

PACE OCI Pre-launch ETU Spectral Characterization and Performance

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ABSTRACT

The Ocean Color Instrument (OCI) is the primary sensor on the upcoming Plankton, Aerosol, Cloud ocean Ecosystem (PACE) mission. OCI is a new type of sensor compared to NASA's ocean color heritage sensors VIIRS, MODIS, and SeaWiFs. Unlike its heritage sensors, OCI has two slit grating hyperspectral spectrographs in addition to a fiber-coupled multiband filter spectrograph. The two hyperspectral spectrographs provide continuous coverage from 340nm to 885nm in the UV to NIR range. These spectrographs use programmable CCD detectors that aggregate multiple CCD pixels that can effectively provide various spectral resolutions. The fiber-coupled multiband filter spectrograph provides seven discrete spectral bands from 940nm to 2260nm.

OCI completed system level testing of the Engineering Test Unit (ETU) in June 2021 at the Goddard Space Flight Center (GSFC). The ETU contains one of the slit grating spectrographs (600nm to 885nm) and the fiber-coupled spectrograph. The ETU was tested in thermal vacuum (TVAC) in February 2020 and January 2021 to assess characterization and performance compliance to design requirements. This paper presents an overview of the spectral performance of the OCI ETU for relative spectral response (RSR), integrated Out-of-Band response (IOOB), system gain, band centers, and bandwidths.

Keywords: PACE, OCI, Pre-Launch, RSR, Performance

1. INTRODUCTION

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission [1] will extend and improve the data record of NASA's satellite observations of global ocean biology, aerosols, and clouds. The primary sensor on-board the PACE platform is the Ocean Color Instrument (OCI) [2]. The OCI is a new type of sensor that builds on the design of the heritage sensors MODIS [3], VIIRS [4], and SeaWiFS [5-7], as well as lessons learned from the prototype sensor ORCA [8,9]. OCI is a scanning radiometer with hyperspectral coverage from the ultraviolet (UV) to the near infrared (NIR) wavelength range and a fiber-coupled multiband filter spectrograph in the short-wave infrared (SWIR) spectral region. The pre-launch system level testing of the Engineering Test Unit (ETU) was completed in June 2021 at the Goddard Space Flight Center (GSFC). The ETU is a risk reduction measure that will inform the test campaign and hardware design of the Flight Unit. The Flight Unit test campaign is expected to begin in early 2022. During the ETU test campaign, the VIS-NIR hyperspectral bands and the fiber-coupled filter SWIR bands were tested in TVAC for their spectral characterization and performance compliance to design requirements. This paper will present the results for relative spectral response, integrated out-of-band response (IOOB), absolute gain, band centers and bandwidths. Section 2 will provide an overview of the OCI. Section 3 will describe the test setup and measurements. Section 4 will describe the analysis. Section 5 will present the results. Section 6 will provide concluding remarks.

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2. OCI OVERVIEW

OCI has two slit grating hyperspectral spectrographs and a fiber-coupled multiband filter spectrograph. The two hyperspectral spectrographs provide continuous coverage from 340 nm to 885 nm in the UV to NIR range and use programmable CCD detectors that aggregate multiple CCD pixels that can effectively provide various spectral resolutions. The fiber-coupled multiband filter spectrograph provides seven discrete bands from 940 nm to 2260 nm.

OCI uses a rotating telescope assembly that consists of a primary mirror, depolarizer, and a flat mirror, spinning at approximately 6 Hz. The telescope rotates perpendicular to the spacecraft motion, with an Earth view (EV) and a dark view (DV) on each scan. The Earth view has an angular range of $\pm 56.5^\circ$ where 0° corresponds to nadir and the dark view is an internal dark with an angular size of 5° at approximately 180° . OCI uses a two-sided Half Angle Mirror (HAM), spinning at approximately 3 Hz, that de-rotates the light as it continues to the main optical sub bench. The light passes through a slit, field lens, and is reflected by a collimator mirror. The light is then split by two dichroic filters into three spectral regions: approximately 340 nm – 605 nm for the UV-VIS Focal Plane Assembly (FPA), 605 nm – 905 nm for the VIS-NIR FPA, and 905 nm – 2400 nm for the SWIR Detector Assembly (SDA).

For the UV-VIS and VIS-NIR FPAs, the slit images are spectrally separated by a grating and then focused by a lens array onto a CCD. Each CCD is 128 pixels in the cross-track direction by 512 pixels in the along-track/spectral direction. The slit is imaged onto each CCD as 128 pixels in the cross-track and 8 pixels in the along-track and that image is dispersed by the grating in the along-track across the 512 pixels. Each CCD uses time delay integration (TDI) where the charge transferred in the cross-track direction is synchronized with the telescope rotation rate. This means the readout of each physical pixel is the result of aggregated 128 pixels. These physical pixels are further aggregated into 8 cross-track pixels x 8 spectral pixels called science pixels. A science pixel corresponds to 1km on Earth at nadir with a 5 nm bandwidth. However, the aggregation can be set to 1,2,4, or 8, in each direction independently allowing for higher spatial or spectral resolution.

