

Spatial characterization of PACE OCI ETU using time-delay mode

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ABSTRACT

The OCI (Ocean Color Instrument) is the main sensor on the upcoming PACE (Plankton Aerosol Cloud ocean Ecosystem) mission. OCI has two hyperspectral CCD sensors covering 340nm to 885nm and 9 SWIR (Short Wave IR) bands from 940nm to 2260nm. SWIR bands have nominal 1km ground pixel size and CCD bands have native 1/8 km ground pixel size in diagnostic mode that will be aggregated into 1km pixels to improve SNR and meet the data rate constraints. OCI has a rotating telescope that is synchronized to the readout of the CCD and SWIR detectors. Full pre-launch system level testing for the OCI ETU (Engineering Test Unit) was completed in June 2021.

With time-delayed scan mode, a sub-pixel level time-delay step is applied to the detector readout. This sub-pixel level time-delay step causes a sub-pixel level shift in the start of the data collection. After collecting time-delay step scans with different step sizes, a scan profile with sub-pixel resolution can be constructed. 1/8 and 1/4 of CCD pixel resolutions were achieved using this mode. In this paper, the OCI time-delayed scan mode will be described as well as how it was used to calculate OCI's high spatial resolution PSF (Point Spread Function), IFOV (instantaneous Field of View), MTF (Modulation Transfer Function), and BBR (Band to Band Registration).

Keywords: PACE, OCI, time-delay, PSF, MTF, IFOV

1. INTRODUCTION

NASA's latest earth-observing satellite for global ocean color, biogeochemistry, atmosphere and clouds is the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission [1]. PACE's primary sensor is the Ocean Color Instrument (OCI) [2], which is being built at NASA Goddard Space Flight Center based on the design of heritage Earth observing sensors such as MODIS[3], VIIRS[4] and SeaWiFS[5]. OCI uses gratings for spectral light dispersion and consists of two CCD arrays for hyperspectral channels from 340nm to 885nm and spectrally filtered Short Wave Infrared (SWIR) detectors. OCI has the ability to be programmed for data read rate, telescope scanning rate, and aggregation in both spatial and spectral domains. OCI's time-delay mode adds a slight delay-time into normal scanning mode. This small time-delay makes it so that the OCI scan position is shifted in sub-pixel increments. By applying systematic time-delay values to OCI, spatial subsampling measurements are possible and a much higher spatial resolution PSF can be calculated compared to the nominal OCI spatial resolution. This paper will present the results of PSF, IFOV, MTF and BBR using high spatial resolution using data acquired with OCI in time-delay mode.

2. OCI OVERVIEW

OCI has a rotating telescope that consists of a primary mirror, depolarizer, and flat mirror, spinning at 5.7Hz. OCI's rotating telescope scans the Earth perpendicular to the direction of spacecraft motion with an earth view (EV) range of ± 56.5 degree from nadir. OCI's dark view (DV) at approximately 180° from nadir is recorded together with the EV data every scan. OCI has a two-sided Half Angle Mirror (HAM), rotating at half the speed of the rotating telescope, that reflects the light into the main optical module. The light passes through a slit, field lens, and is reflected by an off-axis parabolic mirror which collimates the light. The light is split by two dichroic filters onto a UVVIS (340-605 nm) Focal Plane Assembly (FPA), a VIS-NIR (600-890 nm) FPA, and a SWIR (940-2260 nm) Detector Assembly (SDA). Each FPA uses a grating to separate the slit image into monochromatic light, which is then focused onto a CCD array. For the SDA, the collimated slit image is projected onto a micro lens array with optical fibers.

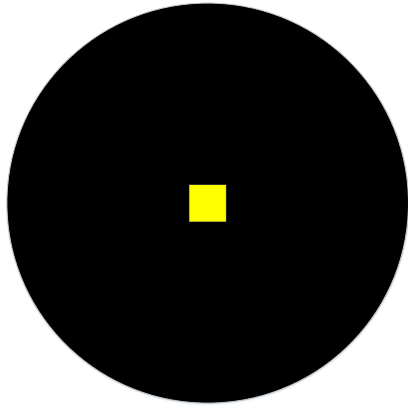
For the UVVIS FPA and the VIS-NIR FPA, the slit image after the grating is focused onto a CCD array by a lens array. Each CCD array has 128×512 physical pixels, 128 pixels for the spatial dimension and 512 pixels for the spectral dimension. The slit image is 8 physical pixels in the along-track direction and 128 physical pixels in the scan-direction. The light is dispersed by a grating and projected onto 512 pixels in the spectral dimension of the CCD array. Each CCD has time delay integration (TDI) that transfers electrons (the signal) in the scan-direction, synchronized with the telescope rotation speed. TDI combines 128 signals into one pixel to improve signal to noise ratio (SNR). Each CCD can be programmed with independent spatial or spectral physical pixel aggregation into 1, 2, 4, or 8 pixels to further improve SNR. The aggregation of 8 spatial pixels by 8 spectral pixels is called a science pixel. A science pixel has a 1km footprint on the Earth at nadir with a 5nm bandwidth. The output without any aggregation is referred to as 'DN of a physical pixel'.

The SDA consists of a fiber-coupled multiband filter spectrograph. The slit image is projected onto a micro-lens array with 16 optical fibers. Each fiber is connected to a detector assembly, which consists of a dichroic filter, a lens assembly, and two detectors, either InGaAs or HgCdTe. The SDA has 32 detectors and 7 spectral bands. Depending on the mode, multiple detector signals are aggregated into one band similar to the CCD TDI to increase SNR. Two of the SDA bands, 1250 nm and 1615 nm, have two gain settings, standard gain (SG) and high gain (HG). Therefore, there are 9 SWIR bands: 940 nm, 1038 nm, 1250 nm SG, 1250 nm HG, 1378 nm, 1615 nm SG, 1615 nm HG, 2130 nm, and 2260 nm. The native SDA detector pixel size is the science pixel (1km footprint) unlike the CCD detectors.

