

# Results from Solar Reflective Band End-to-End Testing for VIIRS F1 Sensor Using T-SIRCUS

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## ABSTRACT

Verification of the Visible Infrared Imager Radiometer Suite (VIIRS) End-to-End (E2E) sensor calibration is highly recommended before launch, to identify any anomalies and to improve our understanding of the sensor on-orbit calibration performance. E2E testing of the Reflective Solar Bands (RSB) calibration cycle was performed pre-launch for the VIIRS Flight 1 (F1) sensor at the Ball Aerospace facility in Boulder CO in March 2010. VIIRS reflective band calibration cycle is very similar to heritage sensor MODIS in that solar illumination, via a diffuser, is used to correct for temporal variations in the instrument responsivity. Monochromatic light from the NIST T-SIRCUS (Traveling Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources) was used to illuminate both the Earth View (EV), via an integrating sphere, and the Solar Diffuser (SD) view, through a collimator. The collimator illumination was cycled through a series of angles intended to simulate the range of possible angles for which solar radiation will be incident on the solar attenuation screen on-orbit. Ideally, the measured instrument responsivity (defined here as the ratio of the detector response to the at-sensor radiance) should be the same whether the EV or SD view is illuminated. The ratio of the measured responsivities was determined at each collimator angle and wavelength. In addition, the Solar Diffuser Stability Monitor (SDSM), a ratioing radiometer designed to track the temporal variation in the SD Bidirectional Reflectance Factor (BRF) by direct comparison to solar radiation, was illuminated by the collimator. The measured SDSM ratio was compared to the predicted ratio. An uncertainty analysis was also performed on both the SD and SDSM calibrations.

**Keywords:** NPP, VIIRS, pre-launch, calibration

## 1. INTRODUCTION

The VIIRS F1 sensor is a cross-track scanning radiometer developed for the NPP (NPOESS Preparatory Project) mission and is capable of making continuous global observations of the Earth intended for use in scientific studies of land, ocean, and atmosphere.<sup>1-3</sup> The design of VIIRS was heavily influenced by heritage sensor MODIS.<sup>4</sup> VIIRS RSB consists of 14 spectral bands covering a range of approximately 0.4 – 2.3  $\mu\text{m}$  with resolutions at nadir of 375 m (3 bands) and 750 m (11 bands). In order to maintain the reflective band calibration on-orbit, VIIRS was equipped with three on-board calibration devices: the SD, the Solar Attenuation Screen (SAS), and the SDSM.

VIIRS F1 sensor will rely on regular solar observations on-orbit for RSB calibration (similar to the heritage sensor MODIS<sup>5</sup>). These observations can occur once per orbit over the South pole for approximately three minutes. During these observations, solar illumination, scattered off the SD, will be used to correct for temporal variations in the instrument radiometric responsivity over the sensor lifetime. However, the SD is fabricated

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from space-grade Spectralon\*, the performance of which is known to degrade over time from exposure to the sun. The degradation of the SD BRF will be tracked by the SDSM, a ratioing radiometer which relates near simultaneous measurements of direct solar illumination to solar illumination diffusely reflected off the SD. It is important that the RSB on-orbit calibration cycle be performed during pre-launch testing, in order to identify any issues and/or anomalies as well as test the validity of the calibration cycle under controlled conditions.

E2E testing of the VIIRS F1 RSB calibration cycle was performed in March 2010 at the Ball Aerospace facility in Boulder CO. VIIRS had been successfully integrated into the NPP spacecraft two months earlier. The NIST T-SIRCUS<sup>6</sup> was transported to Boulder to act as a source for E2E testing (as well as spectral testing<sup>7</sup>). The T-SIRCUS was used to illuminate both the EV (through an integrating sphere) and SD view (via a collimator) using monochromatic light and was monitored in real-time. In addition, both paths into the SDSM were simultaneously illuminated.

E2E testing was not part of the baseline validation testing of VIIRS F1 sensor performed at the sensor subcontractor (Raytheon El Segundo). The E2E test was conducted during NPP spacecraft level testing to investigate whether this type of test setup could validate the VIIRS RSB calibration cycle pre-launch. Further, the use of tunable lasers in the calibration is in the exploratory phase. As such, this work is focused as much on the application of this technology to the calibration of VIIRS as to the results of the analysis.

This paper will compare the sensor responsivities derived from T-SIRCUS data for both views in order to assess the on-orbit SD calibration cycle as well as the SDSM calibration. Section 2 will review the design of the on-board RSB calibrators, Section 3 will provide a brief overview of the T-SIRCUS and a description of the test setup, Section 4 will establish the analysis methodology, and Section 5 will discuss the results of this analysis including the measurement uncertainty.

## 2. RSB ON-BOARD CALIBRATOR OVERVIEW

### 2.1 Solar Diffuser and Solar Attenuation Screen

VIIRS on-orbit calibration is reflectance based with reference to the SD. The SD BRF was characterized pre-launch by the sensor subcontractor [then Raytheon Santa Barbara Remote Sensing (SBRs)].<sup>8</sup> The BRF was measured at six wavelengths (0.4, 0.5, 0.6, 0.7, 0.9, and 1.7  $\mu\text{m}$ ), nine incident angles designed to replicate the range of possible on-orbit solar observations, and two angles of reflectance [corresponding to the Rotating Telescope Assembly (RTA) and SDSM views].

The SD views the sun through the SAS. Unlike MODIS, the VIIRS SAS is fixed; consequently only one radiance level is available for on-orbit calibration per band. The vignetting function of the SAS was measured pre-launch by the sensor subcontractor;<sup>8</sup> at normal incidence, the transmission is about 0.13. In addition, no aperture door was incorporated into VIIRS design (in contrast, MODIS has an aperture door). As a result, the SD will be exposed to greater potential degradation of its BRF on-orbit than MODIS. Improvements in the design and pre-launch characterization of VIIRS (particularly with regard to the SDSM) will enable accurate tracking of this degradation.

