



Technical Note

Linearity Assessment from the Plankton, Aerosol, Cloud, and Ocean Ecosystem Ocean Color Instrument Pre-Launch Testing and On-Orbit Operations

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Abstract: Satellite observations have become increasingly important in scientific studies of the Earth's climate, especially for oceanographic science. A next generation sensor known as the Ocean Color Instrument (OCI) was launched in February 2024 onboard the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) platform, and will extend the data set of on-orbit scientific observations used for ocean and atmospheric science research. Delivering high quality data from a space-borne sensor requires the instrument to be well calibrated; while much of the calibration can be performed on-orbit, some aspects of the calibration must be measured or the mechanisms verified pre-launch. One aspect of the OCI calibration that is novel to its design (for a space-based sensor) is its ability to perform linearity measurements on orbit. When viewing the Sun reflected off a dim diffuser with ~2–3% reflectance, the sensor is capable of recording successive pixels with increasing integration times. The result is a series of light levels measured from the same source in a given scan line. These measurements are then used to assess the linearity. During the pre-launch test campaign, this mechanism was verified using a known source in the Earth view portion of the scan. Results from these tests form a baseline that was verified once on-orbit (and the calibration may be replaced if the linearity is shown to change). The linearity measured both prior to launch and post-launch will be assessed in this work.

Keywords: PACE; OCI; pre-launch; post-launch; linearity



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1. Introduction

Satellite remote sensing for ocean, cloud, and aerosol science was enhanced by the launch on 8 February 2024 of the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) satellite, featuring a payload of the Ocean Color Instrument (OCI) and a pair of polarimeters (SPExone and HARP2) [1–3]. OCI is based on the heritage design of earlier sensors widely used in ocean science research, including MODIS, VIIRS, and SeaWiFS [4,5], while also incorporating a number of design improvements. OCI is a grating spectrometer with hyperspectral coverage from about 315 nm to 895 nm, with nine additional filtered channels in the short-wave infrared (SWIR) spectral region, compared to the filtered radiometers that characterize earlier sensors. An additional improvement was the inclusion of a special operating mode that allows the linearity of the hyperspectral channels to be tested and characterized on orbit. OCI's detectors in the hyperspectral region have the ability to hold the charge for different multiples of the integration time in a single scan line. This capability, coupled with a dim target viewing the Sun, allows the instrument to sample the dynamic

range in a single scan using an extended uniform source. This instrument mode is referred to as progressive time-delay integration, or pTDI.

A comprehensive ground test campaign was performed to assess the instrument performance to a series of design requirements (intended to ensure high quality performance once on orbit) and to characterize the performance metrics necessary to transfer the calibration to on-orbit operations [3]. The linearity characterization is one of the key performance metrics for OCI, as characterization of the linearity is necessary for the correct calibration of the instrument. The measurements and results of the pre-launch characterization of linearity for the OCI Flight instrument as well as early on-orbit performance will be described in this work (results from the OCI engineering test unit were presented in [6]). The pre-launch results form a baseline for measurements performed on-orbit to be compared against, so that the linearity correction can be tracked and possibly updated on orbit. As the deviations from linearity are non-negligible, this correction is necessary in order to ensure OCI produces high quality data products for the science community. Section 2 will briefly describe the OCI instrument and the linearity tests; Section 3 will provide an overview of the analysis methodology; and Section 4 will review the analysis results, including a comparison to early on-orbit measurements, followed by the conclusions in Section 5.

2. Overview

2.1. OCI Overview

The optical design of OCI has been described in detail in [1–3], so only the relevant aspects of the design will be discussed in this section. The Earth is viewed through the aperture of a rotating telescope that spins at roughly 6 Hz in a plane tilted ± 20 degrees from perpendicular to the direction of the spacecraft motion. The Earth is viewed between ± 56 degrees off nadir, and there are two calibration views (a dark view for offset subtraction at 180 degrees off nadir, and a view of the solar diffuser assembly at about -90 degrees off nadir). The solar calibration assembly includes three diffusers used to view the Sun; only one of these diffusers is of interest for the purposes of this work, a dim diffuser with a reflectance of $\sim 2\text{--}3\%$. It is this dim diffuser that is used as a source for pTDI on orbit.