For the SDA, the slit is imaged onto a micro-lens array with 16 fibers. Each fiber is fed to a separate assembly with a lens, dichroic filter, and two detectors, which can be either InGaAs or HgCdTe. The 32 SDA detectors provide multiple detectors that are aggregated into 7 discrete spectral bands. Two of these bands, the 1250 nm and the 1615 nm bands, are dual gain bands, each with a standard gain (SG) and high gain (HG) channel for a total of 9 SDA channels in the SWIR. The spatial size of each SDA readout is the very similar to a science pixel from the CCDs and is fixed.

The ETU is limited to only the VIS-NIR FPA and the SDA with only 10 detectors such that each of the 9 SDA channels has only one detector except for the 1038 nm band that has two aggregated detectors. The bands analyzed in this paper are 55 hyperspectral bands from 615 nm to 885 nm, with 5 nm spacing, and 9 filtered SWIR bands: 940 nm, 1038 nm, 1250 nm, 1250 nm HG, 1378 nm, 1615 nm, 1615 nm HG, 2130 nm, and 2260 nm. The results in this paper are for HAM side A only. HAM side B showed very similar results.

3. TEST MEASUREMENTS

The ETU was tested in two sessions. The VIS-NIR FPA was characterized in January 2020 and the SDA was characterized in February 2021. Both tests were performed with the ETU in a TVAC chamber at the GSFC. The test program used the Goddard Laser for Absolute Measurement of Radiance (GLAMR) as a monochromatic source. The laser source is fed into a 20 inch integrating sphere with three NIST traceable calibrated radiometers. The aperture of the integrating sphere has an 8 inch diameter placed 8 inches from the TVAC chamber window and the center of the integrating sphere aperture was aligned with the ETU's nadir position. A description of GLAMR can be found in [10].

To characterize the VIS-NIR FPA, GLAMR was stepped from ~ 590 nm to ~ 890 nm in ~ 1 nm steps. One region from ~ 740 nm to ~ 750 nm was stepped in ~ 0.2 nm steps so the 745 nm band could be characterized in higher resolution. The out-of-band region from ~ 340 nm to ~ 590 nm was stepped in ~ 5 nm steps. To characterize the SDA, GLAMR was stepped from ~ 900 nm to ~ 2400 nm with ~ 1 nm steps for in-band regions and ~ 10 nm steps in out-of-band regions. For in-band wavelength measurements GLAMR was set to output 90% of the expected maximum radiance on orbit for each band. When the wavelength measurement was in-band for a high gain band, GLAMR was set to output 90% of the clipping radiance. The VIS-NIR FPA bands from 660 nm to 715 nm are high gain bands. The SDA bands 1038 nm, 1250 nm HG

and 1615 nm HG are also high gain bands. For out-of-band measurements GLAMR was set to its maximum radiance output.

Each step is set to take 15 seconds of dark and 40 seconds of light using the GLAMR shutter. The 15 seconds of dark is used to offset correct the measured radiance by the GLAMR radiometers. The 40 seconds of light provides at least 100 scans per HAM side. As the telescope scans across the Earth view, the 8 inch aperture of the integrating sphere provides a uniform view of 40 science pixels. Each collect therefore provides at least 4000 ETU samples to be averaged per HAM side, per band. Each GLAMR collect was measured with the ETU CCD aggregation set to 8 cross-track pixels by 1 spectral pixel. This was done so that analysis could be performed at the highest spectral resolution, while improving SNR. However, for the analysis in this paper, the ETU counts for the 8x1 pixels were aggregated offline to 8x8 science pixels to characterize the science level bands with 5 nm bandwidths.

4. DATA ANALYSIS

The GLAMR collects are used to determine the absolute spectral response (ASR) and subsequently the relative spectral response (RSR) per band, per HAM side, with the following equations respectively

$$ASR(\lambda) = \frac{dn(\lambda)}{L(\lambda)} \quad (1)$$

$$RSR(\lambda) = \frac{ASR(\lambda)}{\max[ASR(\lambda)]} \quad (2)$$

where λ is the GLAMR input wavelength, L is the GLAMR input radiance, and dn is the offset corrected digital number ETU response. The ETU response is offset corrected for each scan by subtracting the average digital number count (DN) of the internal dark view pixels from the digital number count of the Earth view pixels.

$$dn = DN_{EV} - \overline{DN_{DV}} \quad (3)$$

For each GLAMR wavelength collect the response is then calculated as the average over the integrating sphere aperture and over all scans where the GLAMR shutter is open separated by HAM side. The GLAMR input wavelength is measured in vacuum and averaged over each collect while the GLAMR shutter is open. The GLAMR radiance is measured by the radiometers near to the exit aperture of the integrating sphere. The radiometer signal averaged over each preceding dark with the GLAMR shutter closed is subtracted from the radiometer signal during the light exposure when the GLAMR shutter is open. This offset corrected signal is converted to absolute radiance using NIST calibration tables. The average of this radiance is then multiplied by the transmission of the TVAC chamber window. From there the other band metrics can be calculated and compared to design specifications and requirements. The absolute system gain is calculated as the integration of the absolute spectral response over all source wavelengths per band, per HAM side. Here gain is the inverse of K_1 as defined in the calibration plan [11].