### 2.2 Solar Diffuser Stability Monitor

Degradation in the SD BRF from about 0.41 – 0.94  $\mu\text{m}$  will be tracked on-orbit by the SDSM. The SDSM is a ratioing radiometer that compares direct solar illumination with light transmitted by the SAS and then diffusely reflected off the SD. The direct solar illumination is viewed through an attenuation screen, the transmission of which was characterized pre-launch by the sensor subcontractor (then Raytheon SBRs).<sup>8</sup> The SDSM contains an integrating sphere embedded with eight detectors filtered to match VIIRS moderate resolution bands in the visible and near infrared (with the exception of the eighth detector at 935 nm, which has no corresponding VIIRS band). A fold mirror directs light into this integrating sphere from one of three views: solar, SD, or dark (the dark view is used as a zero reference for the detectors). A stepping motor rotates this fold mirror through these positions every three scans repeatedly during an RSB calibration cycle.

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

The SDSM collects data during multiple on-orbit RSB calibrations over the sensor lifetime. A time-series of the ratios of the solar and SD signals will be used to track the SD BRF degradation, and to correct the responsivity on-orbit. Due to the fact that the same SDSM optics, detectors, and electronics are used for both SDSM solar and SD paths, any slow changes in their performance will not affect the quality of the SD BRF degradation monitoring.

### 3. TEST OVERVIEW

#### 3.1 T-SIRCUS

NIST has developed a laser-based facility known as SIRCUS for use in radiance and irradiance responsivity calibrations.<sup>6</sup> A portable version known as T-SIRCUS (or Traveling SIRCUS) was transported to Ball Aerospace in Boulder CO during March 2010 for VIIRS spacecraft level testing. SIRCUS consists of a series of tunable lasers; for E2E testing, a Ti:sapphire laser was used in continuous wave mode to produce monochromatic illumination at 742 nm and 852 nm (and frequency doubling was used to reach 442 nm).

The T-SIRCUS was used to feed two sources via fiber optics: an integrating sphere and a collimator. The integrating sphere was positioned in the EV at a scan angle of about  $-0.2$  degrees (VIIRS nadir view is defined as 0 degrees). The sphere was approximately 76.2 cm (30 inches) in diameter with an exit aperture of about 25.4 cm (10 inches). The sphere was mounted on a scissor jack with its exit aperture approximately 121.9 cm (4 ft) from the telescope aperture at nadir. Two radiance monitors were used to track the radiance output from the sphere in real-time. The monitors were positioned just off the optical path, one above and one below.

The collimator was positioned to fully illuminate both the SD through the SAS and the solar entrance aperture of the SDSM. The exit aperture of the collimator was about 63.5 cm (25 inches) in diameter. The collimator was also mounted on a scissor jack, by which the angle of the incident light on the SD was varied. A total of seven collimator positions were performed covering five different angles, listed in Table 1 in the order performed. Note that the first, fourth, and fifth positions are repeated measurements of roughly the same angle. An irradiance monitor was positioned near the center of the collimator exit aperture, from which real-time tracking of the irradiance was performed.

Table 1. Collimator positions measured during E2E testing. Angles are relative to VIIRS coordinate system.

Position	Date	Declination	Azimuthal	Wavelengths (nm)
1	3/19/2010	22.52	16.31	742, 852
2	3/19/2010	13.64	16.87	742, 852
3	3/19/2010	30.09	16.34	742, 852
4	3/19/2010	22.37	16.44	742, 852
5	3/20/2010	22.38	16.52	742, 852
6	3/20/2010	30.44	15.21	742, 852
7	3/20/2010	13.63	15.07	442, 742, 852

#### 3.2 Collimator Uniformity

The collimator beam was known to be spatially nonuniform. Different portions of the collimator beam illuminated the irradiance monitor, SD, and SDSM views. As a result, correction factors relating the collimator illumination at VIIRS SD view as well as the SDSM SD and solar views to the irradiance monitor view were calculated.

After most collimator positions, the collimator was repositioned to illuminate a large Spectralon panel at roughly the same angle as was incident on VIIRS. A CCD camera was used to photograph the Spectralon panel. From these images, the uniformity correction factor was determined.

### 3.3 Test Description

For E2E testing, VIIRS was operated in diagnostic mode, during which 2048 unaggregated moderate resolution (750 m at nadir) EV samples were recorded covering scan angles from about -18.2 degrees to 18.2 degrees. This corresponds to a subset of the full operational mode EV data. Each sample has an angular resolution of approximately 0.017776 degrees. The integrating sphere was positioned in the EV and fully illuminated samples between scan angles of about -1.0 degree to 0.7 degrees. During the course of each scan, 48 moderate resolution samples were also recorded in each of the three calibration views: Space View (SV), SD, and On-Board Calibrator Blackbody (OBC BB). In addition, VIIRS was operated in fixed high gain mode, which restricts all dual gain bands to their low radiance settings.

VIIRS data for E2E testing was recorded in a three data collection cycle. During the first collection, the SD and SDSM were illuminated, while the EV was dark. For the second collection, the EV was illuminated, while the SD and SDSM views were dark. For the last collection, both the EV and SD views were dark. Each of these collections contained 128 VIIRS scans (roughly 3.8 minutes). For most collimator positions, this cycle was conducted twice per measured wavelength (except Position 5 when it was conducted only once). Data collections were performed with the SIRCUS output at 442 nm, 742 nm, and 852 nm (442 nm was only measured once during collimator Position 7); this corresponds to VIIRS bands M2, M6, and M7 (see Table 2).

In addition, during the first collection in each cycle, the SDSM mirror was rotating and data was recorded. The SDSM detectors corresponding to the bands measured are listed in Table 2.

Table 2. VIIRS bands (and corresponding SDSM detectors) used in E2E testing.

Band	Center $\lambda$ (nm)	Bandwidth (nm)	SDSM Detector
M2	445	18	2
M6	746	15	6
M7	865	39	7

## 4. METHODOLOGY

### 4.1 SD Calibration

In order to test the SD calibration cycle, the ratio (RR) of the calculated responsivities (g) from both the EV and SD paths was computed, or

$$RR = \frac{g_{SD}}{g_{EV}}. \quad (1)$$

Here the instrument responsivity is defined as the ratio of the detector response (background subtracted digital response) to the at-sensor radiance. Ideally, the instrument responsivities for the EV and SD paths should be equal. As a result, RR will depend on how well the components in the optical path were characterized as well as knowledge of the input radiance (or irradiance).

