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Monochromatic measurements of the JPSS-1 VIIRS polarization sensitivity

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Polarization sensitivity is a critical property that must be characterized for spaceborne remote sensing instruments designed to measure reflected solar radiation. Broadband testing of the first Joint Polar-orbiting Satellite System (JPSS-1) Visible Infrared Imaging Radiometer Suite (VIIRS) showed unexpectedly large polarization sensitivities for the bluest bands on VIIRS (centered between 400 and 600 nm). Subsequent ray trace modeling indicated that large diattenuation on the edges of the bandpass for these spectral bands was the driver behind these large sensitivities. Additional testing using the National Institute of Standards and Technology's Traveling Spectral Irradiance and Radiance Responsivity Calibrations Using Uniform Sources was added to the test program to verify and enhance the model. The testing was limited in scope to two spectral bands at two scan angles; none-theless, this additional testing provided valuable insight into the polarization sensitivity. Analysis has shown that the derived diattenuation agreed with the broadband measurements to within an absolute difference of about 0.4% and that the ray trace model reproduced the general features of the measured data. Additionally, by deriving the spectral responsivity, the linear diattenuation is shown to be explicitly dependent on the changes in bandwidth with polarization state. © 2016 Optical Society of America

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1. INTRODUCTION

For Earth-observing sensors, such as the first Joint Polarorbiting Satellite System (JPSS-1) Visible Infrared Imaging Radiometer Suite (VIIRS) [1], partially polarized scenes are common in the reflected solar region from 400 to 900 nm. As a result, it is important to characterize the sensitivity of the instrument to linearly polarized light in order to ensure that the science data products are accurate. Due to limitations in the available data once the sensor is on orbit, the polarization sensitivity was tested pre-launch by the sensor vendor (Raytheon El Segundo) [2,3]. The result of this baseline testing was unexpectedly large linear diattenuation in the four spectral bands centered between 400 and 600 nm (in many cases the diattenuation was over 3.0% and was as high as 6.4%). A series of actions were taken to investigate this result including improvements to the ray trace model as well as additional testing. One of the additional tests performed used a monochromatic source, the National Institute of Standards and Technology's (NIST's)

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Traveling Spectral Irradiance and Radiance Responsivity Calibrations Using Uniform Sources (T-SIRCUS) [4].

The analysis of the T-SIRCUS polarization test data is the focus of this work. Fourier analysis was used to reduce the data and compute the Mueller matrix components, which were in turn used to construct the linear diattenuation and phase angle [2,5]. The wavelength-dependent linear diattenuation was compared to the ray trace model results, and the linear diattenuation, integrated over each spectral bandpass, was compared to the earlier broadband measurement results. Although the T-SIRCUS measurements were limited in the number of spectral bands measured, the wavelength sampling of the selected bands, and the scan angles at which the measurements were taken, the results were able to validate some aspects of the ray trace model, in particular the large diattenuation predicted at the edges of each bandpass. In addition, the band-dependent results were shown to be comparable to the broadband measurement to within an absolute difference of 0.4% or less, which is within the k = 2 uncertainties for all cases.

A second approach was also proposed, based on the construction of spectral responsivity functions [6,7]. A spectral responsivity function was derived for each polarization state, from which the centroid, bandwidth, and responsivity were determined. How the polarization state effects each of these characteristics was explored. The polarization-state-dependent responsivity was then used to calculate the linear diattenuation and phase angle. A comparison between the two methodologies has shown that the linear diattenuation agrees to within an absolute difference of 0.16%.

Section 2 provides an overview of the VIIRS instrument, the baseline testing performed, the ray trace model, and the T-SIRCUS test setup. The methodology for both analysis approaches is outlined in Section 3. Section 4 details the data analysis performed as well as the results of both approaches. Some conclusions are provided in Section 5.

2. OVERVIEW

A. VIIRS

The JPSS-1 mission, scheduled for launch in early 2017, will carry five Earth-observing sensors including VIIRS. This VIIRS will be the second instrument of its line, the first currently flying on board the Suomi National Polar-orbiting Partnership (SNPP) satellite [8,9], and incorporates much of its design from a heritage sensor, the Moderate Resolution Imaging Spectroradiometer (MODIS) [10]. VIIRS is a cross-track scanning radiometer that observes the Earth through 21 spectral bands and one panchromatic band covering a spectral range from 0.4 to 12.6 μ m and is capable of making continuous global observations twice daily. The science data collected is used to support a number of environmental data records covering land, ocean, and atmospheric science disciplines [11–13].

For the visible and near infrared bands, the VIIRS optical path from the entrance aperture first passes through the rotating telescope assembly (RTA), which is composed of an afocal three-mirror anastigmat followed by a fold mirror [1,8]. The RTA rotates about once every 1.78 s perpendicular to the track direction, viewing a $\pm 56^{\circ}$ swath through the Earth view port. Additionally, the RTA views three calibration targets to maintain the instrument calibration. The light exiting the RTA is directed onto a two-sided rotating fold mirror, referred to as the half angle mirror (HAM), that rotates at half the speed of the RTA, derotating the light beam and directing it into the fixed aft-optics. The path then passes through a fold mirror and a four-mirror anastigmat as it enters the aft-optics. The visible and near infrared light is then reflected by a dichroic beamsplitter onto a focal plane array (FPA).