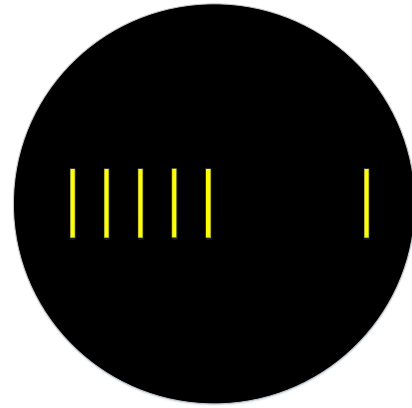
3. TEST CONFIGURATION AND MEASUREMENTS

The ETU was integrated with only the VIS-NIR (red) FPA for hyperspectral bands and 10 SWIR SDA detectors. OCI ETU was tested at the NASA Goddard Space Flight Center from early 2020 to early 2021 for ambient and TVAC (including various temperature changes in vacuum) environments [7].

For the time-delay mode measurements, the line spread function (LSF) test bench included a 2-inch integrating sphere, a science pixel mask (SP mask), or a multi-slit mask (MS mask), and an 8 inch off-axis parabola (OAP) mirror. OCI was on the GAToR platform which can rotate and tilt OCI with sub-physical pixel level pointing accuracy. White light from Halogen lamps or monochromatic light from the Goddard Laser for Absolute Measurement of Radiance (GLAMR) [6] was fed into the 2-inch sphere by optical fiber. The scene mask, SP mask or MS mask, was located in front of the 2-inch sphere exit aperture. The image from the scene mask was projected onto an OAP mirror which collimated the beam. OCI was aligned to the collimated mask image on GAToR. OCI CCD detectors were set to 1×1 (1 physical pixel resolution in the spatial direction and 1 physical pixel resolution in the spectral dimension) aggregation.



Science Pixel (SP) Mask



Multi-Slit (MS) Mask

Figure 1. Projected mask images for the OCI ETU LSF Bench setup.

ETU tests used two time-delay steps, either 1/4 or 1/8 physical pixel. Starting from no time-delay, approximately 35 seconds of OCI measurements, corresponding to ~200 scans, were recorded for each delay step. For a full 1 science pixel measurement with 1/4 physical pixel time-delay steps, 33 or more delay step measurements (200 scans each) are required to cover 8 physical pixels (1 science pixel): $8 \text{ physical pixels} \times 4 \text{ (the number of delay steps for 1 physical pixel)} = 32$ plus zero delay-step. Figure 2 shows each delay step with different symbol and color and how the different time-delay collects are combined into a PSF. Each delay-step measurement is processed with offset correction and scan-averaging. By treating each delay-step measurement as a sub-physical pixel shifted record, the constructed final data output is a combination of all delay-steps applying the corresponding spatial sub-pixel shift. Figure 3 shows OCI's 1 physical pixel signal response for a CCD band (865 nm) and 1 science pixel signal response for a SWIR band (940 nm) with the constructed PSF using time-delay mode data from the 1 SP mask input signal. A 1/4 physical pixel time-delay step is equivalent to a 1/32 science pixel delay step.

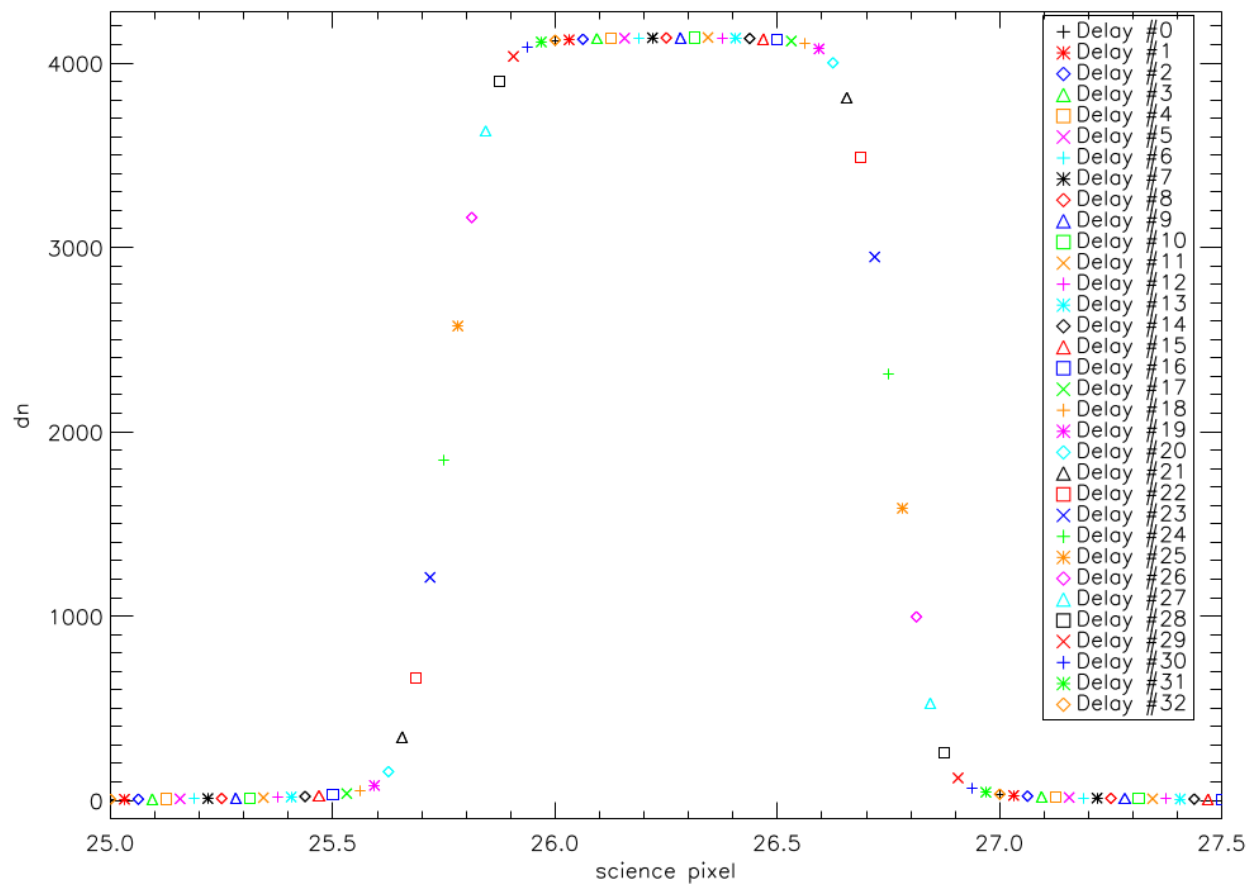


Figure 2. Band 865 nm measurements of the 1 SP mask with 33 delay steps (1/4 physical pixel or 1/32 science pixel delay steps) in different colors and symbols. Note that the same delay step signals (the same color and symbol) have one science pixel spacing.