The responsivity for the EV path is the detector response divided by the product of the integrating sphere radiance and the Response Versus Scan angle (RVS) at the Half Angle Mirror (HAM) Angle of Incidence (AOI) of the integrating sphere, or

$$g_{EV} = \frac{dn_{EV}}{RVS_{EV}L_{EV}}. \quad (2)$$

The RVS is the variation in instrument response to HAM AOI and was described in.<sup>9</sup> For this test, the EV HAM AOI was about 36.3 degrees. The EV radiance ( $L_{EV}$ ) was determined from the average radiance retrieved from the two monitors on the integrating sphere.

The responsivity for the SD path is the detector response divided by the product of the collimator irradiance, the SAS transmission, the BRDF of the SD at the RTA reflectance angle, the cosine of the projection angle onto

the SD, and the RVS at the SD scan angle, or

$$g_{SD} = \frac{dn_{SD}}{RVS_{SD}E_{SD}\tau_{SAS}BRDF_{RTA} \cos(\theta_{SD})}. \quad (3)$$

For VIIRS, the RVS was normalized to the SD HAM AOI of about 60.2 degrees (i.e.  $RVS_{SD} = 1$ ). The SAS transmission is defined as<sup>8</sup>

$$\tau_{SAS}(\delta, \phi) = 0.1261 [1 - 0.1615 \tan(\delta)] [1 - 0.04783 \tan(\phi)], \quad (4)$$

where  $\delta$  and  $\phi$  are the collimator declination and azimuthal angles, respectively. The reflectance off the SD is assumed to be Lambertian in the neighborhood of the RTA reflectance angle (i.e.  $BRF_{RTA} = \pi BRDF_{RTA}$ ). The BRF was measured at component level testing for nine incident angles, two reflectance angles, and six wavelengths. The BRF was fit to the following function of declination and azimuthal angles for each measured wavelength and reflectance angle:<sup>10</sup>

$$BRF(\delta, \phi, \lambda) = c_0(\lambda) + c_1(\lambda)\delta + c_2(\lambda)\phi + c_3(\lambda)\delta^2 + c_4(\lambda)\phi^2 + c_5(\lambda)\delta\phi. \quad (5)$$

The fit coefficients for the RTA reflectance angle are listed in Table 3. The final BRF is determined by interpolating Eq. (5) between wavelengths. The cosine of the projection angle  $\theta_{SD}$  is the dot product of the sun vector and the SD normal vector,<sup>8</sup> or

$$\cos(\theta_{SD}) = \vec{n}_{sun} \cdot \vec{n}_{SD}, \quad (6)$$

where  $\vec{n}_{SD} \equiv (0.29724, -0.21860, 0.92944)$  and

$$\vec{n}_{sun} = \frac{1}{\sqrt{1 + \tan^2(\delta) + \tan^2(\phi)}} [1, -\tan(\phi), \tan(\delta)]. \quad (7)$$

As discussed in Section 3.2, the collimator output is known to be spatially nonuniform. As a result, a correction factor ( $\gamma_1$ ) relating the collimator footprint on the SD to the irradiance monitor position is included, or

$$E_{SD} = \gamma_1 E_{mon}, \quad (8)$$

where  $E_{mon}$  is the irradiance monitor output. The collimator correction factors used in this work are listed in Table 5. The derivation of the collimator uniformity correction factor will be described in a later work. As a result, Eq. (3) becomes

$$g_{SD} = \frac{\pi dn_{SD}}{\gamma_1 E_{mon} \tau_{SAS} BRDF_{RTA} \cos(\theta_{SD})}. \quad (9)$$

Table 3. SD BRF fit coefficients for RTA reflectance angle.<sup>10</sup>

Wavelength (nm)	$c_0$	$c_1$	$c_2$	$c_3$	$c_4$	$c_5$
400	0.999406	0.000947	-0.002517	-0.000004	-0.000010	0.000026
500	1.008981	0.000454	-0.002655	0.000004	-0.000009	0.000032
600	0.998804	0.001787	-0.002700	-0.000044	-0.000009	0.000032
700	0.966439	0.005746	-1.002742	-0.000157	-0.000009	0.000032
900	0.987594	0.002276	-0.002797	-0.000052	-0.000011	0.000025
1700	0.962194	0.005435	-0.002978	-0.000153	-0.000011	0.000032

Table 4. SD BRF fit coefficients for SDSM reflectance angle.<sup>10</sup>

Wavelength (nm)	$c_0$	$c_1$	$c_2$	$c_3$	$c_4$	$c_5$
400	0.906011	0.005525	-0.001012	-0.000064	-0.000020	0.000014
500	0.976150	-0.002411	-0.001104	0.000161	-0.000022	0.000013
600	0.925660	0.003218	-0.001126	-0.000004	-0.000022	0.000014
700	0.921604	0.003537	-0.001184	-0.000008	-0.000023	0.000013
900	0.933213	0.000525	-0.001686	0.000100	-0.000024	0.000039
1700	0.933563	0.000067	-0.001312	0.000096	-0.000027	0.000007

Table 5. Collimator uniformity correction for the SD calibration versus collimator position.

Wavelength (nm)	1	2	3	4	5	6	7
742	0.967	0.965	0.966	0.964	0.958	0.959	0.959
852	0.940	0.937	0.933	0.936	0.924	0.926	0.933

## 4.2 SDSM Calibration

The measured SDSM ratio is defined as follows:

$$R_m = \frac{DN_{SD} - DN_{dark}}{DN_{solar} - DN_{dark}}. \quad (10)$$

The  $R_m$  is determined every three scans and is trended over a particular calibration cycle as well as across calibration cycles. This allows for tracking of the temporal changes in the SD BRF.

The irradiance reaching the SDSM integrating sphere aperture using the SD path is

$$E_{SDSM-SD} = \gamma_2 E_{mon} \tau_{SAS} \frac{BRF_{SDSM}}{\pi} \cos(\theta_{SD}) \pi \sin^2(\psi), \quad (11)$$

where  $\tau_{SAS}$  and  $\cos(\theta_{SD})$  are defined in Eqs. (4) and (6), respectively. The SD BRF is described by Eq. (5) using the fit coefficients for the SDSM reflectance angle listed in Table 4. The factor of  $\pi \sin^2(\psi)$  corresponds to the solid angle of the entrance cone on the SDSM for the SD view, where the half angle of the cone,  $\psi$ , is 7.78 degrees.<sup>8</sup>  $\gamma_2 E_{mon}$  is the measured irradiance of the collimator (including uniformity correction factor  $\gamma_2$ ).