OCI has two CCDs (the blue CCD observing wavelengths between roughly 315 nm and 605 nm, and the red CCD observing wavelengths between 595 nm and 895 nm), each composed of a 128×512 array of physical pixels (detectors). Light is separated spectrally by a grating for each CCD in the direction of the larger dimension (referred to as the spectral dimension). The CCDs are divided into 16 taps in the spectral dimension of 32 physical pixels each. The smaller dimension is aligned to the scan direction of the telescope (referred to as the spatial dimension). As the telescope rotates, an image on the ground enters the FOV on the leading edge, and is imaged by the CCD. As the image moves along the spatial dimension of the CCD, it is imaged multiple times. These images are summed via time delay integration (TDI) to improve SNR. The CCDs can both be run in a number of different modes and pixel aggregations; the operating mode of interest for this work is progressive TDI (or pTDI). This mode operates in the native pixel resolution of the CCD. The charge from a given image that is summed across the spatial direction can be held in the serial register and summed with a succeeding image (or a number of them). The number of succeeding images summed can also be varied from one image to the next within a scan line. In this way, a series of pixels of varying effective integration times can be acquired within a given scan. When viewing a uniform source, such as the aperture of an integrating sphere prior to launch or the Sun reflected off the dim diffuser on orbit, the effect is equivalent to measuring multiple light levels. An example of a particular scan using pTDI measured on-orbit is shown in Figure 1. The sequence of the steps is programmable, so that different series of steps are possible; however, there is a limit on the total number of pixels used for pTDI in a scan line. The step sequences used pre-launch and on-orbit were different due to the limitations of the different sources: the sequences are listed in Table 1. The updated on-orbit sequence was used starting in October 2024. The dark view is also recorded using the same series of integration time steps as the source view

to provide the appropriate background subtraction (the increase in dark noise is small, but noticeable). pTDI is intended to only assess the linearity of the readout electronics, and not the linearity of the CCD pixels themselves (note that non-linearity in OCI was mainly in the readout electronics). In addition, this operating mode is only possible for the hyperspectral bands; the SWIR bands integration times are not variable in the same way. The SWIR band linearity was assessed using an approach in which an external source was cycled through a series of radiance levels, which will be described in the next section; note that this is only possible prior to launch.