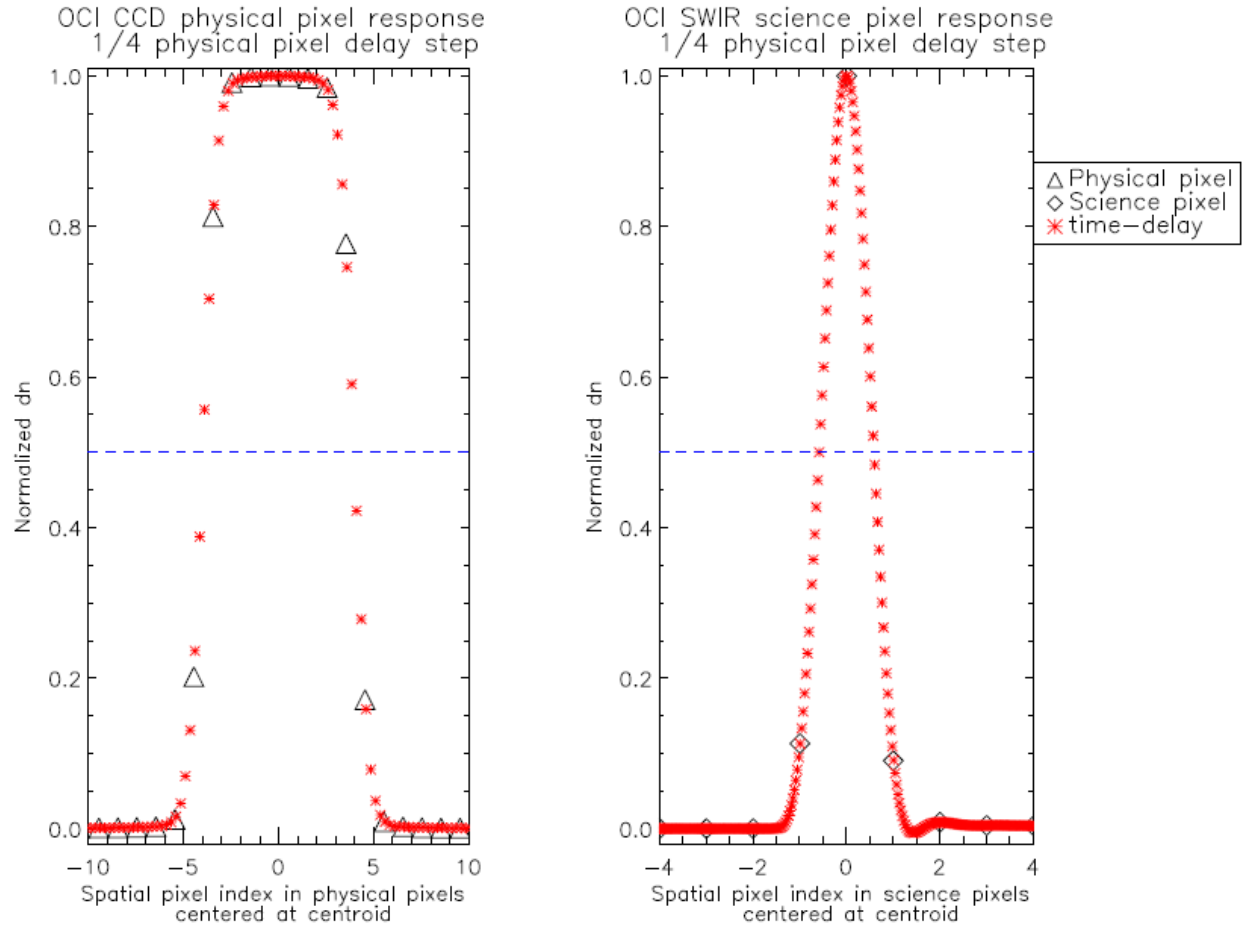


Figure 3. OCI's 1 science pixel mask responses of VIS-NIR CCD band (865 nm) and SWIR band (940 nm). Triangle symbols are CCD's 1 physical pixel responses without time-delay, diamond symbols are SWIR detector's 1 science pixel responses without time delay, and red star symbols are time-delay mode responses with 1/4 physical pixel delay-step.

4. TECHNICAL DETAILS OF TIME-DELAY MODE

The design of the OCI instrument relies on the precise timing between its rotating telescope and detector assemblies. When timing is synchronized, any particular portion of the earth under observation is effectively stationary for the relatively short period of time it is imaged by the instrument instantaneous field of view (IFOV). As previously mentioned, OCI observes a set of static, mask-generated images projected into the IFOV in the form of the collimated light during ground testing. Small changes in timing can be made between the start of a telescope scan and the start of CCD imaging resulting in a temporal shift of the perceived image location relative to a given telescope position. These timing changes also adjust the phasing between the detector pixels and the projected image.

The OCI electronics can independently adjust timing between the CCDs and the SDA. "Time-delay mode" involves injecting cumulative increasing levels of delay between the start of the scan and the start of imaging. Assuming a science pixel image period of τ , during the test OCI inserts increasing delays in increments of $\tau/64$ ($1/8$ of a physical pixel) for the CCD detectors and $\tau/32$ for the SWIR detectors, it steps through each setting until it gets to $33\tau/32$ (at least one step beyond a full science pixel period). OCI observes the projected image for 35 seconds (about 200 scans) at each setting before

proceeding to the next setting. Figure 4 shows the effect of inserting the delay at the start of scan and a representative change in image to detector phasing.