$$\text{gain} = \int_{\lambda_{min}}^{\lambda_{max}} ASR(\lambda) d\lambda \quad (4)$$

where λ_{min} and λ_{max} are the lowest and highest GLAMR source wavelength measurements. The in-band response is defined as the region where the $RSR > 1\%$ or the region between $\lambda_{low1\%}$ and $\lambda_{up1\%}$. The out-of-band response is defined at the region where the $RSR < 1\%$ or the region from λ_{min} to $\lambda_{low1\%}$ and from $\lambda_{up1\%}$ to λ_{max} . The integrated out-of-band response ratio (IOOB) is defined as the ratio of the integrated out-of-band response to the integrated in-band response

$$IOOB = \frac{\int_{\lambda_{min}}^{\lambda_{low1\%}} RSR(\lambda) d\lambda + \int_{\lambda_{up1\%}}^{\lambda_{max}} RSR(\lambda) d\lambda}{\int_{\lambda_{low1\%}}^{\lambda_{up1\%}} RSR(\lambda) d\lambda} \quad (5)$$

where $\lambda_{low1\%}$ and $\lambda_{up1\%}$ is the interpolated input wavelengths at 1% of the maximum response. The bandwidth is defined as the full width at half max (FWHM) and band center is defined as the center of FWHM

$$FWHM = \lambda_{up50\%} - \lambda_{low50\%} \quad (6)$$

$$\lambda_{center} = \frac{1}{2}(\lambda_{up50\%} + \lambda_{low50\%}) \quad (7)$$

where $\lambda_{low50\%}$ and $\lambda_{up50\%}$ is the interpolated input wavelengths at 50% of the maximum. The full width at one percent (FW1P) is defined as

$$FW1P = \lambda_{up1\%} - \lambda_{low1\%} \quad (8)$$

These parameters are shown on a general RSR in Figure 1 for visual reference. Each collect is checked for data quality using criteria including GLAMR stability to automatically remove low quality or invalid measurements.

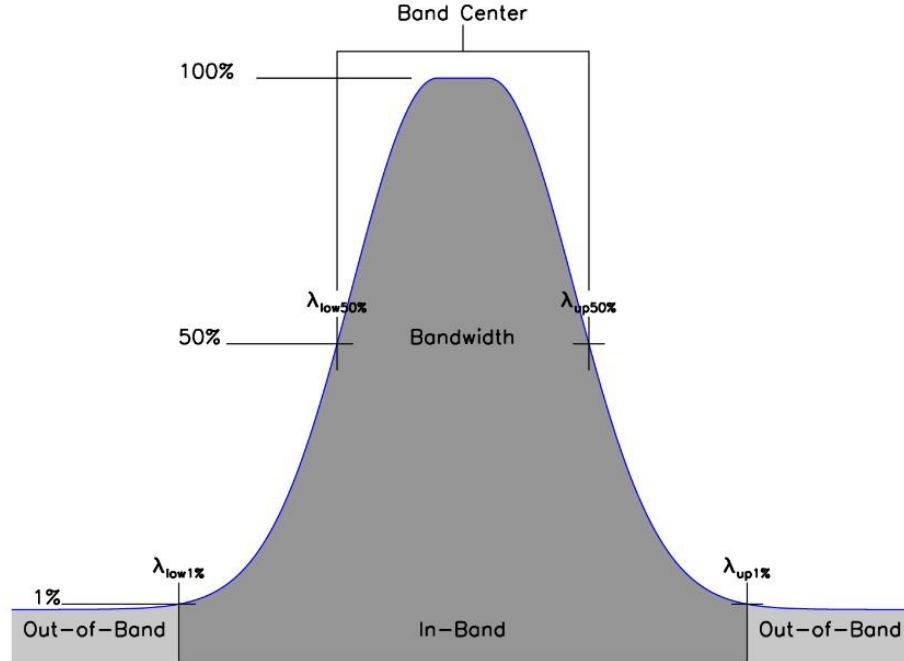


Figure 1. Picture of a general RSR.