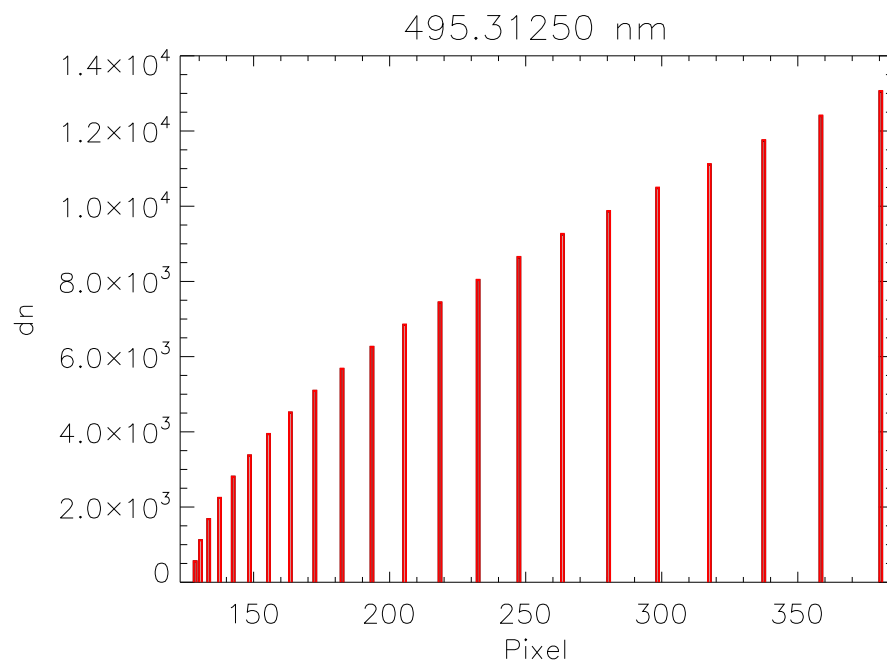


Figure 1. Scan profile for pTDI mode as OCI scans across the dim diffuser.

Table 1. pTDI step sequences used pre-launch and on-orbit.

Pre-launch	Original	1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, and 20
On-orbit	Original	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, and 23
On-orbit	Updated	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 15, 16, 17, 18, 19, 20, 21, 23, 24, and 26

In order to ensure high quality data products for the science community from OCI once on orbit, a number of design requirements were assessed during the ground test campaign. There were three requirements relevant to linearity on OCI. One requires that the curve for instrument response (DN) versus radiance must be monotonic. One limits the maximum allowed non-linearity: less than 6% for all bands between L_{LOW} and L_{MAX} (radiance levels defined in the next paragraph). The final requirement lists a series of stratified limits to the linearity after the correction has been made. For the purposes of this work, we will only examine the residuals from fits to the linearity data to assess the quality of the linearity correction. The assessment of the linearity performance, both pre-launch and on-orbit, will be discussed in Section 4.

A series of radiance levels were defined to facilitate the evaluation of the linearity (as well as other design requirements). L_{LOW} and L_{MAX} set the lower and upper bounds of the expected dynamic range on orbit, from the lowest Ocean radiances to the highest Cloud radiances. In addition, L_{TYP} defines the typical expected Ocean scene radiance. L_{HIGH} is the upper limit of the expected Ocean radiances. L_{BRIGHT} is defined as the predicted Solar radiance levels observed on orbit. Finally, some bands also have a specified radiance

L_{CLIP} , which defines an upper limit to the dynamic range for some bands below the Cloud radiances (to provide better radiance resolution for important spectral regions); the spectral range where L_{CLIP} is relevant is between 655 nm and 720 nm, as well as the SWIR bands 1038 nm, 1250 nm high gain, and 1615 nm high gain.

2.2. Pre-Launch Testing Overview

Linearity testing was performed pre-launch for OCI at the instrument level under both ambient and environmental conditions; in this work, only the tests performed under environmental conditions are assessed. A 20 inch integrating sphere with an 8 inch circular aperture was used, illuminated by a 150 W halogen lamp (covering the visible, near-infrared, and SWIR wavelength regions) and a plasma source (covering the ultraviolet and visible wavelength regions). For this test, OCI was inside a vacuum chamber, and could only view the source through a window at 0 degrees scan angle (OCI was oriented such that the scan plane was perpendicular to gravity; the direction of spacecraft motion was into the floor). Testing was performed at different instrument temperatures: twice at the expected nominal temperature for on-orbit conditions, and once each at the cold and hot extremes expected on orbit.

An uploadable table determines the various integration times of the pixels in a scan line. For the test performed pre-launch, 13 images were taken across the source with the integration time sequence listed in Table 1 (in units of the nominal integration time of 5.4 μ s). The sequence was timed such that all pixels fell within the sphere aperture as seen by OCI; this is shown in Figure 2 (upper plot), where the red line indicates the scan profile of the integrating sphere and the blue symbols represent the locations of the pTDI measurements.