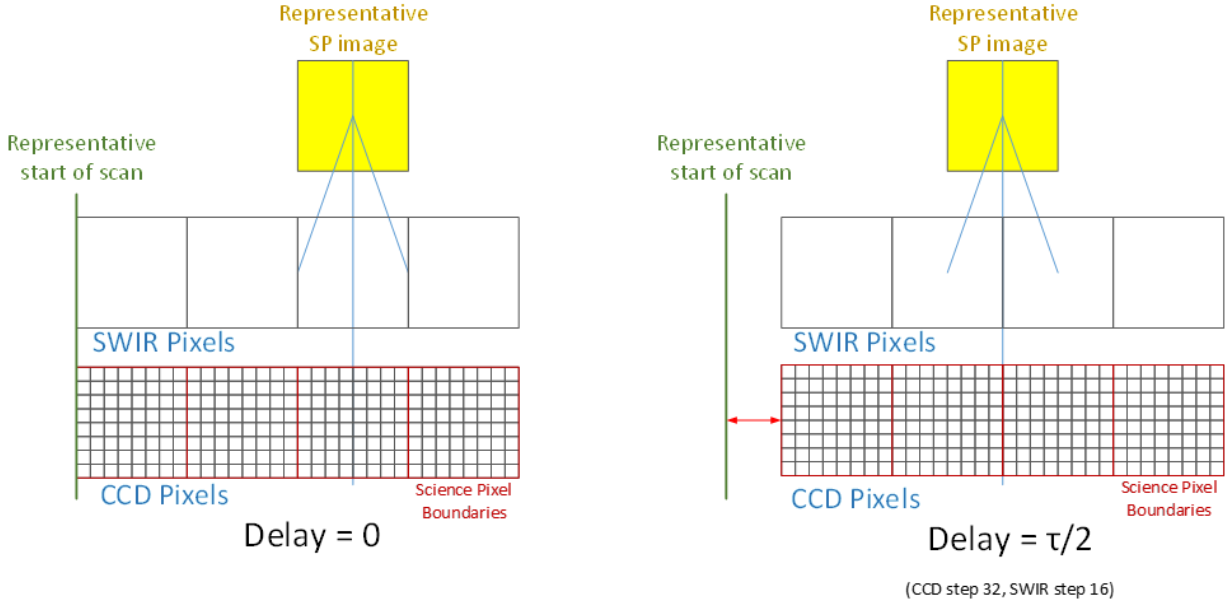


Figure 4. OCI Time-delay phasing example: first image at initial step (delay = 0), second image shows change in phasing at delay = $\frac{1}{2}$ of science pixel image period (step number 32 and/or 16).

It is of note that the CCD and SDA have different delay increments, this is simply a result of limitations in the resolution of adjustments that the electronics could support. The chosen increments made instrument operations and subsequent analysis more straightforward with steps of equal size.

All of these measurements could potentially be done through an adjustment of the projected image, but this may introduce uncertainty in the relative position of each subsequent image. As these time adjustments can be performed within OCI and “on-the-fly”, setup time between delay steps is reduced, significantly increasing the efficiency of testing.

5. DATA ANALYSIS

Each delay-step measurement is processed by subtracting the average digital number (DN) of the dark view from the Earth view DN. The offset corrected digital number (dn) is then

$$dn = DN_{EV} - \overline{DN_{DV}} \quad (1)$$

The centroid of the mask image detected from OCI is calculated to identify the signal image center. If the spatial signal pixel index starts with 0, 1, ..., n-1 then the centroid of the detected the mask image by OCI is calculated by following formula,

$$Centroid = \frac{\sum_{i=0}^{i=n-1} I_i dn_i}{\sum_{i=0}^{i=n-1} dn_i} \quad (2)$$

where I_i is i-th spatial pixel index and dn_i is the signal dn at i-th spatial pixel index. n is the number of spatial pixels for the EV scan.

PSF is the response of an imaging system to a point source. PSF gives the imaging system’s overall performance and MTF is calculated from the normalized Fourier transform of the PSF. MTF provides a quantitative and standardized way to

characterize optical systems. Initially, OCI's PSF was calculated from a science pixel mask source on the LSF bench but the science pixel mask image is not small enough to be used as a point source and there is also uncertainty in mask size. The MS mask consists of a series of 5 one physical pixel size slits with 7.2 physical pixel spacing between the slits as well as another isolated physical pixel slit located 25.2 physical pixels from the last of the first 5 slits. The last isolated slit of the MS mask was used as a point source. However, OCI's requirements for IFOV, MTF, and BBR are based on science pixel aggregation. Therefore, the PSF was calculated using the MS mask by aggregating 8 of OCI's physical pixel responses to make 1 science pixel response. For ETU, time-delay mode measurements were only performed with the 1 science pixel mask and MS mask. In this paper, the calculated PSFs from both the SP mask and MS mask are presented for comparison in Figure 5. In the future, the flight unit test will be performed using a one physical pixel slit mask with time-delay mode instead of the MS mask for PSF and MTF calculations because the first 5 slits of MS mask contaminate the last isolated slit signal due to the SWIR band's slow signal recovery problem (SWIR hysteresis), as shown in Figure 6.

IFOV is calculated from a one science pixel PSF's full width half maximum (FWHM). FWHM is the distance between half maximum positions (blue dashed line) of the PSF in angle as shown in Figure 3.

OCI's spatial BBR requirement states that the BBR between any two bands shall be greater than 80% of one IFOV, which is very close to 1 science pixel size. During the PSF calculation, the centroid of the PSF for each band is calculated and used to estimate the BBR. This paper only shows the minimum % BBR for each band, i.e. the worst BBR between one band and all other bands.

6. RESULTS

All results shown in this paper are only derived from the first HAM side data; the results of both HAM sides are very similar.

6.1 PSF and IFOV

Figure 5 shows the PSF differences between time-delay mode PSFs from the SP mask and the MS mask as input sources for 865 nm VIS-NIR band and 940 nm SWIR band. There is little difference for the VIS-NIR band PSF between the SP and MS mask results due to slit size but there is significant difference in SWIR bands. We investigated the relationships among the source size, detector's IFOV and sampling distance, and concluded that a wide input source (like a SP mask) results in a larger FWHM. As Figure 5 shows, SWIR bands show a residual signal after the maximum signal response because of the SWIR detectors' relative slow signal recovery due to SWIR hysteresis[7], shown in Figure 6. OCI flight SWIR detectors are the same as ETU so SWIR hysteresis will be present in flight data as well. However, a correction method is being developed and will be applied to the flight SWIR data. In figure 5, before the maximum signal, the MS mask PSF shows a small signal ramp because of SWIR hysteresis from the previous 5 slit signals of the MS mask. The SP mask SWIR IFOV is wider than the MS mask SWIR IFOV because the SP mask light source is wider than the MS mask light source. Therefore, all IFOV, MTF, and BBR measurements were calculated from MS mask data to reduce SWIR hysteresis effects and for correct IFOV measurements. For flight unit testing, a 1 physical pixel mask will be used to calculate the PSF, MTF, IFOV, and BBR using time-delay mode. Figure 7 shows the calculated IFOV values, with the IFOV requirement denoted by the blue dashed lines. Each SWIR detector shows a different IFOV, but all are within the required range from 0.076 degree to 0.093 degree.