There are nine visible and near infrared spectral bands located on this FPA (whose temperature floats with the instrument); the panchromatic band is located on an adjacent temperature-controlled FPA. During T-SIRCUS polarization testing, measurements were made within the bandpass of only three bands: two spectral bands (M1 and M4) and the panchromatic band (DNB, or Day–Night Band). Both spectral bands have 16 Si-PIN detectors, arranged in a linear array perpendicular to the scan direction on the focal plane; each

Table 1.	Center Wavelengths (λ_c) and Bandwidths (BW)
for the Ba	nds Measured in T-SIRCUS Polarization Tes	sting

Band	$\lambda_C[\mathbf{nm}]$	BW [nm]
M1	412	20
M4	555	20
DNB	700	400

detector has a resolution of about 750 m at nadir (from a nominal altitude of 828 km). Bands M1 and M4 have two gain states (high and low); the radiance levels tested were within the range of the high gain state only. The DNB is a 4-stage CCD array, of which only the lowest gain stage recorded any meaningful signal, and aggregates its sub-pixels such that it reads out the equivalent of 16 spectral band detectors each with a resolution of about 750 m at nadir. The light is collected by each detector after it passes through a spectral bandpass filter, defined by the center wavelengths and bandwidths listed in Table 1.

B. Baseline Testing

The baseline polarization sensitivity test was performed at the Raytheon El Segundo facility in December 2013 [2,3]. A 100 cm diameter integrating sphere with a 30 cm circular aperture fed by a number of lamps was used as a source. The light exiting the sphere was then incident on a sheet polarizer [14] mounted in the rotation stage. The polarizer was rotated from 0° to 360° in increments of 15°. Two test configurations were used: one with a long-wave blocking filter [15] used for the spectral bands centered below 500 nm (placed before the polarizer in the optical path) and one without any filter for all other bands. VIIRS then measured the linearly polarized light exiting the sheet polarizer and Fourier analysis was used to determine the linear diattenuation of the instrument [2,3]. The four spectral bands centered from 400 to 600 nm were observed to have linear diattenuations of over 3.0%, with up to 6.4% in the 412 nm band. In addition, significant scan angle and detector dependence were observed. These results at the time were unexpected and three actions were initiated: repeat the test at a later date with additional scan angles to confirm the initial results; improve the ray trace modeling; and include additional, limited testing using a monochromatic source. The purpose of the last two actions was to investigate the root cause of the larger than expected linear diattenuation.

The second run of the baseline testing was performed at the Raytheon El Segundo facility in November 2014, using the same setup as the first test while including additional scan angles not measured during the initial test. The results of this test confirmed the initial results as well as validated the method proposed to interpolate the initial baseline testing results between scan angles.

C. Modeling

A ray trace model of the VIIRS optical train was constructed by Raytheon as part of the sensor development for SNPP VIIRS [3]. The model was used to estimate the polarization sensitivity of SNPP VIIRS using each band's central wavelength, but the predictions and measurements did not agree well (in particular the detector dependence and scan angle dependence were not well described). Component measurements of the JPSS-1 spectral band filters had shown that the difference in transmittance between *s*- and *p*-polarization was much larger on the edges of the bandpass and also larger when compared to the SNPP filters (the filters had been redesigned to reduce outof-band leaks observed for SNPP). Although this phenomenon is well documented [16], it was assumed that because of the low angle of incidence on the filters, this effect would be small.

The model was revisited for JPSS-1 VIIRS in part to help explain the larger than expected polarization sensitivities observed [3]. The model was expanded for JPSS-1 VIIRS by using 25 wavelengths to better sample the bandpass. In addition, it incorporated the JPSS-1-specific filter and other component measurements. The model predicted that the large banddependent polarization sensitivities were due to large diattenuation on the edges of the bandpass where the spectral response curves were steepest. Essentially, the bandpass was shifting as the polarization state changed from *s*- to *p*-polarization. The model agreement with the measured values was much improved, but there were still some discrepancies.

D. T-SIRCUS

NIST has developed a portable, laser-based facility for use in radiance and irradiance responsivity calibration known as T-SIRCUS [4]. T-SIRCUS was transported to the Raytheon El Segundo facility in December 2014 for JPSS-1 VIIRS instrument-level testing of the spectral response functions, as well as the limited polarization measurements which are the focus of this work. The spectral bands selected for polarization testing were M1 and M4 (see Table 1). The wavelength regions from 397 to 424 nm and from 543 to 565 nm are accessed by the second harmonic of a custom optical parametric oscillator pumped at 532 nm by a frequency-doubled Nd:YVO₄ laser. While the laser pulse frequency is about 80 MHz, this is well above the VIIRS frequency response, so the laser is treated as a continuous wave. The oscillator output decreases near the long side of the M4 bandpass; as a result, the wavelength region from 566 to 572 nm is accessed using a Rhodamine 6G dye laser, pumped by a continuous wave Nd:YVO₄ laser. The bandwidth of the optical parametric oscillator is ~0.02 nm in the 400 nm region and ~0.03 nm in the 550 nm region; the bandwidth of the dye laser is also ~ 0.02 nm [3].

E. Test Setup

The T-SIRCUS lasers fed a 100 cm NIST integrating sphere with a 30 cm circular aperture designed to overfill the VIIRS aperture with monochromatic illumination. A NIST transfer radiometer mounted directly into the sphere monitored the radiance output and provided feedback to the laser power stabilizer [3]. Light exiting this integrating sphere illuminated a sheet polarizer [14] mounted in a rotary stage, which could be rotated from 0° to 360°. The now linearly polarized light entered the VIIRS telescope aperture. Supplemental stray light and polarizer efficiency tests were performed using additional elements added to the path. Two stray light tests were conducted: one with an obscuration inserted into the path between the integrating sphere and the rotating sheet polarizer, and one with the source off. The efficiency of the sheet polarizer was measured by inserting an additional fixed polarizer of the same type into the path between the rotating polarizer and the VIIRS

aperture. The measured polarizer efficiency is used to correct the linear diattenuation. Various baffling was used to minimize contamination for other sources or paths.