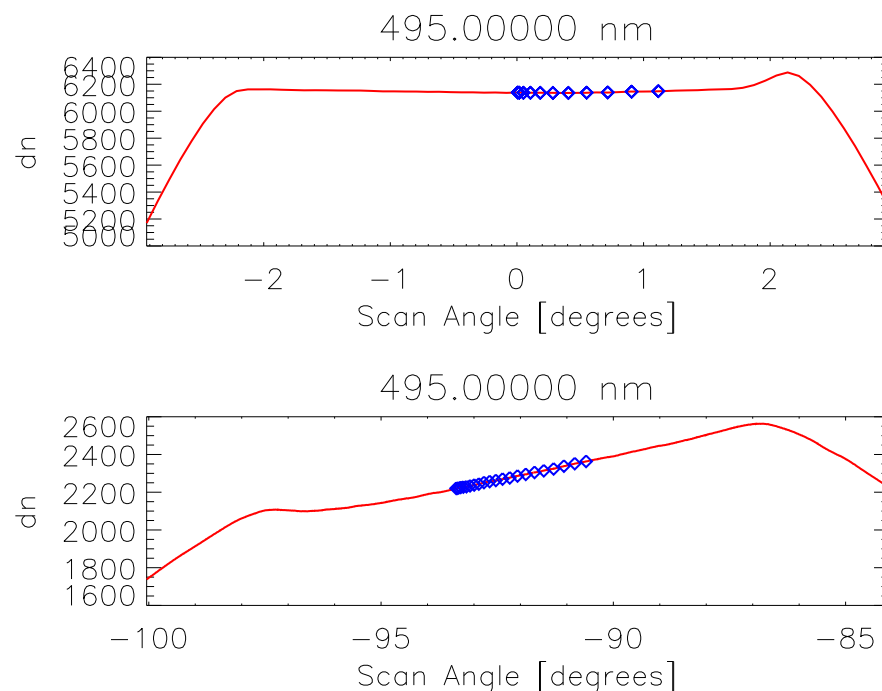


Figure 2. Scan profiles for the uniformity data from pre-launch (upper plot) and on-orbit (lower plot), show by the red lines. The blue dots represent the scan angle locations of the pTDI pixels.

A series of lamp levels were used, by varying the voltage supplied to each lamp type. This had the effect of overlapping the integration time sequences to more finely sample the linearity curve. The plasma and halogen lamps were used separately, each with its own sequence of voltage levels. An example of the overlapping of the integration time sequences for a particular band is shown in Figure 3. The different color/symbol combinations represent the different lamp configurations relevant for this band. Note that K_5 is the linearity correction that will be defined in Section 3.

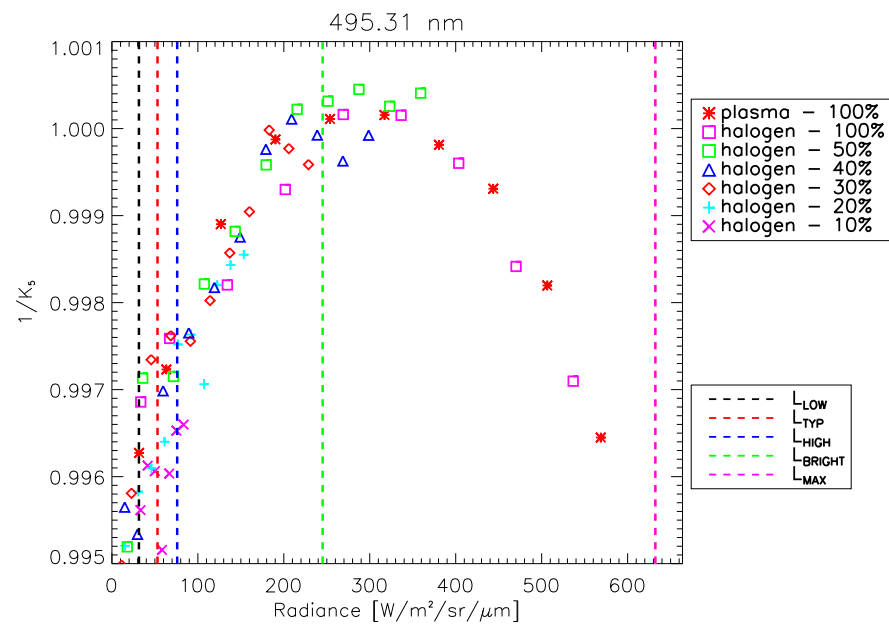


Figure 3. pTDI data from a number of different lamp configurations overplotted.