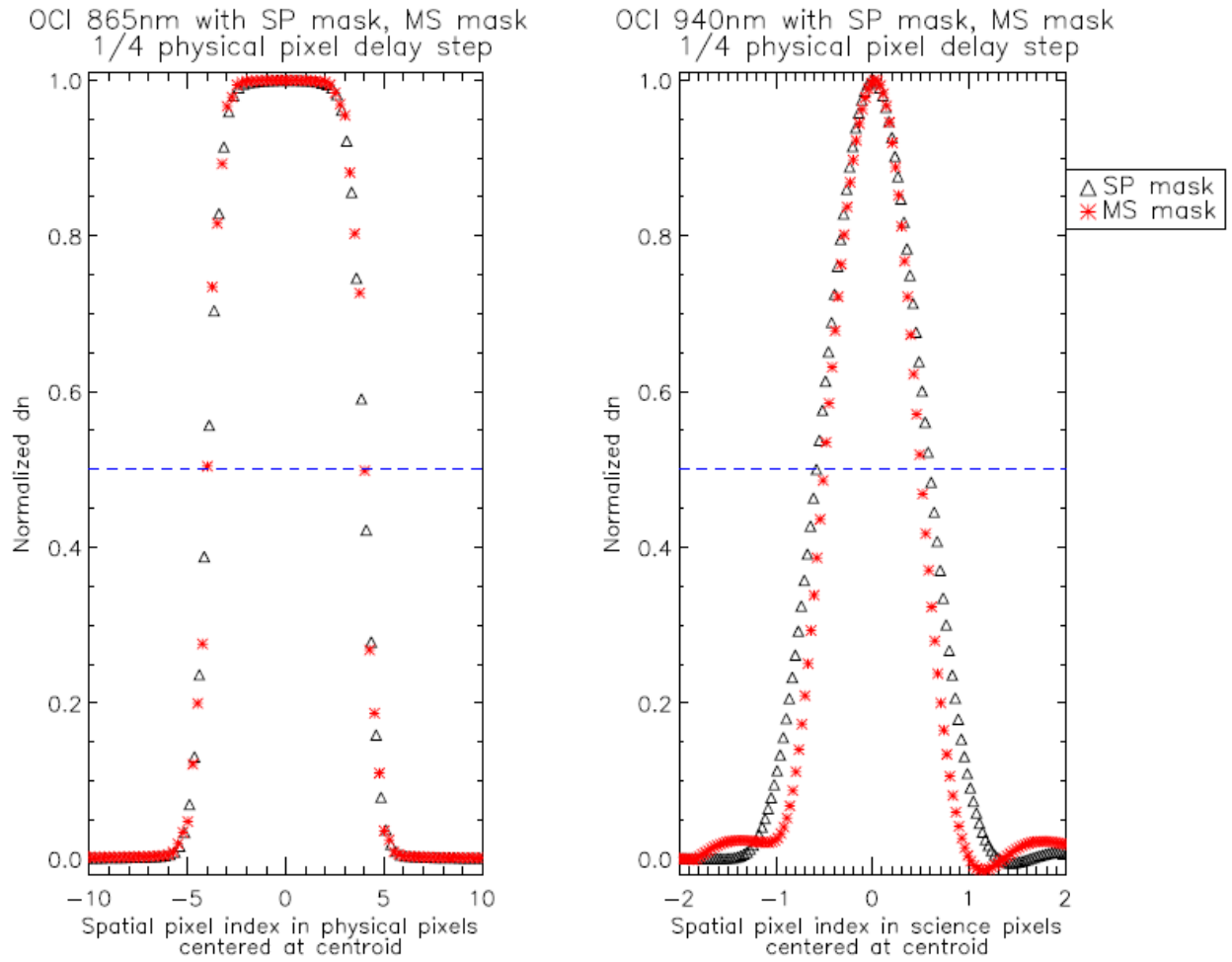


Figure 5. PSF comparisons between SP mask and MS mask sources with time-delay mode. Left plot is CCD detector PSF at 865 nm band; right plot is SWIR detector PSF at 940 nm.