The VIIRS instrument was set to operational mode with the telescope fixed, staring at the source. Bands M1 and M4 were operated in fixed high gain while the DNB was in auto gain. The VIIRS was mounted on a rotary table, such that the instrument could view the source from different scan angles; for T-SIRCUS testing, the VIIRS was positioned to view the source at -8° and $+45^{\circ}$ scan angles.

For all tests (stray light, efficiency, and sensitivity), the polarizer sheet was rotated from 0° to 180° in 15° increments. The polarizer sheet dwelled at every angle for a given amount of time before transitioning to the next polarizer angle. A shutter on the source was used to provide a dark offset correction.

3. METHODOLOGY

A. Fourier Analysis

Fourier analysis was used to analyze the JPSS-1 VIIRS polarization sensitivity measurements [2], including those acquired using T-SIRCUS [5]. The following Fourier expansion was used to model the offset corrected sensor response (dn) at a given wavelength (λ) and polarization angle (θ) :

$$dn(\lambda,\theta) = \frac{1}{2}c_0(\lambda) + c_2(\lambda)\cos(2\theta) + d_2(\lambda)\sin(2\theta),$$
 (1)

where the zeroth- and second-order Fourier coefficients are given by

$$\frac{1}{2}c_0(\lambda) = \frac{1}{\pi} \int_0^{\pi} \mathrm{d}\theta \, d\, n(\lambda,\theta),\tag{2}$$

$$C_2(\lambda) = \frac{2c_2(\lambda)}{c_0(\lambda)} = \frac{4}{\pi c_0(\lambda)} \int_0^{\pi} \mathrm{d}\theta \, d\, n(\lambda, \theta) \cos(2\theta), \qquad (3)$$

$$D_2(\lambda) = \frac{2d_2(\lambda)}{c_0(\lambda)} = \frac{4}{\pi c_0(\lambda)} \int_0^{\pi} \mathrm{d}\theta \, dn(\lambda,\theta) \sin(2\theta). \tag{4}$$

Note that the measurements were limited to polarization angles between 0° and 180°. As a result, the first-order Fourier coefficients are underdetermined (however, given the high polarizer efficiency measured during the test, they are expected to be very small). The third- and fourth-order coefficients were investigated and found to be negligible. Here the coefficients C_2 and D_2 are the Mueller matrix components m_{12} and m_{13} [17]. The Fourier expansion given in Eq. (1) can be rewritten as

$$dn(\lambda,\theta) = \frac{1}{2}c_0(\lambda)\{1 + a_2(\lambda)\cos[2\theta + 2\delta_n(\lambda)]\},$$
 (5)

where

$$a_2(\lambda) = \frac{\sqrt{C_2^2(\lambda) + D_2^2(\lambda)}}{\sqrt{a_2^{\text{eff}}(\lambda)}},$$
(6)

$$\delta_2(\lambda) = \frac{1}{2} \tan^{-1} \left[\frac{D_2(\lambda)}{C_2(\lambda)} \right].$$
 (7)

Here the polarizer efficiency is determined from

$$a_2^{eff}(\lambda) = \sqrt{C_2^2(\lambda) + D_2^2(\lambda)},$$
(8)

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using the polarizer efficiency data. Note that a_2 is the linear diattenuation and δ_2 is the phase angle.

For comparison to earlier broadband measurements of the polarization sensitivity [2,3], the average of the above Fourier analysis over the bandpass, weighted by the spectral response of the instrument and the broadband input spectrum, was estimated by

$$C_2(B) = \frac{\int d\lambda C_2(\lambda) RSR(\lambda) L_{source}(\lambda)}{\int d\lambda RSR(\lambda) L_{source}(\lambda)},$$
(9)

$$D_2(B) = \frac{\int d\lambda D_2(\lambda) RSR(\lambda) L_{source}(\lambda)}{\int d\lambda RSR(\lambda) L_{source}(\lambda)},$$
 (10)

where *B* indicates a spectral-band-dependent quantity. Here RSR denotes the spectral transmittance [18] and the broadband source profile is represented by L_{source} . For band M1, the source spectra includes both the output from the spherical integrating source (SIS) and the transmittance of a long-wave blocking filter, which reduced the out-of-band contributions [2,3]. The Fourier coefficients generated from Eqs. (3) and (4) were resampled to 1 nm from the measured T-SIRCUS wavelengths. Then, the band-dependent linear diattenuation and phase angle are defined as

$$a_2(B) = \frac{\sqrt{C_2^2(B) + D_2^2(B)}}{\sqrt{a_2^{\text{eff}}(B)}},$$
 (11)

$$\delta_2(B) = \frac{1}{2} \arctan\left[\frac{D_2(B)}{C_2(B)}\right].$$
 (12)

For clarity in the plots, here $0 \le \delta_2(B) < \pi$. The above analysis was also performed on the ray trace model data.

B. Absolute Spectral Response

Based on the work in [6,7], we can define the absolute spectral response (ASR) as

$$ASR(\lambda, \theta) = \frac{dn(\lambda, \theta)}{L(\lambda, \theta)},$$
(13)

where *L* is the radiance at the VIIRS aperture and *dn* is the offset corrected sensor response. Here $RSR(\lambda, \theta) = ASR(\lambda, \theta) / max[ASR(\lambda, \theta)]_{\lambda}$.