5. RESULTS

5.1 VIS-NIR FPA Results

The VIS-NIR FPA provides 55 bands from 615 nm to 885 nm with 5 nm spacing. Each of these bands are characterized and analyzed to check compliance to performance specifications. Figure 2 shows a linear plot of the in-band RSR profile for 9 select bands from the VIS-NIR FPA. The circles show the measured points. All the bands show a similar profile. The 745 nm band is the best example in the middle plot because GLAMR was stepped through with the smallest step size of ~ 0.2 nm in that region. The other bands were only measured at 1 nm resolution. Figure 3 shows a log plot of the out-of-band RSR for the same select bands. The profiles show clear crosstalk within the VIS-NIR FPA spectral region and a clear drop off outside the spectral region of the VIS-NIR FPA. The crosstalk peaks are generally at $\sim 10^{-4}$ and the out of FPA region is generally at $\sim 10^{-6}$. This 10^{-6} represents the measurement noise floor using the ~ 4000 samples. The dotted red lines are negative RSR values plotted as the absolute value on the log plot. Two negative crosstalk peaks are seen on either side of the in-band region for most VIS-NIR FPA bands. The crosstalk is expected to improve on the Flight Unit. The out-of-band measurements below 550 nm were improved by feeding GLAMR into a 2 inch integrating sphere. This was needed because the GLAMR radiance output in the 20 inch sphere was below the lowest radiance expected on orbit which resulted in a noise floor that was higher than expected at $\sim 10^{-4}$. Unfortunately, the 2 inch integrating sphere measurements were

performed in ambient without the NIST traceable radiometers. However, these measurements show that the RSR can be measured down to the noise floor for wavelengths below 550 nm.

Figure 4 shows all the VIS-NIR FPA bands characterized for band center, bandwidth, absolute system gain, and integrated out-of-band response ratio. The top left plot shows that the nominal band center is no more than 1.2 nm different from the measured band center with the highest difference of -1.15 nm observed for band 740 nm. The trend of this plot shows the non-uniform spectral dispersion across the FPA. The top right plot shows the measured bandwidths are all close to the specified 5 nm bandwidth and well within ± 1 nm tolerance. The highest difference from the specified bandwidth is 4.88 nm observed for band 660 nm. The trend shows a slight rise across the FPA. The apparent “jaggedness” in the top two plots may be due to the 1 nm measurement resolution shown in Figure 2, such that the peak in-band response measured may not be the actual maximum in-band response location. The difference between the measured maximum wavelength and the actual maximum wavelength is oscillating across the FPA as the 1 nm measurement steps do not follow the non-uniform band spacing as seen in the top left plot of Figure 4. The bottom left plot in Figure 4 is measured absolute system gain shown as $1/K_1$. The high gain bands from 690 nm to 715 nm are clearly seen. The bottom right plot is the integrated out-of-band response ratio. All bands are below the 1% design requirement.