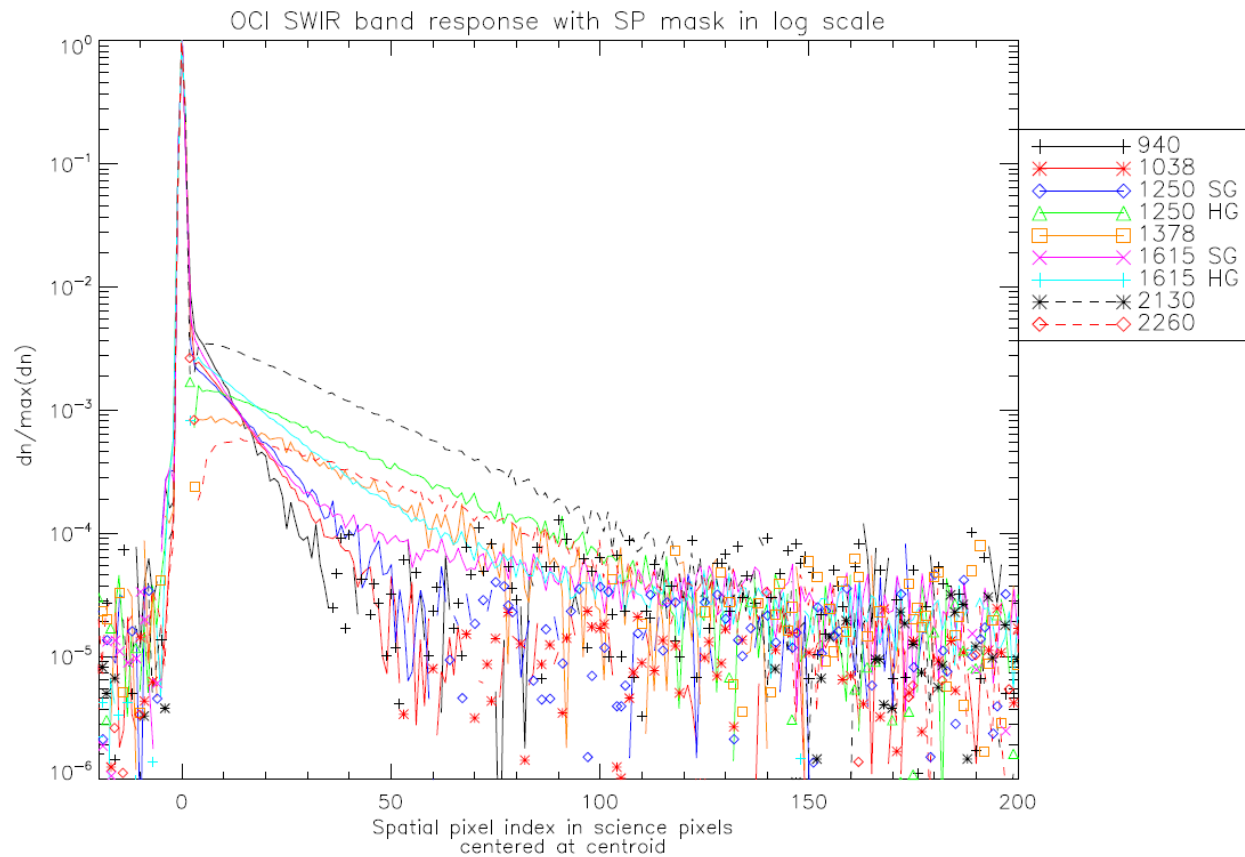


Figure 6. SWIR band residual signal after a maximum signal. SWIR band normalized responses to 1 science pixel mask input on a log scale. Symbols for different bands are absolute values of negative dn values.

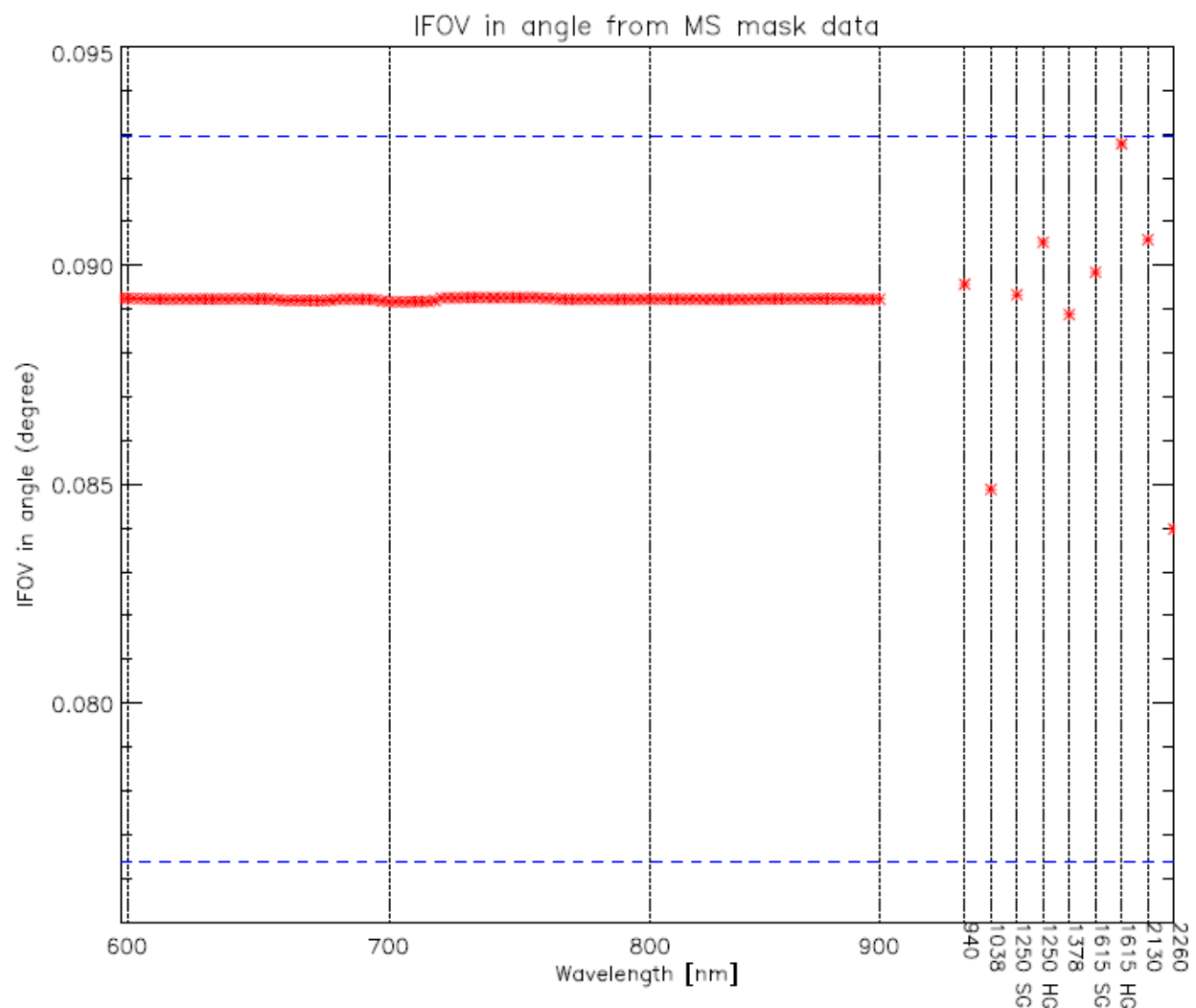


Figure 7. IFOV values in angle for VIS-NIR bands and SWIR bands. Blue-dashed lines are the requirement range for IFOV.