Following [6,7], we can further define the detector responsivity (*R*), the spectral band centroid (λ_c), and spectral bandwidth (BW) in terms of the ASR, or

$$R(\theta) = \int d\lambda ASR(\lambda, \theta),$$
 (14)

$$\lambda_{c}(\theta) = \frac{\int d\lambda A \mathrm{SR}(\lambda, \theta)}{\int d\lambda \mathrm{ASR}(\lambda, \theta)} = \frac{\int d\lambda A \mathrm{SR}(\lambda, \theta)}{R(\theta)},$$
 (15)

$$BW(\theta) = \frac{\int d\lambda ASR(\lambda, \theta)}{\max[ASR(\lambda, \theta)]_{\lambda}} = \frac{R(\theta)}{\max[ASR(\lambda, \theta)]_{\lambda}}.$$
 (16)

The ASR constructed in Eq. (13) is equivalent to a series of measurements where the input spectrum is flat. To consider the effects on Eqs. (15) and (16) of different input spectra, the ASR was modified as follows [6,7]:

$$ASR'(\lambda, \theta) = ASR(\lambda, \theta) \frac{L_{source}(\lambda)}{L_{source}^{AVG}},$$
 (17)

where L_{source} is an input source spectral radiance and $L_{\text{source}}^{\text{AVG}}$ is the average source spectral radiance, or

$$L_{\text{source}}^{\text{AVG}} = \frac{\int d\lambda L_{\text{source}}(\lambda) \text{ASR}(\lambda, \theta)}{R(\theta)}.$$
 (18)

By ratioing to the average source spectral radiance, the ASR' is only modified by the relative shape of the source spectrum. In this work, two input spectra were considered: the top of the atmosphere (TOA) and spherical integrating source (SIS). The TOA spectrum provides some indication of the expected on-orbit behavior and the SIS spectrum connects these measurements to the broadband characterization. Note that in this formulation, the responsivities derived from ASR and ASR' are the same [the areas under the ASR and ASR' curves are equal due to the normalization to L_{source}^{AVG} in Eq. (17)].

The Fourier components used in the polarization analysis were defined in Eqs. (2), (3), and (4). If we assume that the light exiting the integrating sphere is unpolarized, then the radiance transmitted by the rotating polarizer is independent of polarization angle, or $L(\lambda, \theta) \rightarrow L(\lambda)$. Then using Eqs. (14) and (16), the Fourier coefficients are rewritten as

$$C_2(B) = \frac{2}{\pi R(B)} \int_0^{\pi} \mathrm{d}\theta \, \cos(2\theta) R(\theta), \tag{19}$$

$$D_2(B) = \frac{2}{\pi R(B)} \int_0^{\pi} \mathrm{d}\theta \,\sin(2\theta) R(\theta), \qquad (20)$$

where $R(B) = \langle R(\theta) \rangle_{\theta}$.

The band-dependent linear diattenuation is then defined as 2 1

$$a_{2}(B) = \frac{2}{\pi R(B)} \frac{1}{\sqrt{a_{2}^{\text{eff}}(B)}} \times \left[\int_{0}^{\pi} d\theta_{1} R(\theta_{1}) \int_{0}^{\pi} d\theta_{2} R(\theta_{2}) \cos(2\theta_{1} - 2\theta_{2}) \right]^{\frac{1}{2}}.$$
(21)

The band-dependent phase is also defined as

$$\delta_2(B) = \frac{1}{2} \tan^{-1} \left[\frac{\int_0^{\pi} d\theta \sin(2\theta) R(\theta)}{\int_0^{\pi} d\theta \cos(2\theta) R(\theta)} \right].$$
 (22)

The result is now explicitly in terms of the polarizationstate-dependent responsivity, which is the product of the maximum ASR over wavelength and bandwidth. As mentioned earlier, the spectral splitting in the transmittance of the *s*- and *p*-polarization states was the predicted cause of the larger than expected polarization sensitivities observed for JPSS-1 VIIRS. This is largely manifested by the shifting of the bandwidth with polarization state, as is clear from Eq. (21).

4. RESULTS

A. Data Quality and Reduction

The wavelengths measured during T-SIRCUS polarization testing are listed in Table 2, grouped by HAM side, scan angle, and test type. During testing, the VIIRS was continually collecting data in operational mode with the telescope locked in position staring through the sheet polarizer at the exit port of the NIST

Table 2. T-Sl	RCUS Polarization Measurements
Performed as	a Function of Wavelength, HAM Side,
Scan Angle, a	Ind Test Type (Stray Light, Polarizer
Efficiency, or	Polarization Sensitivity) ^a

Test Type	HAM Side	Scan Angle	Wavelengths
Dark	1	-8	NA
Obscuration	1	-8	415, 559
Polarizer Efficiency	1	-8	401, 412, 420 559
Polarization Sensitivity	1	-8	397, 400, 402, 404, 406, 408, 410, 413, 415, 417, 419, 421, 424 543, 546, 547, 548, 550, 552, 553, 555, 556, 558, 560, 561, 562, 564, 567, 569, 572
Polarization Sensitivity	0	-8	543, 545, 547, 548, 550, 553, 556, 559, 562, 564, 567, 569, 572
Polarization Sensitivity	1	+45	397, 399, 402, 404, 406, 408, 410, 413, 415, 417, 419, 421, 424 543, 545, 547, 549, 551, 552, 553, 554, 556, 558, 559, 561, 562, 564, 567, 569, 572