The irradiance illuminating the SDSM integrating sphere aperture using the solar path is

$$E_{SDSM-solar} = \gamma_3 E_{mon} \tau_{SDSM}. \quad (12)$$

$\tau_{SDSM}$  is the transmission factor for the SDSM screen. This transmission includes the cosine of the projection angle onto the SDSM screen. In addition, because the detectors are located inside the SDSM integrating sphere, each detector has a direct view of the reflection of the image on the inside of the sphere. This results in each detector observing a slightly different radiance based on its location inside the integrating sphere.<sup>8</sup> Note that the collimator uniformity correction ( $\gamma_2$ ) for the SDSM SD view is different from the correction for the solar view of the SDSM ( $\gamma_3$ ).

The theoretical SDSM ratio is the ratio of Eqs. (11) and (12), or

$$R_c = \frac{\gamma_2}{\gamma_3} \frac{\tau_{SAS}}{\tau_{SDSM}} \cos(\theta_{SD}) BRF_{SDSM} \sin^2(\psi). \quad (13)$$

The source irradiance cancels (excepting the uniformity corrections) and what remains is the ratio of the transmission factors in each optical path. Note that the transfer function from the SDSM integrating sphere aperture to the SDSM detector is common to both paths and would also cancel in the ratio.

### 4.3 Uncertainty Analysis

The following uncertainty analysis uses the standard uncertainty propagation to combine the individual uncertainties involved in the present experiment to a total uncertainty.<sup>11</sup>

The measurement uncertainty in the EV responsivity is given by the standard uncertainty propagation, or

$$\frac{u^2(g_{EV})}{g_{EV}^2} = \frac{u^2(dn_{EV})}{dn_{EV}^2} + \frac{u^2(RVS_{EV})}{RVS_{EV}^2} + \frac{u^2(L_{EV})}{L_{EV}^2}. \quad (14)$$

The SD responsivity uncertainty is also given by the standard uncertainty propagation, or

$$\begin{aligned} \frac{u^2(g_{SD})}{g_{SD}^2} = & \frac{u^2(dn_{SD})}{dn_{SD}^2} + \frac{u^2(RVS_{SD})}{RVS_{SD}^2} + \frac{u^2(\gamma_1)}{\gamma_1^2} + \frac{u^2(E_{SD})}{E_{SD}^2} \\ & + \frac{u^2(\tau_{SAS})}{\tau_{SAS}^2} + \frac{u^2(BRF_{RTA})}{BRF_{RTA}^2} + \frac{u^2[\cos(\theta_{SD})]}{\cos^2(\theta_{SD})}. \end{aligned} \quad (15)$$

Since most of these factors were measured independently [ $\tau_{SAS}$ ,  $BRF_{RTA}$ ,  $L_{EV}$ ,  $E_{SD}$ , and  $\cos(\theta_{SD})$ ], it is assumed that these factors have no correlations with any other factor. In addition, although  $dn_{SD}$ ,  $dn_{EV}$ ,  $RVS_{EV}$ , and  $RVS_{SD}$  were all measured using VIIRS detectors, they were measured separately and therefore are also assumed to be uncorrelated with the other uncertainty sources. The measurement uncertainty in the responsivity ratio is then

$$\frac{u^2(RR)}{RR^2} = \frac{u^2(g_{SD})}{g_{SD}^2} + \frac{u^2(g_{EV})}{g_{EV}^2} \quad (16)$$

The uncertainty in the calculated SDSM ratio is

$$\begin{aligned} \frac{u^2(R_c)}{R_c^2} = & \frac{u^2(\tau_{SAS})}{\tau_{SAS}^2} + \frac{u^2(\tau_{SDSM})}{\tau_{SDSM}^2} + \frac{u^2[\cos(\theta_{SD})]}{\cos^2(\theta_{SD})} \\ & + \frac{u^2(BRF_{SDSM})}{BRF_{SDSM}^2} + 4 \frac{u^2[\sin(\psi)]}{\sin^2(\psi)} + \frac{u^2(\gamma_2)}{\gamma_2^2} + \frac{u^2(\gamma_3)}{\gamma_3^2}. \end{aligned} \quad (17)$$

Since all of these factors in  $R_c$  were measured independently, it is assumed that there are no correlations between the uncertainties of the various factors.

## 5. ANALYSIS RESULTS

### 5.1 SD Calibration

#### 5.1.1 Data Reduction

The integrating sphere aperture covered an arc of about 2 degrees of scan angle centered roughly on nadir. From this region, 90 moderate resolution (750 m) samples were extracted (samples 970-1059). These 90 samples were averaged for every scan (ideally there are 128 scans per data collection) and for each VIIRS detector (16 detectors per VIIRS moderate resolution band). In addition, the 48 samples extracted from both the SD and OBC BB views were similarly averaged (note that calibration view data is reported in 14 bits while EV data is automatically truncated from 14 to 12 bits by VIIRS; in this analysis all calibration view data is first truncated to 12 bits to remove any potential bias). For each average, those points more than three standard deviations from the mean were excluded. The OBC BB was maintained at approximately 292 K throughout the testing; as a result, the OBC BB data was used as a zero reference for both the EV and SD data. The resulting scan dependent  $dn_{EV}$  and  $dn_{SD}$  were substituted into Eqs. (2) and (9), respectively.

The integrating sphere radiance and collimator irradiance were tracked in real-time by monitors (two monitors on the sphere and one monitor on the collimator). The output of each monitor was provided in volts, and was converted to either radiance or irradiance (the average of the two radiance monitors is used here) using NIST provided monitor calibration coefficients determined post-test. The output from each monitor was obtained

about every 10 s. Linear interpolation was used to acquire the radiance or irradiance at the particular VIIRS time stamp associated with each scan. The resulting scan dependent  $L_{EV}$  and  $E_{SD}$  were input into Eqs. (2) and (9), respectively.