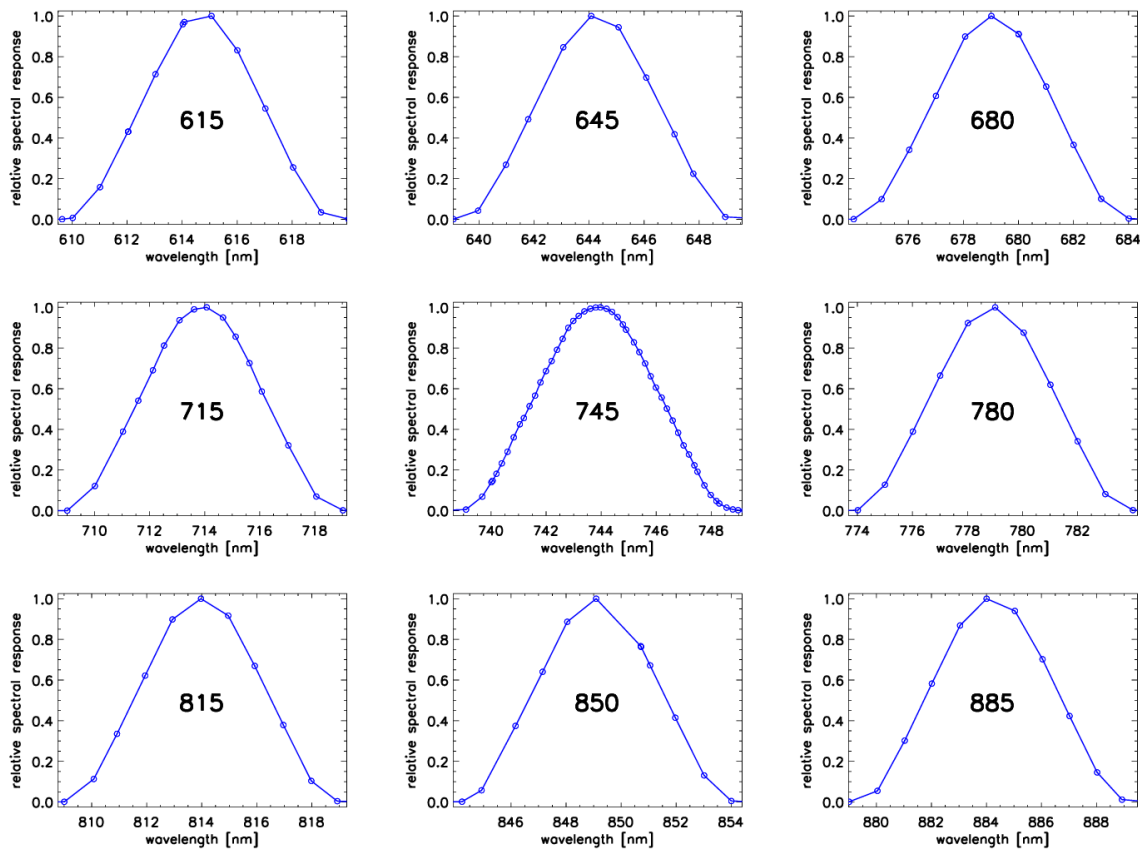


Figure 2. Measured in-band RSR for 9 select bands in the VIS-NIR FPA. Circles are individual measurements. The nominal band center is displayed on each plot.

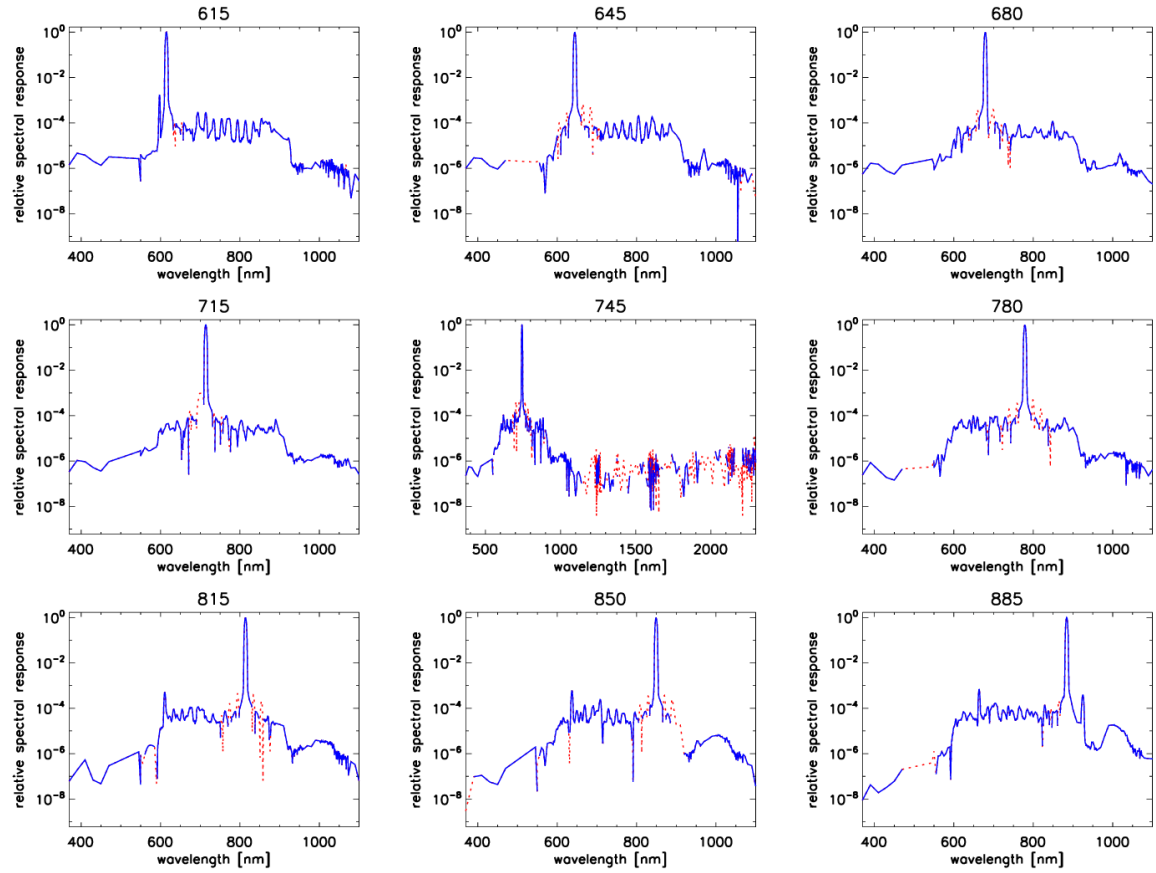


Figure 3. Out-of-band RSR for 9 select bands from the VIS-NIR FPA in log scale. The blue line is positive RSR values and the red dotted line is negative RSR values plotted as the absolute value. The middle plot (745 nm band) is plotted with the full range of GLAMR wavelengths, while the remaining bands have the wavelength range truncated to exclude the SWIR. The nominal band center is in the title for each plot.