"Wavelengths are given in nm and were rounded to the nearest nm. Scan angles are given in degrees.

integrating sphere. For every scan, bands M1 and M4 collected 6304 pixels for each detector, while the DNB collected 4064 pixels for each detector in fixed aggregation mode 1. The average and standard deviation of each detector's response was determined every scan. For each wavelength, the rotating polarizer was cycled in 15° increments from 0° to 180°. The polarizer paused at each angle for 45 or 75 s (depending on the test). As the telescope was staring at the source, the background signal was generated using a shutter located on the optical table. The shutter cycle was 18 or 30 s, depending on the test. The shutter open and closed times and the polarizer angle dwell times were correlated with the VIIRS scan times to determine which scans for a particular polarizer angle were signal and which were background. As the shutter was not synched to the VIIRS scan rate, the data was screened to eliminate scans during which the shutter changed positions (observed through higher standard deviations over pixels). In addition, the laser wavelength occasionally drifted during testing; as the transmittance of the *s*- and *p*-polarization can be very sensitive to wavelength depending on the location in the bandpass, a threshold of 0.15 nm from the average wavelength was used to remove data contaminated by wavelength drift. After the data was filtered, the average of the valid background scans was subtracted from the average of the valid signal scans to produce the dn for each polarizer angle and wavelength. Note that for some polarizer angle-wavelength combinations, no valid scans remained after the data screening.

The Fourier coefficients in Eqs. (2)-(4) were determined from all of the polarizer measurements for each wavelength (13 discrete polarizer angles, assuming each angle contains some valid data). If no valid data was collected for a given polarizer angle, two approximations were used to reconstruct some of the missing data. First, as 0° and 180° effectively produce the same polarization state, if one of these two angles was missing, it was replaced by the other. Second, if data for a single polarizer angle was missing while the angles immediately preceding and following it were valid, then a linear interpolation across the interval was made. After these approximations were made, there were still a number of wavelengths for which some polarizer angles did not contain useful data, which would prevent the direct integration of the Fourier coefficients. In these cases, a function fit was used to determine the zeroth- and second-order Fourier coefficients. The wavelength-dependent Fourier coefficients were then resampled to 1 nm, from which the wavelength-dependent linear diattenuation and phase angle were determined from Eqs. (6) and (7).

The band-dependent Fourier coefficients were generated from Eqs. (9) and (10) by integrating the resampled, wavelengthdependent Fourier coefficients over the bandpass, weighted by the spectral transmittance of the system and the appropriate source profile. To compare to earlier broadband polarization measurements, the broadband source profile was used for band M4; for band M1, the combination of the broadband source profile and the transmittance of a long-wave blocking filter was used. As the measurements for the DNB did not cover the entire bandpass, the band-dependent Fourier coefficients could not be generated. Then, the band-dependent linear diattenuation and phase angle were estimated from Eqs. (11) and (12), where the average of the measured polarizer efficiency for a given band was used (98.3% for band M1 and 98.7% for band M4).

To construct the ASR, the radiance after the polarizer needed to be determined. However, the radiance monitor is mounted inside the integrating sphere. To estimate the radiance postpolarizer, the ASR constructed during spectral testing [18] was used in the ratio to the zeroth-order Fourier coefficients (essentially the unpolarized dn), so that the spectral radiance of the source includes the transmittance of the polarizer sheet. This radiance is then inserted into Eq. (13) along with the polarized dn to form the polarized ASR. As noted above, usable data was not collected for some wavelength–polarizer angle combinations; in these cases, the data was reconstructed using the Fourier analysis performed above [see Eq. (1)]. In addition, the zeroth-order Fourier component is effectively the unpolarized ASR.

All results shown in the subsequent plots and tables are derived from measurements made at -8° scan angle using HAM side 1. Unless otherwise noted, these results were indicative of the other conditions measured.

B. Uncertainty

In order to determine whether the T-SIRCUS polarization measurements were consistent with the broadband measurements, the underlying uncertainties were propagated through Eqs. (1)–(11) using a standard uncertainty analysis [19]. A full uncertainty analysis was similarly performed for the broadband measurements [2]. First, the standard deviations over all

samples were determined for each valid scan. These standard deviations were propagated to the dn for each detector, HAM side, scan angle, wavelength, and polarization angle. These statistical uncertainties were combined through a root sum square with a stray light pedestal (measured from the obscuration configuration) and a measure of repeatability (the difference between the measurements at 0° and 180°). The uncertainty on the polarizer angle was determined from the efficiency testing by estimating the deviation in the alignment of the polarization axis of the polarizer angle uncertainties were then propagated through the integrals for the Fourier coefficients in Eqs. (2)–(4), and then to the wavelength-dependent linear diattenuation and phase angles in Eqs. (6) and (7).

In order to determine the uncertainties for the banddependent linear diattenuation and phase angles in Eqs. (11) and (12), the uncertainties are first propagated through the band-dependent Fourier coefficients in Eqs. (9) and (10). An estimate of the uncertainty in the RSR was determined from separate spectral testing [18] and the wavelength uncertainty was determined using the standard deviation of the wavelength measurements for a given set of polarizer angles. The input spectra used here were considered model inputs, and therefore did not contribute to the overall uncertainty. The uncertainty was then propagated from the band-dependent Fourier coefficients to the band-dependent linear diattenuation and phase angles in Eqs. (11) and (12). However, the bandpass was coarsely sampled; as a result, some additional uncertainty was necessary to account for the limited number of wavelengths measured across each bandpass. The effect of the sampling error was estimated by taking the difference between the linear diattenuation determined with and without resampling the Fourier coefficients to 1 nm. In addition, the broadband measurement uncertainty includes a contribution to account for the difference between the SIS and TOA spectra; this was also included here by differencing the linear diattenuation determined from the ray trace model using the two source spectra. The final uncertainty on the linear diattenuation was taken to be the root sum square of the propagated uncertainty, the sampling error, and the SIS-TOA differences.