Using Eqs. (2) and (9), the EV and SD responsivities were determined on a scan by scan basis. Since the EV and SD data was recorded at separate times, the scan averaged EV and SD responsivities were calculated for each data collection. These scan averaged responsivities were then substituted into Eq. (1), from which the responsivity ratio was determined for each three data collection cycle. The average of the two collection cycles per collimator position was then calculated.

The following sections will only discuss the results for HAM side A, but both HAM sides yield consistent results.

### 5.1.2 Data Quality

A number of data quality checks were performed during the processing of the data for the SD calibration. Listed below are the major findings of those checks.

Some of the data collections did not contain the full expected 128 scans of VIIRS data (collections at Positions 3 and 5, both at 852 nm). For those collections, the data was retained for those scans that appeared to be valid data (i.e. they were consistent with the data collections in which all scans were present).

The signal observed in the SD view when the EV was illuminated via the integrating sphere was negligible; in contrast, the response reported in the EV when the SD was illuminated via the collimator was between 2 dn and 3 dn for most cases. This is the possible result of scatter from the collimator reaching the EV, and as such has no real effect on the calibration. In addition, the data from the dark collections was analyzed and the resulting dn was negligible for all cases.

The standard uncertainty of the EV dn was determined over scans at each sample and also over samples at each scan (similarly for the SD dn). For the SD view, the two methods were comparable. However, for the EV, the standard uncertainty over samples was slightly lower than the standard uncertainty over scans. This indicates that the integrating sphere had higher spatial stability than temporal stability (and that the measured SNR was closer to the true sensor SNR using the first method).

The stability of the sources was also tracked via their respective monitors. The two monitors on the integrating sphere showed some fluctuation over time (they both individually exhibited one sigma variation within about 0.3 % at 742 nm and 0.6 % at 852 nm); in addition, the two monitors varied in approximately the same manner. However, the monitors were offset from each other by about 0.4 % for 742 nm and 0.6 % for 852 nm. The collimator monitor recorded one sigma temporal variation of up to about 0.7 % (0.8 %) at 742 nm (852 nm) over a particular data collection.

The EV dn and monitor radiances had similar temporal trends, and as such the calculated EV responsivity at each scan was generally consistent over time. In contrast, the SD dn and collimator irradiance had different temporal dependencies, with the result being that the calculated SD responsivity was not necessarily constant over scans; an example of this behavior is plotted in Figure 1 which shows the scan by scan EV and SD responsivities for M6 collimator Position 7 (second data collection). The inability of the collimator monitor to effectively track the incident irradiance was a major source of uncertainty for the SD responsivity.

### 5.1.3 SD Uncertainty Analysis

The uncertainty propagation for the SD calibration was defined by Eq. (16). The individual uncertainties that were used in Eq. (16) are described in this section. In general, each uncertainty contributor was the combination of precision (random) and accuracy (biases) uncertainties.

The uncertainty in the SD and EV dn was a combination of the precision and accuracy uncertainties. The precision uncertainty was the standard deviation over all samples and scans in a given data collection. The accuracy uncertainty accounted for any biases between the SD or EV and the OBC views (since any biases common to all sectors canceled in the background subtraction). The known biases between sectors were either accounted for in the processing (truncation of calibration views to 12 bits before processing begins) or not

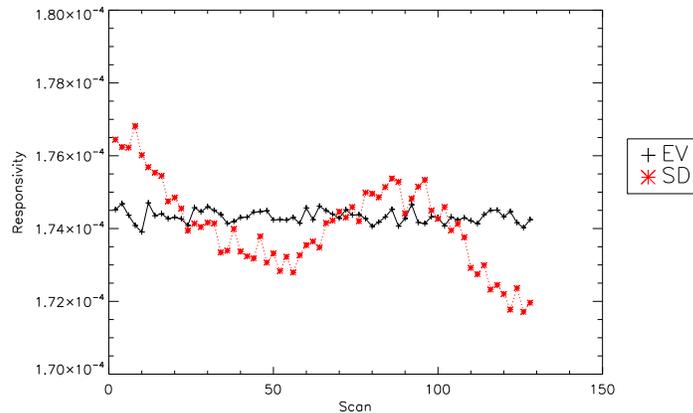


Figure 1. M6 scan dependent responsivities (both EV and SD) from collimator Position 7, measurement 2.

applicable (biases due to aggregation or auto/fixed gain differences); as a result, no accuracy uncertainty was included here.

The RVS uncertainties were determined during ambient phase testing at the instrument level. The band average values used in this work were 0.000570 [M6] and 0.000558 [M7], and were used for both SD and EV angles. These values are the Root Sum Square (RSS) of fitting and measurement uncertainties.<sup>9</sup> The uncertainties associated with the EV radiance were the combination of precision and accuracy uncertainties. The precision uncertainty was determined by calculating the one sigma variation over all radiance monitor values for a particular data collection (both monitors). The accuracy uncertainty was the average offset between the two radiance monitors over a data collection. The total radiance uncertainty was the RSS of the precision and accuracy uncertainties. The uncertainty in the SD irradiance was the one sigma variation over all irradiance monitor values in each data collection (precision uncertainty). The accuracy uncertainty was undetermined. The uncertainty in the SAS transmission and the SD BRF were determined by the sensor subcontractor,<sup>8</sup> and are 0.24 % and 1.09 %, respectively. The cosine of the projection angle was determined from alignment measurements made using theodolites and Eq. (6). The measurements were assumed to be known to 0.01 degrees. That uncertainty was propagated through Eq. (6). The uncertainty in the collimator uniformity correction is currently in progress and is left for future work. The final responsivity uncertainties were determined by Eqs. (14) and (15). Then, the uncertainty in the responsivity ratio at a particular data collection cycle was determined from Eq. (16).