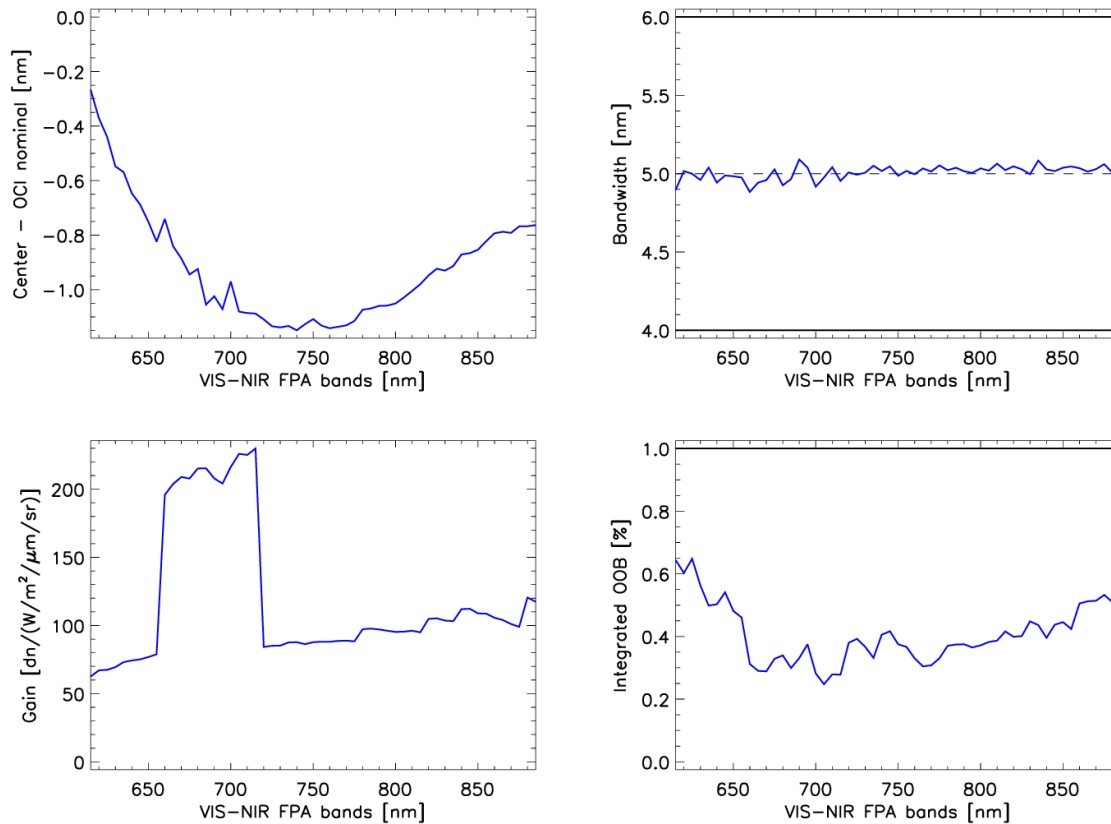


Figure 4. Results for all VIS-NIR FPA bands. Top left plot shows the spectral dispersion as the difference from the measured center to the nominal center of each band. Top right shows the bandwidth for each band (blue line), and the required tolerance (black lines) about the specified value (dashed line). Bottom left shows the measured absolute system gain. Bottom right shows the integrated out-of-band response ratio (blue line) and its specified limit (black line)

5.2 SDA Results

The SDA provides the 9 bands as shown in Table 1. Each of these bands are characterized and analyzed to check compliance to performance specifications. Figure 5 shows a linear plot of the in-band RSR profile for all SDA bands. The circles are the measured points. All bands show that the 1 nm measurement steps sufficiently resolve the in-band RSR above 90%. The 5 nm measurement steps out-of-band did not sufficiently resolve the band edges from 90% to 1%. In order to get more accurate results, component level measurements of the SDA were used to help interpolate between the 5 nm steps down to 1%. This was done for all bands except the 1250 nm bands. This was especially needed for the 1378 nm band. The 2260 nm band was measured above 2300 nm but the NIST calibration tables for the GLAMR radiometers above 2300 nm were not available as of this writing and so the SDA component level measurements were used to extrapolate down to 1%. The test plan for the 1 nm step wavelength ranges were determined from modeled RSR. Preliminary analysis was done during testing and the initial 1 nm wavelength ranges were not wide enough. However, due to time constraints, additional measurements were only made for the 1250 nm bands and the 2260 nm band. This lesson from the ETU test campaign will help inform the Flight test campaign. Most bands show a clear “hump” on the upper edge of the band. This is thought to be due to the edge effects of the filters. Figure 6 shows a log plot of the out-of-band RSR for all SDA bands. Some out-of-band response features can be found in all bands. Most features are at or below 10^{-4} . The “dense” areas in the line plots that appear to be noisier are the 1 nm measurement resolution of the in-band measurements for the other SDA bands.

