.014 | 1.013 | 1.011 | 1.010 | 1.010 | 1.010 | 1.009 | 1.000 | 1.002 | 0.993 |
| **Inst.** | **Expanded Uncertainty (*k* = 2)** |
| VXR | 0.025 | 0.024 |  | 0.021 |  | 0.019 | 0.019 | 0.020 |  |  |  |  |
| SR | 0.033 | 0.032 | 0.033 | 0.032 | 0.030 | 0.031 | 0.031 | 0.030 | 0.030 | 0.098 | 0.032 | 0.035 |
| FS | 0.033 | 0.032 | 0.032 | 0.031 | 0.029 | 0.029 | 0.028 | 0.028 | 0.028 | 0.108 | 0.037 | 0.040 |

# DISCUSSION

Although the large sphere results are within the validation uncertainties, the observation that they differ statistically from the small sphere results warrants discussion. Since the small sphere is the basis for the large sphere radiances assigned by Exelis and the NIST measurements of the small sphere agrees well with the FASCAL calibration values, it appears that there are unidentified biases in the large sphere spectral radiances by Exelis or the NIST validation method of the large sphere. The latter possibility is less likely given the small sphere results and that the three NIST instruments are internally consistent for the large sphere results. Examples of bias that could possibly exists in the Exelis transfer method are size-of-source effects, spectral stray light, or non-linearity associated with the OL 750.

If the large sphere was brighter, especially in the Vis/NIR, during the calibration measurements compared to its output during the validation by NIST during the following week, and if the large sphere monitor detectors were stable and the NIST measurements of the large sphere and NPR reliable, then the ratio of their outputs during calibration, *S*c, to validation, *S*v, should follow the ratios *R*p/*R*m. The ratios *S*c/*S*v and the average observed validation ratios *R*p/*R*m at the ABI bands for the SR‑3500 and the FieldSpec 3 are illustrated in Fig. 6, along with the VXR ratios. For the spectrometers, the mean ratio is over both spectrometers and all levels; for the VXR the mean is at the VXR channels for all levels. The uncertainties presented in Fig. 6 are the Type A uncertainty in the mean ratios; they are not the full validation uncertainties reported in Table 10. It can be observed that the sphere monitor ratios do not follow the NIST validation results, indicating either that they do not track the sphere output or that the validation results are incorrect.

|  |
| --- |
|  |
| Figure 6. Comparison of the large sphere monitor output during calibration and validation to the results of the validation exercise. |

The setup used by Exelis includes a custom Exelis luminance photometer in addition to the OL 750. This photometer was mounted under the OL 750 and viewed a region of the large sphere exit aperture about 11.7 cm below the center, making measurements at the beginning and end of a particular level. The purpose of the luminance probe, which is calibrated by NIST, is for validation – its values are not used to adjust the large sphere spectral radiance values. In light of the observed differences between the two spheres, we examined the luminance probe data, see Fig. 7. The predicted luminance is calculated from the large sphere spectral radiances, and the measured luminance is the observed value. This result is in agreement with the Vis/NIR validation results at 550 nm.

|  |
| --- |
|  |
| Figure 7. Histogram of the luminance meter ratios, for all 24 levels during the calibration and the validation subset measured the following week. The mean is 1.013 with a standard deviation of 0.002. |

Of the possible sources of bias in the transfer from the small sphere to the large sphere using the OL 750, the size-of-source effect would seem the most plausible. Spectral stray light is unlikely because the OL 750 is a double monochromator, and the spectral distributions of the two sources are similar, so any effect would nearly cancel. Non-linearity is unlikely because the results do not depend on the radiance level of the large sphere. Therefore, as a post deployment activity, the size-of-source sensitivity of the OL 750 was tested at the Exelis laboratory in Rochester, NY, using an FEL-type lamp to illuminate a 25.4 cm-square Spectralon® plaque, and the OL 750 measured the spectral radiance with and without an on-axis obscuration disc that filled the OL 750’s field-of-view. The resulting size-of-source was about 0.2 % at 400 nm, increasing to about 0.44 % at 1300 nm and between 0.3 % and 0.5 % to 2500 nm. Definitive testing would need to utilize a source the same size of the large sphere’s exit aperture, which was 50.8 cm in this work.

A final point to consider is the veracity of the spectral radiance values assigned to the reference sources at the time of the April 2013 calibration/validation exercise. The NPR was calibrated on FASCAL in March 2013 and those values were used in the analysis. In April 2014, it was recalibrated. The results were compared at the VXR channels. The agreement was within 0.5 % for 412 nm to 550 nm and 0.3 % to 0 % for 661 nm to 870 nm. The Exelis small sphere was calibrated in November 2011 and those values were used in the analysis. In April 2014, it was also recalibrated on FASCAL, and these results indicate a decrease of 2 % at 400 nm, 0.5 % to 1 % in the visible, no change at 1610 nm, and a less than 0.5 % increase at 2250 nm. The small sphere was operated only once between the April 2013 measurements and the April 2014 FASCAL calibration, so the reason for the change, especially evident in the blue, is not understood. Note that if the April 2014 calibration values were applicable at the time of the calibration/validation exercise, the ratios for the small sphere and the large sphere *R*p/*R*m would follow the change in the small sphere determined by FASCAL – decreasing where FASCAL reported the small sphere decreased from 2011 to 2014. Except at 412 nm in the ASD and SEI measurements of the small sphere, all of the results would still fall within the expanded uncertainties (*k* = 2), but the difference in the mean of the small sphere vs. large sphere ratios would remain.

# SUMMARY

The Exelis method of assigning NIST-traceable values of spectral radiance to the ABI spectral radiance standard, a 1.65 m-diameter integrating sphere source was validated within the comparison uncertainties by independent measurements using a NIST integrating sphere source calibrated at the NIST FASCAL facility and three portable transfer radiometers. The results at the water vapor band at 1380 nm were consistent, indicating good repeatability of the environmental conditions in the cleanroom. The spectral radiance of the Exelis reference standard was also validated within the comparison uncertainties at the ABI bands, but we found that there is a difference of about 1 % in the two sphere results. However, given that the ABI radiometric calibration combined standard uncertainty for all ABI channels below 3 µm is 3 %, an additional 1 % uncertainty would only increase the uncertainty from 3 % to 3.2 %. Spatial size-of-source effects in the OL 750 transfer radiometer may be responsible for the apparent overestimates of the large sphere spectral radiances. The variability seen in Level 24 with the InGaAs sphere monitor at all three channels is not understood, since in the SWIR for Level 24, the SR-3500 and the FieldSpec 3 (excluding the 2.25 µm band) do not show this increased variability compared to the brighter levels. The increased variability of the Si sphere monitor at 470 nm is also not understood. The proposed method to maintain the spectral radiance scale on the ABI sphere using its internal monitor photodiodes was reevaluated as a result of the validation exercise.

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# Certain commercial equipment, instruments, or materials are identified in this chapter to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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