C. Fourier Analysis

The measured response for band M1 to illumination at 408 nm versus polarizer angle is shown in Fig. 1(a) for all detectors. Similar plots of the measured dn are shown in Figs. 1(b)– 1(d) for band M1 illuminated at 417 nm, band M4 illuminated at 547 nm, and band M4 illuminated at 555 nm. In all of the subfigures, the symbols represent the measured response and the lines denote the Fourier expansion in Eq. (5). Each detector is represented by a different symbol/color as defined in the legend. The Fourier expansion describes the data very well with only the zeroth- and second-order terms (as expected from Malus's Law), indicating that the first, third, and higher orders in the expansion are very small. In addition, note that the amplitude and phase of the two-cycle oscillation is very consistent from detector to detector for the data measured at 408 nm; for the other measurements shown, the amplitude and phase vary considerably over detectors. The observations have shown that the two-cycle amplitude and phase vary with wavelength and scan angle as well as detector.



Fig. 1. Measured dn versus polarizer angle for band M1 at 408 nm (a), band M1 at 417 nm (b), band M4 at 547 nm (c), and band M4 at 555 nm (d). The legend defines the different symbol/color combinations which correspond to each detector.

The linear diattenuation for band M1, derived from the resampled Fourier coefficients and weighted by the spectral transmittance of the system as well as the broadband source radiance, is shown in Fig. 2(a). Each detector is represented by a different symbol/color as defined in the legend. The weighting decreases the diattenuation on the edges of the bandpass, but two spikes remain where the spectral transmittances increase sharply on either side of the high response zone where the diattenuation is smaller. Figure 2(b) graphs the spectrally weighted diattenuation derived from ray trace modeling; note that the general features of the model reproduce the measurements well. This confirmed that splitting between the transmittance of s- and p-polarization states occurred [16]. Similarly, the measured and modeled weighted linear diattenuation for band M4 are plotted in Figs. 3(a) and 3(b). A similar profile is observed in the measured M4 diattenuation in that the two spikes



Fig. 2. Measured weighted diattenuation versus wavelength for band M1 (a) and modeled weighted diattenuation versus wavelength for band M1 (b). The legend defines the different symbol/color combinations which correspond to each detector.



Fig. 3. Measured weighted diattenuation versus wavelength for band M4 (a) and modeled weighted diattenuation versus wavelength for band M4 (b). The legend defines the different symbol/color combinations which correspond to each detector.

at the edges of the bandpass with a decrease in between were observed; this loosely corresponds with the model profile. However, some differences exist with the model output in that the oscillations observed in the middle of the bandpass are absent from the model and that the spike on the long side of the M4 bandpass is much smaller. The wavelengths at which the linear diattenuation approaches zero in the center of the M4 bandpass correspond to wavelengths where both the underlying Fourier components pass through zero; these wavelengths correlate to a phase angle shift of 90° [5]. Analysis has shown that a similar phase shift pattern occurs in the same spectral region for the DNB data, indicating that this phenomenon is not caused by the spectral band filters. In addition, the modeled bandpass is wider than the measurement, particularly on the shorter wavelength side.

Figure 4 shows the band-dependent linear diattenuation for the band M1 data. Here the T-SIRCUS measurements (black) are compared to the broadband measurements (red) and ray trace model results (blue). The k = 2 uncertainties are also included for the measurements (dashed lines), which indicate that the two measurements agree (the absolute difference is within 0.4% for all detectors). The results are consistent for both measured M1 cases (at -8° and $+45^{\circ}$ scan angles). The phase angle is not shown, but is consistent with the broadband measurements to within 0.6° for all conditions. The model also is consistent with the measurements in both cases. The banddependent M4 diattenuation is graphed in Fig. 5. Again, the k = 2 uncertainties were included and the results indicate that the two measurements agree to within an absolute difference of 0.3% (including for the measurement conditions not shown: -8° scan angle, HAM side 0 and $+45^{\circ}$ scan angle, HAM side 1). However, the observed detector dependence was not captured well by the ray trace model for band M4. This is partially the result of the model not capturing the shift in the phase angle that occurred in the center of the bandpass and also overestimating the relative importance of the diattenuation on the longer wavelength side of the bandpass (see Fig. 3).



Fig. 4. Plots of the diattenuation showing band M1 at -8° scan angle, HAM side 1. Black "+" indicates T-SIRCUS measurements, red "*" denote broadband measurements, and blue " \Diamond " refer to the model. Dashed lines indicate the extent on the k = 2 uncertainties.

The phase angle comparison showed good agreement for the low number detectors, and increasing for the higher number detectors, with a difference of up to $\sim 6.5^{\circ}$.

D. Absolute Spectral Response

The ASR functions for all measured polarization states as well as with the unpolarized ASR are shown in Fig. 6 for band M1 using detector 9 data. A similar plot is shown in Fig. 7 for band M4. The general shape of the bandpass is well described in both cases [18], even though the measurements coarsely sampled both bandpasses. The 0° and 180° polarization angles were treated separately to help quantify the repeatability; in general, the ASR agreed to within 1% with differences of as high as 3% at the lowest response levels. The ASRs constructed for the remaining detectors and measurements show similar variability,



Fig. 5. Plots of the diattenuation showing band M4 at -8° scan angle, HAM side 1. Black "+" indicates T-SIRCUS measurements, red "*" denote broadband measurements, and blue " \Diamond " refer to the model. Dashed lines indicate the extent on the k = 2 uncertainties.