6.2 Spatial MTF (cross-track)

OCI's MTF requirement is measured at specific spatial frequencies: 0, 0.25, 0.5, 0.75, and 1. The spatial frequency unit for the MTF requirement is in fractions of Nyquist frequency (frequency/Nyquist frequency). MTF is normalized at a frequency of 0. MTF requirements for OCI are for the MTF to be greater than 0.9 at a frequency ratio of 0.25, 0.7 at a frequency ratio of 0.5, 0.5 at a frequency ratio of 0.75, and 0.3 at a frequency ratio of 1. Figure 8 shows the calculated MTF values at frequency ratios of 0.25, 0.5, 0.75, and 1 with requirement values shown by blue dashed lines. All VIS-NIR bands meet the requirements, but many SWIR bands do not meet the requirements because the SWIR hysteresis causes a long tail of unrecovered signal. For flight test, MTF values will be calculated from single physical slit mask data. The single physical mask data will improve the measured SWIR PSF due to less light exposure (less hysteresis) and narrower slit will reduce the uncertainty in IFOV calculation.

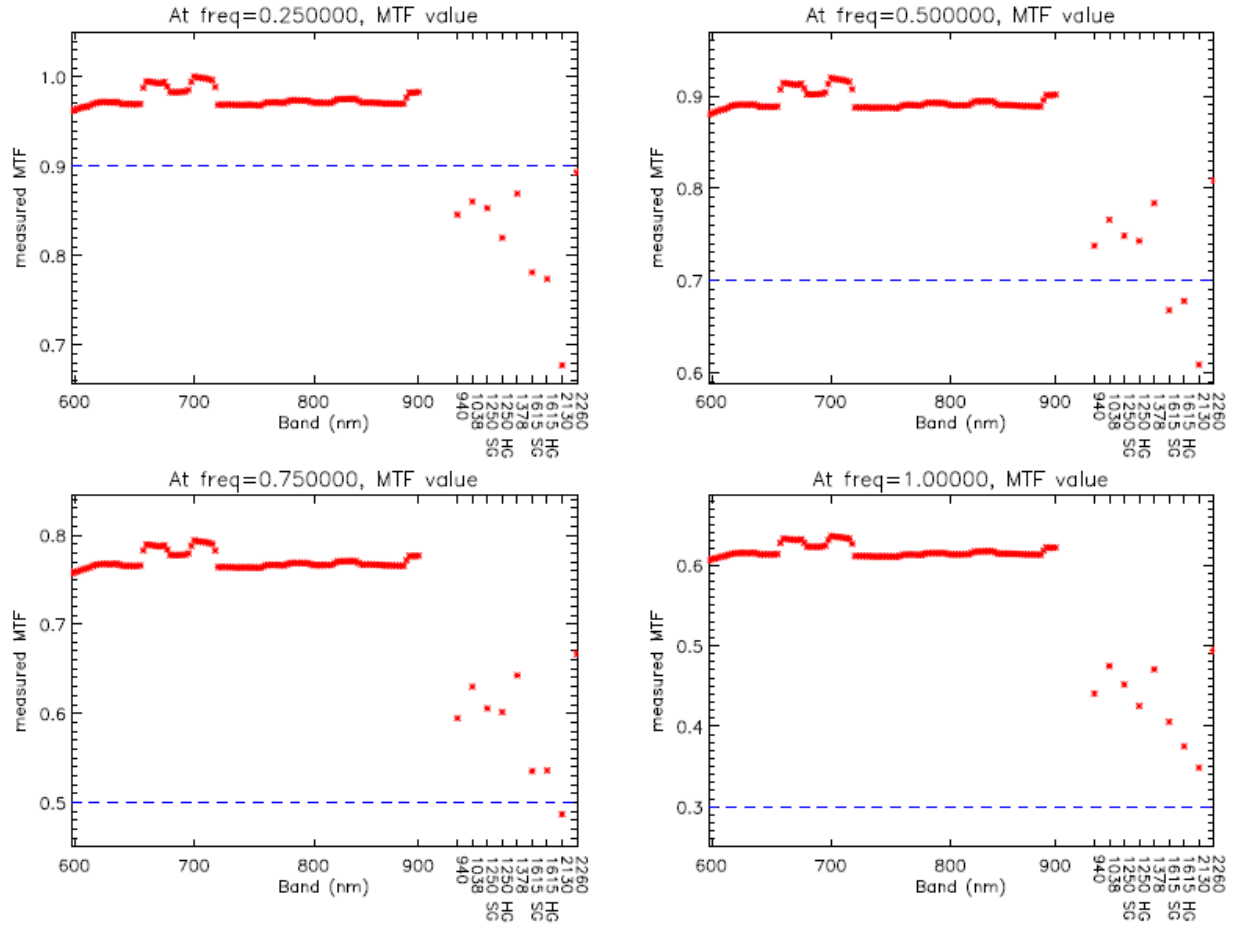


Figure 8. MTF values for VIS-NIR bands and SWIR bands at frequency ratios of 0.25, 0.5, 0.75, and 1. MTF values should be higher than the blue-dashed lines to meet the MTF requirement.

6.3 Spatial BBR

Figure 9 shows the minimum % BBR for VIS-NIR bands and SWIR bands. Time-delay mode gives higher spatial resolution of signal which provides a better estimation of centroid and BBR calculation. Without SWIR bands, VIS-NIR bands have very good BBR (more than 87%). CCD bands receive continuous spectrally dispersed light via the grating so the CCD bands have good BBR. However, the SWIR bands have independent detectors and readout electronics with detector specific delays. Therefore, there are significant differences within the spatial centroids of SWIR bands and this makes it impossible to achieve greater than 80% BBR for SWIR bands. OCI can be programmed to change the CCD FPA readout timing. For flight unit testing, red FPA and blue FPA readout timings will be programmed such that the CCD centroids are as close as possible to the centroids of SWIR bands but a few SWIR bands still may not meet the BBR requirement.