Additional tests were performed at each selected lamp level with the instrument in nominal operating mode, denoted by the red line in the upper plot of Figure 2. These data collects were used to determine any residual sphere uniformity in the scan direction, and apply a correction.

All bands were also tested using a more traditional approach where the radiance level of the source was varied to cover the dynamic range. Both white light and monochromatic sources were used, although only the results from the monochromatic source will be described here. Goddard Laser for Absolute Measurement of Radiance (GLAMR) [7], a system of tunable lasers, provided the monochromatic light for the OCI pre-launch testing. As the SWIR bands could not use the pTDI operating mode, the assessment of their non-linearity was performed using GLAMR; for the hyperspectral bands, GLAMR provided a check on the non-linearity calculations using pTDI.

2.3. On-Orbit Testing Overview

On orbit, the source is the Sun reflected off a dim diffuser with $\sim 2\text{--}3\%$ reflectance. The dim diffuser has an Acktar Fractal BlackTM coating on a roughened aluminum substrate [8]. This coating is usually used for stray light suppression. OCI views the diffuser between about -88 and -97 degrees scan angle, as seen in the lower plot of Figure 2, although only the center of this range is considered desirable for calibration. The spacecraft performs a dedicated maneuver that points the solar calibration baffle at the Sun; the Sun then illuminates the dim diffuser. The maneuver maintains the pointing with very little change in the angles on the diffuser (less than 0.01 degrees variation in the solar incidence angle) for about 450 scans (or ~ 75 s). This provides a stable source to perform the calibration. These measurements are performed once a month.

The uploadable table used on orbit acquires 23 images across the source with the integration time sequences listed in Table 1 (in units of the nominal integration time of $5.4 \mu\text{s}$). The original sequence was updated to include data above L_{MAX} starting in October 2024 (with 22 images across the source). The sequences were timed such that all pixels fell within the center of the dim diffuser as seen by OCI; this is shown in Figure 2 (lower plot), where the red line indicates the scan profile of the dim diffuser and the blue symbols represent the locations of the pTDI measurements. Note that the low end of the measured range for pTDI is limited by the reflectance of the dim diffuser; for much of the red CCD, the minimum radiance measured was above L_{TYP} , while the minimum radiance is below

L_{LOW} for most of the blue CCD. As mentioned previously, the SWIR bands cannot use the pTDI mode and so no on-orbit assessment of their linearity is possible.

3. Analysis Methodology

The general calibration equation for OCI on-orbit is given by [3]

$$L = K_1 K_2 K_3 K_4 K_5 K_p dn \quad (1)$$

where L is the top-of-atmosphere radiance and dn is the offset corrected digital counts. The corrections (K_i) applied to the digital counts, which are assumed to be independent, are as follows: K_1 is the radiometric gain determined pre-launch and updated on-orbit, K_2 is the time-dependent drift in the gain, K_3 is the correction to the gain for instrument temperature changes, K_4 is the response versus scan angle variation, K_5 is the linearity correction, and K_p is the polarization correction. For the purposes of this test, K_2 and K_p are assumed to be 1 and $K = K_1 K_3 K_4$. Rearranging, the linearity correction is then

$$\frac{1}{K_5} = \frac{K dn}{L} \quad (2)$$

As the linearity correction is defined to be unity at the fixed on-orbit calibration point, the curves are normalized at L_{BRIGHT} ; this results in the K factor above effectively canceling out. The radiance is determined from a monitor on the sphere (pre-launch) or calculated from the solar observations (on-orbit). The predicted on-orbit radiance is estimated via

$$L = \frac{1}{d_{ES}^2} \cos \theta_{sun} \int E_{sun}(\lambda) RSR(\lambda) BRDF(\lambda) d\lambda \quad (3)$$

where d_{ES} is the Earth–Sun distance in AU, $\cos \theta_{sun}$ is the projection of the solar illumination on the diffuser, E_{sun} is the spectral irradiance of the Sun [9], RSR is the relative spectral response of a OCI spectral band [3], and $BRDF$ is the bi-directional reflectance distribution function of the dim diffuser. The $BRDF$ is also angle dependent, such that as OCI scans across the diffuser the changes in angle must be taken into account.