Table 1 shows the performance of the SDA bands. The measured band centers and bandwidths are all within tolerance of the specified values. The measured full width 1% are all below the limit of twice the bandwidth. The integrated out-of-band response ratios are all below the limits. The 1378 nm band was usually the band closest to the limits. The 1378 nm

is the narrowest band with the tightest limits and suffered the most by not getting enough measurements on the upper edge of the band as seen in Figure 5. The 1378 nm band is a water vapor band, but due to the minimal light path through atmosphere, the effects appeared to be minimal and no correction was made. The absolute system gain is also in Table 1 for reference. All bands will have more detectors on the Flight Unit so the ETU gain is not representative of the Flight Unit. The ETU has only one detector per band except for the 1038 nm band which has two detectors.

Table 1. Results for SDA bands and comparison to requirements.

Band Name	Specified Center [nm]	Measured Center [nm]	Specified Bandwidth [nm]	Measured Bandwidth [nm]	Specified full width 1% limit	Measured full width 1%	Specified IOOB Limit [%]	Measured IOOB [%]	System Gain [dn/(W/m ² /sr/μm)]
940 SG	940 ± 4	939.5	45 ± 4	44.6	≤ 90	57.2	≤ 1.0	0.17	191.8
1038 HG	1038 ± 2	1038.2	75 ± 4	74.7	≤ 150	95.0	≤ 1.0	0.13	947.9
1250 SG	1250 ± 4	1250.3	30 ± 4	28.9	≤ 60	38.7	≤ 1.0	0.12	274.1
1250 HG	1250 ± 4	1250.8	30 ± 4	28.6	≤ 60	38.3	≤ 1.0	0.12	659.5
1378 SG	1378 ± 2	1378.5	15 ± 2	13.3	≤ 30	21.7	≤ 0.7	0.17	297.4
1615 SG	1615 ± 10	1619.4	75 ± 10	74.2	≤ 150	91.3	≤ 1.0	0.09	618.3
1615 HG	1615 ± 10	1619.0	75 ± 10	74.3	≤ 150	92.0	≤ 1.0	0.09	1095.7
2130 SG	2130 ± 5	2130.7	50 ± 5	50.5	≤ 100	63.9	≤ 1.0	0.10	2006.8
2260 SG	2260 ± 10	2257.9	75 ± 5	72.7	≤ 150	105.8	≤ 1.0	0.17	2443.4

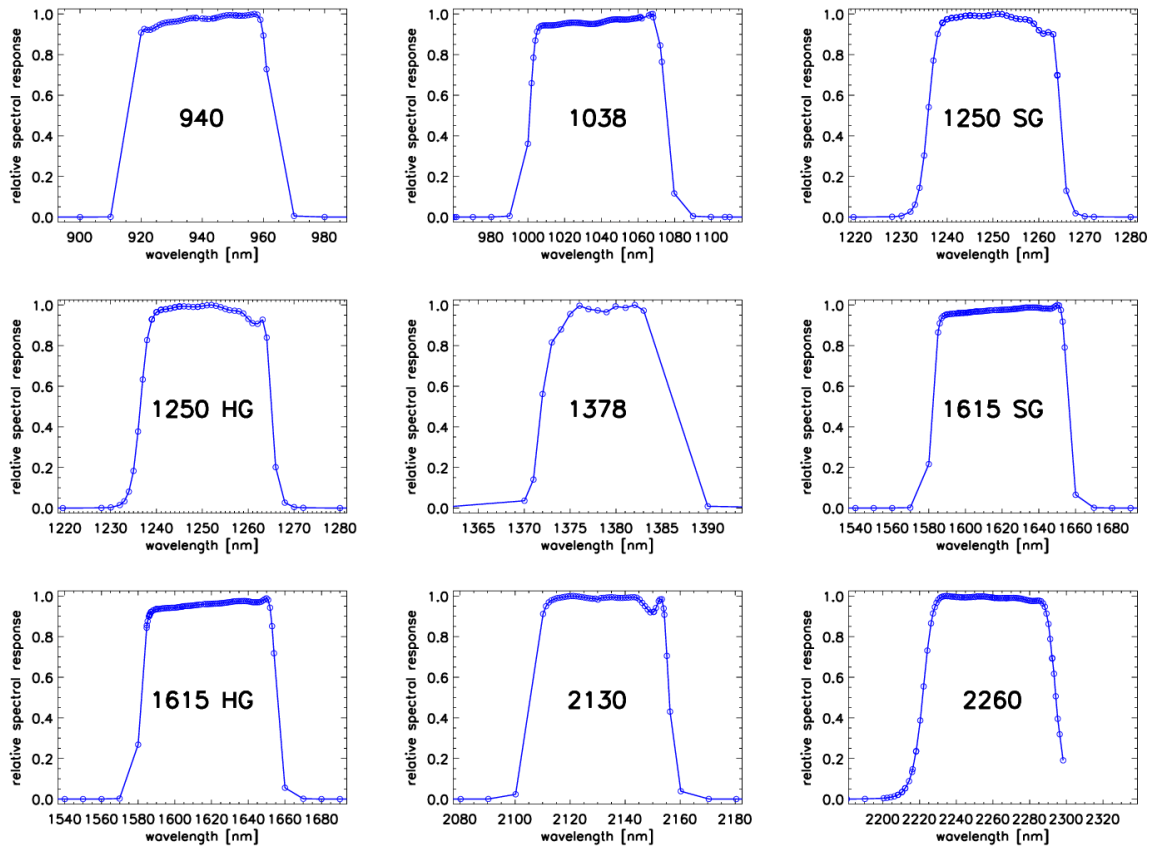


Figure 5. Measured in-band RSR for all SDA bands. Circles are individual measurements. The band name is displayed on each plot.