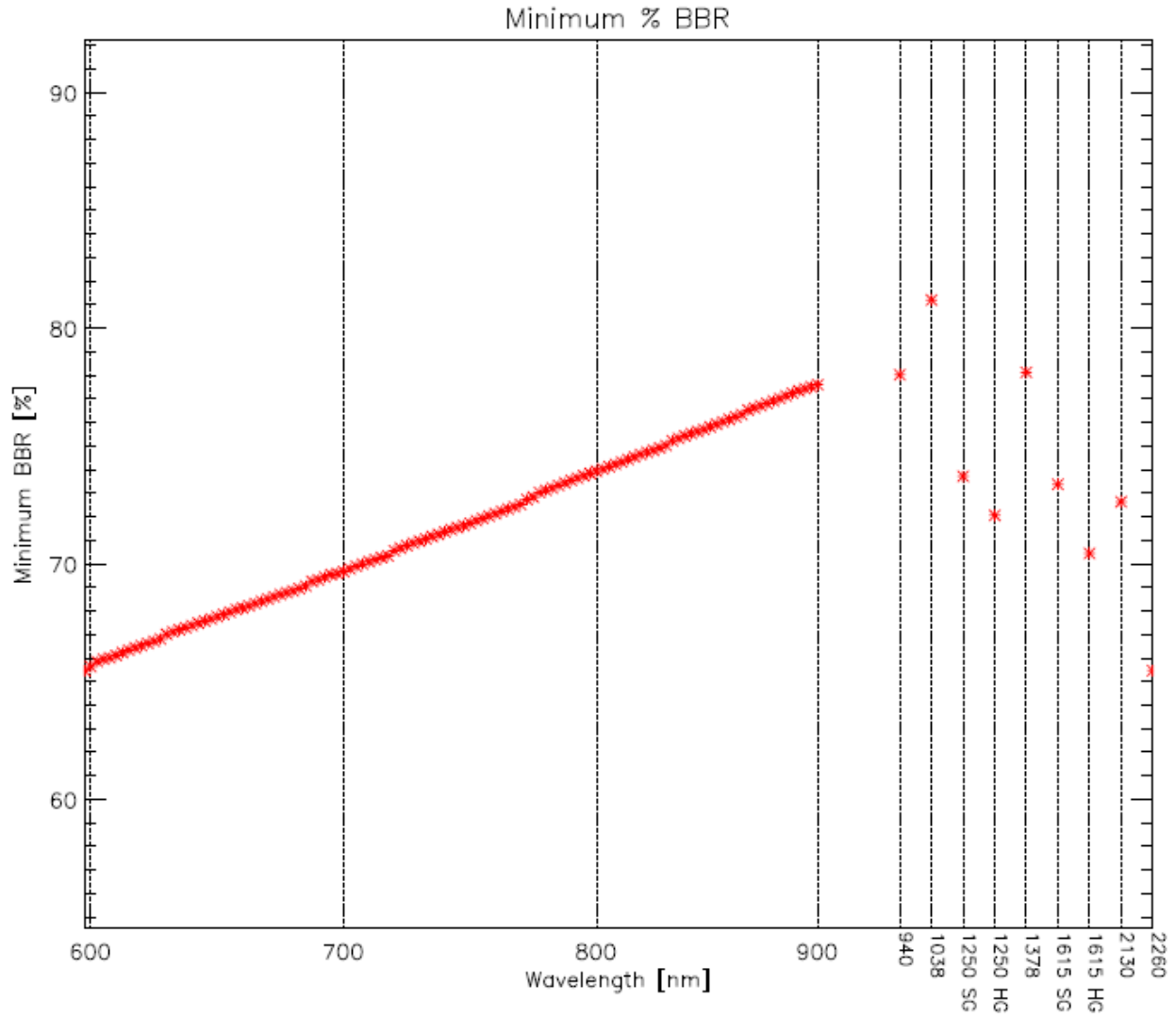


Figure 9. Minimum % BBR calculated from time-delay mode signal with MS mask.

7. CONCLUSIONS

The OCI ETU test showed the usefulness of time-delay mode for spatial sub-pixel level measurements and successfully demonstrated that time-delay mode worked properly as planned. Time-delay mode was an especially useful test mode for SWIR bands because of their 1 science pixel native resolution. Without time-delay mode, it would be very difficult to accurately estimate OCI's spatial characteristics. For the upcoming flight unit test campaign, time-delay mode will also be used to characterize along-track PSF and MTF using a slanted slit scene mask.

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REFERENCES

- [1] Werdell, P., Behrenfeld, M., Bontempi, P., Boss, E., Cairns, B., Davis, G., Franz, B., Gliese, U., Gorman, E., Hasekamp, O., Knobelspiesse, K., Mannino, A., Martins, V., McClain, C., Meister, G., and Remer, L., "The plankton, aerosol, cloud, ocean ecosystem (PACE) mission: Status, science, advances," *Bulletin of the American Meteorological Society* 100, 1775–1794 (2019).
- [2] Gorman, E. T., Kubalak, D. A., Patel, D., Dress, A., Mott, D. B., Meister, G., Werdell, P. J., "The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission: an emerging era of global, hyperspectral Earth system remote sensing," *Proc. SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII*, 111510G (10 October 2019)
- [3] Barnes, W. L. and Salomonson, V. V., "MODIS: A global imaging spectroradiometer for the earth observing system," in [Optical Technologies for Aerospace Sensing: A Critical Review], 10269, 102690G, International Society for Optics and Photonics (1992).
- [4] Murphy, R., Ardanuy, P., De Luccia, F. J., Clement, J., and Schueler, C. F., "The visible infrared imaging radiometer suite," in [Earth science satellite remote sensing], 199–223, Springer (2006).
- [5] Barnes, R. A. and Holmes, A. W., "Overview of the SeaWiFs ocean sensor," in [Sensor Systems for the Early Earth Observing System Platforms], 1939, 224–233, International Society for Optics and Photonics (1993).
- [6] Barsi, J. A., McCorkel, J., McAndrew, B., Zukowski, B., Shuman, T., Johnston, S., Markham, B., "Spectral testing of the Landsat-9 OLI-2 instrument using the Goddard Laser Absolute Measurement of Radiance (GLAMR)," *Proc. SPIE 10764, Earth Observing Systems XXIII*, 1076405 (7 September 2018)
- [7] Meister, G., Knuble, J. J., Chemerys, L. H., Choi, H., Collins, N. R., Eplee, R. E., Gliese, U., Gorman, E. T., Jepsen, K., Kitchen-McKinley, S., Lee, S., McIntire, J. W., Patt, F. S., Tse, B. C., Waluschka, E., Werdell, P. J., "Test Results from the Prelaunch Characterization Campaign of the Engineering Test Unit of the Ocean Color Instrument of NASA's Plankton, Aerosol, Cloud and Ocean Ecosystem Mission" *Front. Remote Sens.*, 23 June 2022 Sec. Multi- and Hyper-Spectral Imaging <https://doi.org/10.3389/frsen.2022.875863>