Fig. 6. Band M1 ASR shown for detector 9. The legend defines the different symbol/color combinations which correspond to each polarization state (and "un" refers to the unpolarized ASR).

although there is a fair amount of detector dependence. The unpolarized ASRs multiplied by the SIS and TOA spectra as described by Eq. (17) are shown in Figs. 8 and 9 for bands M1 and M4 respectively. The SIS spectrum increases from blue to red and is fairly smooth, while the TOA spectrum decreases with increasing wavelength and includes some structure. Thus, the SIS spectrum shifts the ASR curves toward longer wavelengths, whereas the TOA spectrum shifts the bandpass toward shorter wavelengths (while also imparting some structure in the center of the M1 bandpass).

The centroids for bands M1 and M4 derived using a flat spectrum ASR are plotted in Figs. 10(a) and 10(b). The flat spectrum ASR was also used to estimate the band M1 and M4 bandwidths, plotted in Figs. 11(a) and 11(b). Note that the centroids and bandwidths derived from the unpolarized data are plotted as the disconnected points at 195°. Although these figures only show results using data from -8° scan angle, HAM side 1, their behavior is indicative of all of the measurements listed in Table 2. The variation in centroid is small for both bands, up to ~0.2 nm for band M1 and ~0.3 nm for band M4. In contrast, the bandwidth varies by up to ~1.5 nm for band M1 and ~1.6 nm for band M4. There are also noticeable detector-to-detector differences in the



Fig. 7. Band M4 ASR shown for detector 9. The legend defines the different symbol/color combinations which correspond to each polarization state (and "un" refers to the unpolarized ASR).



Fig. 8. Band M1 ASR shown for detector 9. The legend defines the different symbol/color combinations which correspond to the unpolarized ASR' for different input spectra.

bandwidth variation with polarizer angle, particularly for band M4 where the smallest variation is as low as \sim 0.5 nm. As noted above, the changes in the bandwidth correlate to the observable polarization sensitivity; the band M4 detectors with the greatest bandwidth variation exhibit the largest polarization sensitivity and the detectors that show the smallest bandwidth changes have the lowest polarization sensitivity. The average centroids and bandwidths derived from the flat spectrum, unpolarized ASRs are listed in Table 3, compared to the results derived from separate spectral testing [18]. In general, the results agree to within 0.6 nm for the centroid and 1.3 nm for the bandwidth. Note that the bandpass in polarization testing was much less finely sampled than in the spectral testing. This particularly effects the bandwidth estimates, which explains the deviations of the bandwidth versus polarizer angle from a two-cycle oscillation in Fig. 11(b) for some detectors.

Using Eq. (17) to simulate the effects on the centroids and bandwidths of different source spectra, the band M1 centroids are shown as a function of polarization state in Fig. 12(a) for the flat spectrum, in Fig. 12(b) for the SIS spectrum, and in Fig. 12(c) for TOA spectrum. The band average values are listed in Table 3. The input spectrum has only a limited effect on the centroid, with variation of less than ~ 0.7 nm for all



Fig. 9. Band M4 ASR shown for detector 9. The legend defines the different symbol/color combinations which correspond to the unpolarized ASR' for different input spectra.





Fig. 10. Plots are shown of the band centroid for band M1 (a) and for band M4 (b) versus polarization state. The legend defines the different symbol/color combinations which correspond to each detector. Note that the unconnected data at 195° in each plot represents the centroid derived from unpolarized data.

cases. The band M4 bandwidths are graphed in Fig. 13(a) for the flat spectrum, in Fig. 13(b) for the SIS spectrum, and in Fig. 13(c) for TOA spectrum as a function of polarization angle. Table 3 lists the band average values for each input spectrum. Note that some of the detectors do not follow a two-cycle curve in the plots; this is likely due to the coarse sampling of the bandpass, particularly on the edges of the bandpass where the response is rapidly changing. This indicates that the bandwidth is poorly determined in some cases. The band average bandwidths tend to be lower when the ASR' is weighted by the SIS spectrum, by ~1.4 nm for band M1 and ~0.3 nm for band M4; and higher when the ASR' is convolved with the TOA spectrum, by ~0.2 nm for band M1 and ~0.1 nm for band M4. In addition, the bandwidth variation over the



Fig. 11. Plots are shown of the bandwidth for band M1 (a) and for band M4 (b) versus polarization state. The legend defines the different symbol/color combinations which correspond to each detector. Note that the unconnected data at 195° in each plot represents the bandwidth derived from unpolarized data.

Table 3.	Measure	d Band Avera	ge Centro	oids,	
Bandwidt	hs, and F	Responsivities	Determin	ned from	the
Unpolarize	ed ASR'	Compared to	Spectral	Testing	
Results [1	8] ^a				

Band	Spectra	Centroid	Bandwidth	Responsivity
M1	Flat	411.2	16.9	18.7
M1	SIS	411.9	15.5	_
M1	TOA	411.0	17.1	_
M1	Spectral	411.8	18.2	19.2
M4	Flat	556.8	18.4	34.5
M4	SIS	557.0	18.1	_
M4	TOA	556.5	18.3	_
M4	Spectral	556.9	18.1	34.7

"The centroids and bandwidths are given in units of [nm] and the responsivities are given in units of $[dn/(W/m^2/sr/\mu m)]$.

detectors differs depending on the input spectra; the maximum bandwidth changes with polarization state are ~0.9 and ~1.5 nm for band M1 using the SIS and TOA spectra, respectively, and ~2.1 and ~0.8 nm for band M4 using the SIS and TOA spectra, respectively. Because the responsivity is invariant under the convolution defined in Eq. (17), the bandwidth as defined by Eq. (16) will change with the input spectra as the factor max [ASR'(λ , θ)] $_{\lambda}$ varies. Furthermore, the bandwidths derived from the unpolarized data should be roughly equivalent to the average over all the bandwidths derived from the polarized data; however, as seen in Figs. 13(a) and 13(c), this is not always the case.