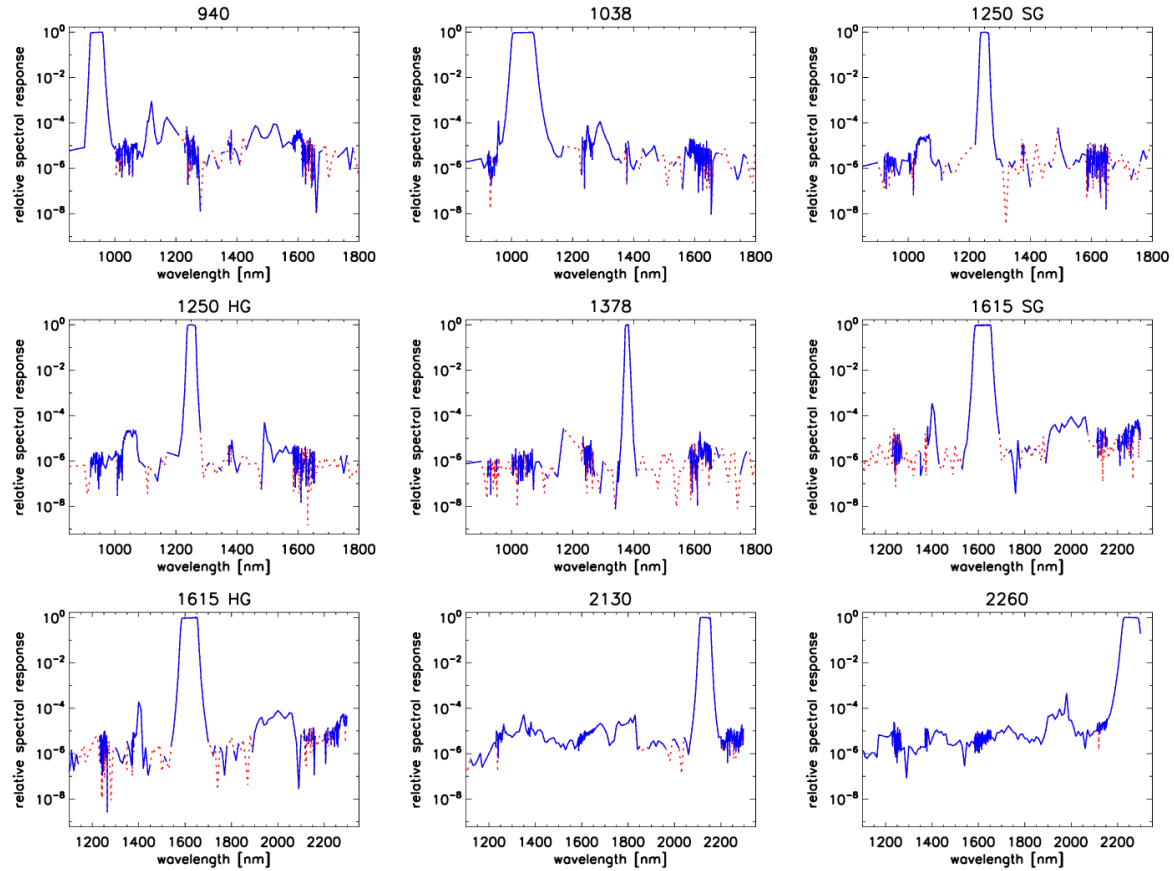


Figure 6. Out-of-band RSR for all SDA bands in log scale. The blue line is positive RSR values and the red dotted line is negative RSR values plotted as the absolute value. The band name is the title in each plot.

6. CONCLUSION

The ETU test campaign was completed in June 2021. The spectral characterization was measured in TVAC using GLAMR as a monochromatic source. All the tested VIS-NIR and SDA bands were found to be within requirements. The crosstalk found in the VIS-NIR FPA RSR measurements will be eliminated (or at least reduced) for the Flight Unit. Measuring the spectral characteristics is a large test that requires hundreds of measurements taken over many days in TVAC. There was a lot of work done before testing began to be able to efficiently record and tag data so it could be quickly processed and evaluated during testing. It was especially important to see the results of the hyperspectral bands because the spectral performance for the VIS-NIR FPA (grating) is more difficult to predict than for the SWIR bands (spectral band pass filters). Lesson's learned during the first ETU TVAC test campaign in February 2020 helped the second ETU TVAC test campaign in January 2021 and both serve as good preparation for Flight Unit testing.

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