#### 5.1.4 SD Calibration Results

The derived M6 and M7 responsivity ratios for each detector and collimator position are shown in Figure 2. In the case of M6, all collimator positions were within approximately 2 % of one. In addition, the responsivity ratio tended to increase over detectors for all collimator positions (particular Positions 1 and 7). For M7, all positions were within about 4 % of unity, with the exception of Position 7 which was between 4 % and 6 % below one. Here the detector variation was again roughly increasing, but more uniformly over collimator position than for M6. This detector trend likely resulted from detector dependence in the collimator uniformity correction (the RTA footprint on the SD was slightly different for each detector and band, which in turn required a slightly different collimator correction). The detector dependent collimator correction is left for future work. Although E2E testing was also conducted at 442 nm (M2) for collimator Position 7, the digital response was too low to accurately determine the responsivity ratio ( $dn_{SD} \sim 6$  and  $dn_{EV} \sim 15$ ).

Measurement repeatability was investigated both on short time scales (minutes) and long time scales (hours). The collimator was positioned three times at roughly the same angle (Positions 1, 4, and 5 in Table 1). The interval between Positions 1 and 4 was about 6 hours and the interval between Positions 4 and 5 was about 16 hours. For M6 (see the black crosses, green triangles, and yellow squares in the left-hand plot of Figure 2), the ratios were within 1.0 % of unity for all detectors for Positions 4 and 5; however, the ratios derived from Position

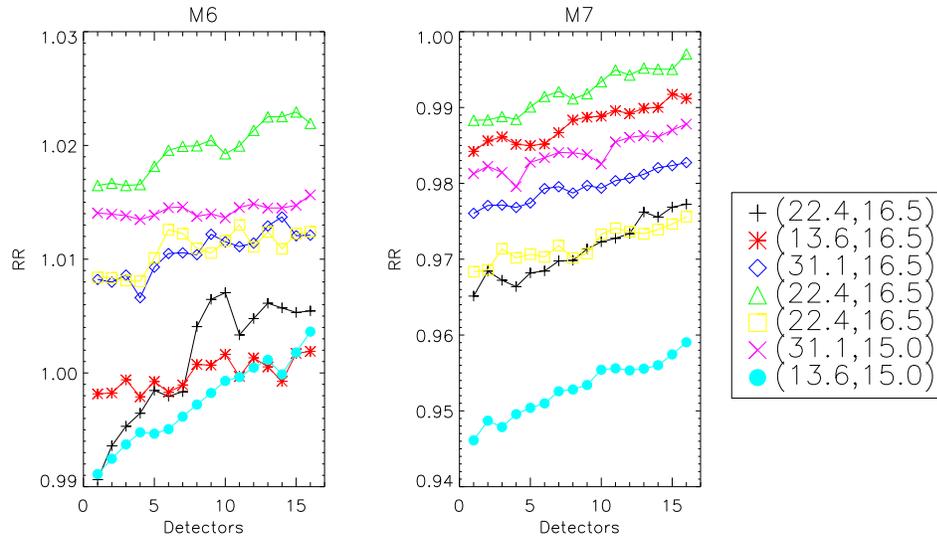


Figure 2. M6 and M7 responsivity ratios versus VIIRS detector. Collimator positions are given in (declination angle, azimuthal angle).

1 were lower (between 0.5 % and 2 % below one). In addition, the detector variation was greater for Position 1. In contrast, the M7 ratios derived from Positions 1 and 5 were within 0.5 % of each other (although between 2 % and 4 % below one), while the ratios from Position 4 were between 0.5 % and 1.5 % below one (see the black crosses, green triangles, and yellow squares in the right-hand plot of Figure 2).

In terms of short term stability, the E2E test was repeated for each collimator position twice within about 30 minutes (except Position 5). The data from each individual collection cycle (SD, EV, dark) was used to derive a responsivity ratio. The comparison of the short term stability is shown in Figure 3 versus detector. Here the solid (dashed) lines indicate the first (second) measurement. For M6, Positions 4 and 7 agreed to within 0.2 %, while Positions 1, 2, 3, and 6 showed discrepancies of up to 1 %. The ratios determined for M7 showed agreement to within 0.5 % for all positions except Position 2, for which short term repeatability was about 2 %.

The discrepancies between the repeated measurements are largely understood by examining the underlying  $dn$ , radiance, and irradiance. In Table 6, the  $dn$ , radiance, and irradiance are listed for M6 detector 9 at each collimator position and measurement repeat (averaged over scans). For the EV, the  $dn$  increased when the radiance increased; however, this was not always the case for the SD measurements. Collimator Positions 2, 3, and 6 actually had lower irradiance for the measurement with higher  $dn$ . This result also held when examining the SD on a scan basis. Thus the discrepancies in the repeatability measurements appear to be largely related to the accuracy of the irradiance monitor output.

The band averaged, one sigma uncertainty estimates based on Eq. (16) are listed in Table 7 for all collimator positions. The BRF uncertainty was the largest contributor for both M6 and M7 (at 1.09 %). Because the main source of uncertainty was not detector dependent, the variation of the uncertainty with detector was small for both bands. Note that the collimator uniformity correction uncertainty was not included (it is expected to be a major contributor).

Figure 4 shows the band averaged responsivity ratio for each collimator position with the uncertainties shown in Table 7. The responsivity ratios were consistent with one for band M6 for most collimator positions (except Position 4). For band M7, only collimator Positions 2, 4, and 6 were consistent with one; all other positions are lower (especially Position 7 which was much lower). The repeated collimator Positions 1, 4, and 5 are consistent with each other (within uncertainties) for both bands. In addition, all short term repeated measurements agreed within the measured uncertainties.

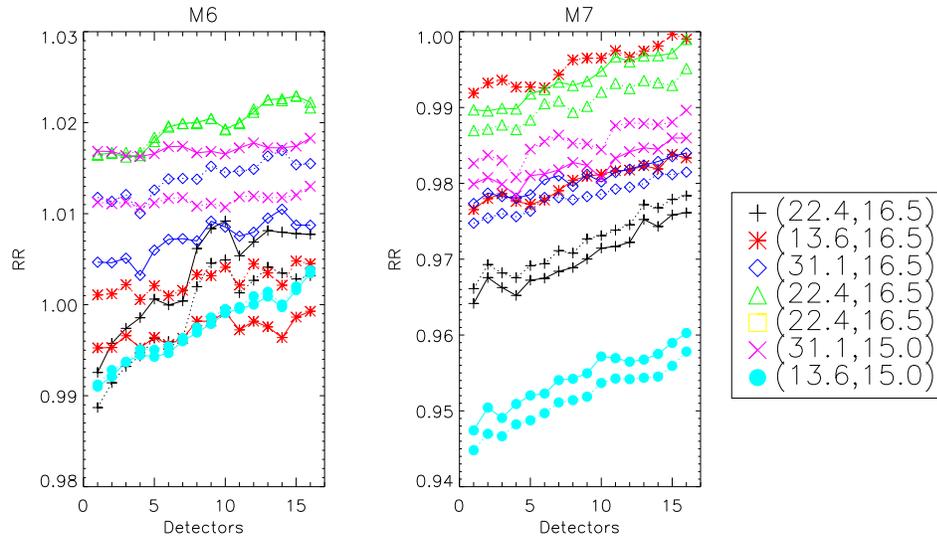


Figure 3. M6 and M7 responsivity ratios - short term stability. Collimator positions are given in (declination angle, azimuthal angle).