The measured band M1 and M4 responsivities as a function of polarizer angle are plotted in Figs. 14(a) and 14(b), respectively. The other measured cases show similar trends with polarization angle. In addition, the responsivity derived from the unpolarized data is shown as the unconnected data at 195° in each subfigure. There is considerable variation in both amplitude and phase across detectors for both bands, but in



Fig. 12. Plots of the band centroid versus polarization state for band M1 using the flat spectrum (a), the SIS spectrum (b), and the TOA spectrum (c). The legend defines the different symbol/color combinations which correspond to each detector. Note that the unconnected data at 195° in each plot represents the centroid derived from unpolarized data.



Fig. 13. Plots of the bandwidth versus polarization state for band M4 using the flat spectrum (a), the SIS spectrum (b), and the TOA spectrum (c). The legend defines the different symbol/color combinations which correspond to each detector. Note that the unconnected data at 195° in each plot represents the bandwidth derived from unpolarized data.

particular for band M4. The responsivities follow a clean twocycle variation for all cases. The band average responsivities are listed in Table 3, and compared to the responsivities constructed from the separate spectral measurements of the ASR [18]; the measurements in general agree well.

From the polarization-state-dependent responsivities, the linear diattenuation was derived based on Eq. (21) and plotted in Fig. 15. The diattenuation derived here (black lines) is compared to the diattenuation derived from Eq. (11) (red lines). Note that a small portion of the data used in the ASR was reconstructed from the Fourier expansion, so the two methods are not completely independent. Nevertheless, the two methodologies agree well, to within 0.16% for band M1 and to



Fig. 14. Plots are shown of the responsivity versus polarization state for band M1 (a) and for band M4 (b). The responsivity is in units of $[dn/(W/m^2/sr/\mu m)]$. The legend defines the different symbol/color combinations which correspond to each detector. Note that the unconnected data at 195° in each plot represents the responsivity derived from unpolarized data.



Fig. 15. Plots are shown of the diattenuation (in %) versus detector derived from the Fourier and ASR analysis for band M1 (a) and for band M4 (c). Black "+" indicates the Fourier analysis and red "*" denote the ASR analysis. The difference between the two methods is plotted for the same data for band M1 (b) and band M4 (d), represented by the blue " \diamond ".

within 0.08% for band M4. In addition, the phase angle was also estimated from Eq. (22) and compared to the results calculated from Eq. (12). The differences between the two approaches was less than 2.3° for band M1 and 3.4° for band M4. As a result, the approach based on the ASR has been shown to produce comparable results in terms of diattenuation and phase angle while explicitly showing the dependence of the underlying physical process than is driving the polarization sensitivities for JPSS-1 VIIRS; the splitting in the transmittance between *s*- and *p*-polarization states manifests itself as the variation of both the bandwidth and responsivity with polarization state, which in turn influences the band-dependent linear diattenuation.

5. CONCLUSIONS

The JPSS-1 VIIRS instrument baseline testing included measurements during which the JPSS-1 VIIRS was shown to have larger than expected polarization sensitivity in the shortest wavelength bands (up to \sim 6.4%, compared to less than \sim 3.0% for SNPP VIIRS). The sensor vendor developed a ray trace model which indicated that the large sensitivities were the result of splitting in the s- and p-polarization transmittance on the edges of the bandpass. A special test was added to the test program using a monochromatic source to in part validate the model and investigate the shifts in the bandpass with polarization state. Limited measurements on bands M1 and M4 were made using the NIST T-SIRCUS at the Raytheon El Segundo facility in December 2014 and were analyzed using Fourier analysis. The monochromatic measurements largely validated the model predictions: larger diattenuation was observed on the edges relative to the center of the bandpass. In addition, when averaged over the bandpass, the T-SIRCUS measurements were consistent with the broadband measurements to within $\sim 0.4\%$ (even with the bandpasses coarsely sampled). However, the model did not fully capture the observed behavior, particularity for band M4 in the center of the bandpass where the phase angle shifted. Additionally, the T-SIRCUS measurements were used to construct spectral responsivity functions for all measured polarization states. The variation in centroid, bandwidth, and responsivity with polarization state was then investigated. Results indicated that the variation in centroid was small (less than ~ 0.3 nm for all cases), and that the variation in bandwidth was relatively large (up to about 1.6 nm). From the responsivity, the linear diattenuation was determined and compared to the Fourier series approach; the results are consistent to within 0.16%. Furthermore, these spectral responsivity functions, derived using a flat spectrum, were convolved with model input spectra: a spectrum to simulate pre-launch testing and a spectrum to estimate the possible on-orbit effects. These monochromatic measurements successfully demonstrated the possible future testing on forthcoming instruments (JPSS-2, JPSS-3, and JPSS-4 VIIRS) as well as the need for component-level measurements useful in the ray trace modeling.

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