Table 6. Short term repeatability for M6 detector 9 (HAM side A). dn, radiance, and irradiance are averaged over scans.

Position	Measurement	$E_{SD}$	$dn_{SD}$	$L_{EV}$	$dn_{EV}$	RR
1	1	5.084	648.2	0.1212	690.5	1.009
1	2	4.979	639.0	0.1216	693.7	1.004
2	1	4.845	615.4	0.1078	618.1	0.999
2	2	4.863	614.5	0.1083	620.3	1.003
3	1	5.096	655.7	0.1105	633.2	1.009
3	2	5.113	653.7	0.1097	628.0	1.015
4	1	4.862	615.4	0.1113	637.3	1.020
4	2	4.844	613.4	0.1116	639.4	1.020
6	1	6.316	777.9	0.1320	756.0	1.016
6	2	6.298	779.9	0.1322	757.4	1.011
7	1	6.502	800.4	0.1387	795.6	0.997
7	2	6.486	798.6	0.1379	791.8	0.998

## 5.2 SDSM Calibration

### 5.2.1 Data Quality and Reduction

Five SDSM samples were recorded every scan for each detector in the SDSM integrating sphere. These five samples were averaged for every scan. The averaged DN from each three scan cycle was used to determine the ratio in Eq. (10). This SDSM ratio was trended versus time for each data collection and collimator angle. In addition, the average of the ratios for each data collection was determined. As the SDSM was illuminated with monochromatic light, only the detector corresponding to the input wavelength was analyzed. As with the SD data, some data collections were missing scans; again, the data was retained for those scans that appeared to be valid data. The collimator uniformity corrections ( $\gamma_2$  and  $\gamma_3$ ) were not applied in this work (the calculation is in progress).

Table 7. Total responsivity ratio uncertainties in percent (one sigma).

Position	1	2	3	4	5	6	7
M6 $u(RR)$	1.49	1.47	1.48	1.47	1.48	1.48	1.55
M7 $u(RR)$	1.73	1.72	1.68	1.73	1.70	1.82	1.74

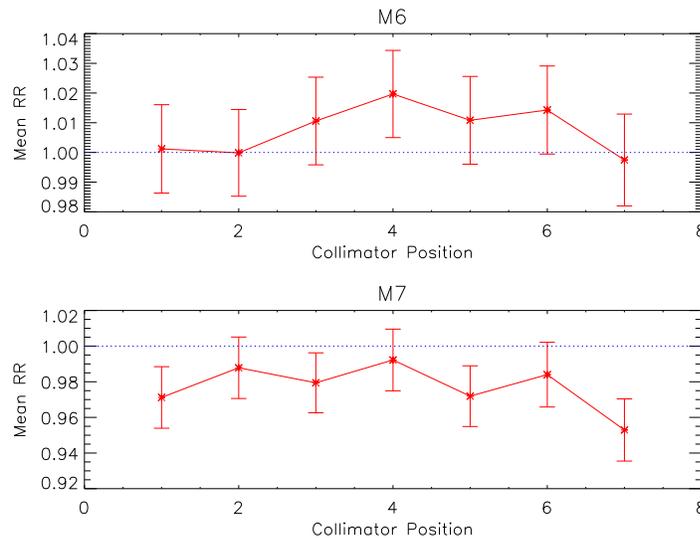


Figure 4. Band averaged responsivity ratios with one sigma uncertainties. Collimator positions are given in (declination angle, azimuthal angle).

### 5.2.2 SDSM Uncertainty Analysis

The uncertainty propagation for the SDSM calibration was defined in Section 4.3. The uncertainties of the measured SDSM ratio as well as the individual uncertainties that were used in the calculated SDSM uncertainty are described in this section, along with the total uncertainty in the calculated SDSM ratio.

Due to the large variability in the SDSM measurement over any given data collection (as shown in Figure 5), the uncertainty in the average SDSM ratio per data collection was taken to be the one sigma standard deviation of all individual SDSM ratios within that data collection.

The uncertainty in the SAS transmission, the SDSM screen transmission, and the SDSM BRF were determined by the sensor subcontractor,<sup>8</sup> and were 0.24 %, 0.67 %, and 1.09 %, respectively. The cosine of the projection angle was determined from alignment measurements made using theodolites. The measurements were assumed to be known to 0.01 degrees. That uncertainty was propagated through Eq. (6). The SDSM entrance cone angle was also assumed to be known to 0.01 degrees; the uncertainty was propagated to the solid angle of the entrance cone. The determination of the uncertainties for the collimator uniformity correction factors is in progress; for the purposes of this work, they are not included in the final results presented below. The total calculated SDSM ratio uncertainties (one sigma) were defined by Eq. (17) for each data collection.

### 5.2.3 Results

The measured SDSM ratios [as defined by Eq. (10)] are plotted in Figure 5. Each color/symbol represents a different collimator position (solid and dashed lines indicating first and second data collections at a particular collimator position). The ratios were between 1.1 and 1.3 for 742 nm and between 1.15 and 1.35 for 852 nm. In addition, the measured ratios exhibited one sigma variation of up to 2.7 % over roughly 3.8 minutes (the temporal fluctuations in the solar view were generally larger than in the SD view). On MODIS, the SDSM also exhibits large variation in any given detector over a typical solar observation; fortunately, all the SDSM detectors vary

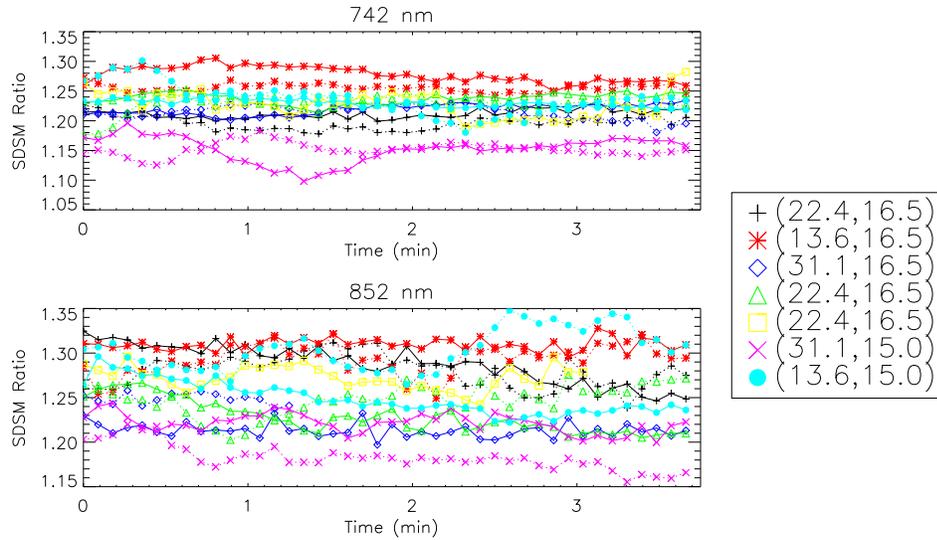


Figure 5. SDSM at 742 nm and 852 nm measured ratios - short term stability.

in roughly the same manner. This allows the temporal variation to be removed using the response of MODIS SDSM detector 9 (936 nm). Due to the fact that T-SIRCUS was a narrow band source, only one SDSM detector recorded a meaningful signal for a particular data collection; as a result, the temporal trend could not be removed in this test using the MODIS methodology.

The measured ratios, averaged over each data collection, are plotted versus collimator position number in Figure 6 for both 742 nm (upper plot) and 852 nm (lower plot). Black crosses and red asterisks indicate the first and second data collections at a particular collimator position (where the uncertainties indicate one standard deviation over that data collection). The measured SDSM uncertainties as defined above were between roughly 0.5 % and 2.7 %. The blue diamonds represent the calculated ratio at each collimator position. The calculated uncertainty was approximately 1.38 % (this number was fairly constant as the major factors were not wavelength or angle dependent). The largest contributors were the SD BRF (1.09 %) and  $\tau_{SDSM}$  (0.67 %). The measurements were consistent with the theoretical values for all positions at 742 nm (with the exception of Position 3, measurement 1). However, most measurements were not consistent with the theoretical results at 852 nm (and sometimes also inconsistent between measurements 1 and 2).

## 6. CONCLUSIONS

E2E testing of a limited number of VIIRS F1 reflective solar bands was conducted in March 2010 at Ball Aerospace in Boulder CO using the NIST T-SIRCUS. The E2E test was an exploration of the use of tunable lasers in the validation of the RSB calibration cycle pre-launch. The goal of the testing was to verify that the responsivities determined from the EV and SD paths were consistent. In addition, the SDSM measurements were compared to modeled results.

The EV / SD responsivity ratios were generally consistent with one for band M6, but only consistent with unity at some collimator positions for band M7. Slight upward trending with detector was observed in the responsivity ratios, which likely results from detector dependence of the collimator uniformity correction. The SDSM measured and theoretical values were generally consistent at 742 nm, but inconsistent at 852 nm. In addition, the SDSM ratios exhibited some temporal variability.

A large source of uncertainty is in the collimator irradiance, which in turn was heavily dependent on the collimator uniformity correction. This correction is very complicated and is still in progress. It is expected that an updated correction will improve the agreement of the responsivity ratios for M7 as well as decrease the

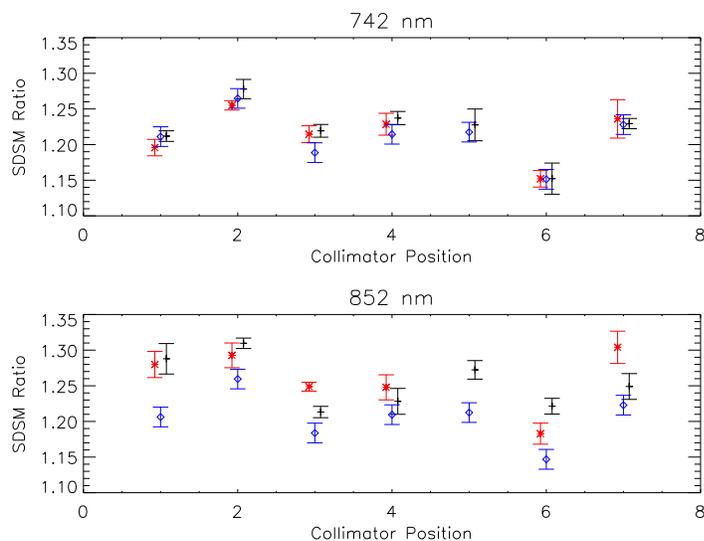


Figure 6. SDSM ratios at 742 nm and 852 nm (measured and calculated) with one sigma uncertainty estimates. Black (red) points indicate data from measurement 1 (2); theoretical values are given in blue.

detector dependence for both bands. In addition, uniformity corrections in the SDSM analysis have yet to be determined, where it is hoped improved agreement for the SDSM ratios at 852 nm will result.

The difficulty of simulating the sun with a ground based source in terms of both footprint and irradiance (as opposed to using the sun directly as was done by OMPS) was surmounted by the test team through the creative use of the NIST T-SIRCUS. The E2E test data provided useful insights into the sensor performance and represents a preliminary rough validation of the RSB calibration cycle. However, improvements in the test setup should increase the accuracy of the measurement (particularly with respect to the collimator irradiance). Future applications of this test methodology should expect to more accurately validate VIIRS RSB calibration cycle pre-launch.

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