K_5 is modeled as a polynomial in dn , or

$$K_5 = a_0 + a_1 dn + a_2 dn^2 + a_3 dn^3 + a_4 dn^4 \quad (4)$$

Data sets of dn and L are acquired from pre-launch testing or on-orbit observations of the dim diffuser, and fit through Equations (2) and (4). The factor K in Equation (2) was determined from separate pre-launch tests [3].

4. Analysis Results

4.1. Data Processing

pTDI data collections were performed for about 300 s (~1750 scans) pre-launch and about 75 s (~450 scans) on-orbit. Figure 1 shows the scan line from pTDI for an on-orbit observation. Note the increasing separation between pixels indicating the number of pixels aggregated is increasing (the pixel sequence was described in Section 2.3). The data collections were averaged over scans for each valid pixel in the scan line, both when viewing the source and when viewing the dark view. The dark view is then subtracted from the source view pixels, matching the pixels with the same aggregation. The radiances were determined from the active monitors on the integrating sphere (pre-launch) or Equation (3) (on-orbit). For both cases, the average of the radiance measurements was used for the analysis: the sphere monitors acquire data about every 10 s pre-launch, and the on-orbit radiance is estimated for every scan. Note that during pre-launch testing, the sphere monitors were limited to 340 nm and above; therefore, no radiance data were available below 340 nm. As a result, the linearity below 340 nm will require special consideration in the following section.

Uniformity data are also acquired prior to the pTDI mode observations (for about 35 s). Examples of the scan profile from uniformity data are shown in Figure 2, where pre-launch and on-orbit profiles are shown by the red line in the upper and lower plots, respectively. The blue symbols indicate the location of the pTDI pixels in scan angle on the profiles. A uniformity correction is derived by ratioing the profile at these pTDI pixel locations to the first pTDI pixel; this correction is then applied to the main pTDI data set. Note that the pre-launch profile is much flatter than the on-orbit profile. The sphere non-uniformity over the aperture was generally very small, with a correction usually under 0.2%. For the on-orbit profile, the non-uniformity correction is up to 6%.

An example of the data derived from pre-launch after the processing described above is shown in Figure 3. The different symbols as defined in the legend denote different pTDI data collections using various lamp levels/configurations. The data from these different levels were spliced together by normalizing the data collections in the radiance range where they overlap. Then, all the data collections are normalized to L_{BRIGHT} , which is the radiance level of the solar calibration on-orbit, and thus all linearity corrections are defined relative to this radiance level.

The GLAMR data collections were performed for about 40 s or 180 s pre-launch (depending on the radiance level), with ~ 15 s dark collects used for offset subtraction recorded between data collections. The GLAMR system was also actively monitored, so that the radiance and wavelength information was acquired at around 0.2 Hz and better than 1 Hz, respectively.

4.2. pTDI Fits

The processed pre-launch pTDI data were then fit using a least squares method to polynomials of different orders (quadratic, cubic, and quartic); this is shown in Figure 4, where the upper plot shows the fits (lines) and the data (symbols) while the lower plot shows the corresponding residuals. Here, the fits are performed on all data from $0.5 * L_{LOW}$ to $1.05 * L_{MAX}$. After comparing the fits for the different orders, the quartic fits were selected for the final processing. Increasing orders beyond quartic did not make any significant improvement, and the fits tended to become unstable outside the fit range.

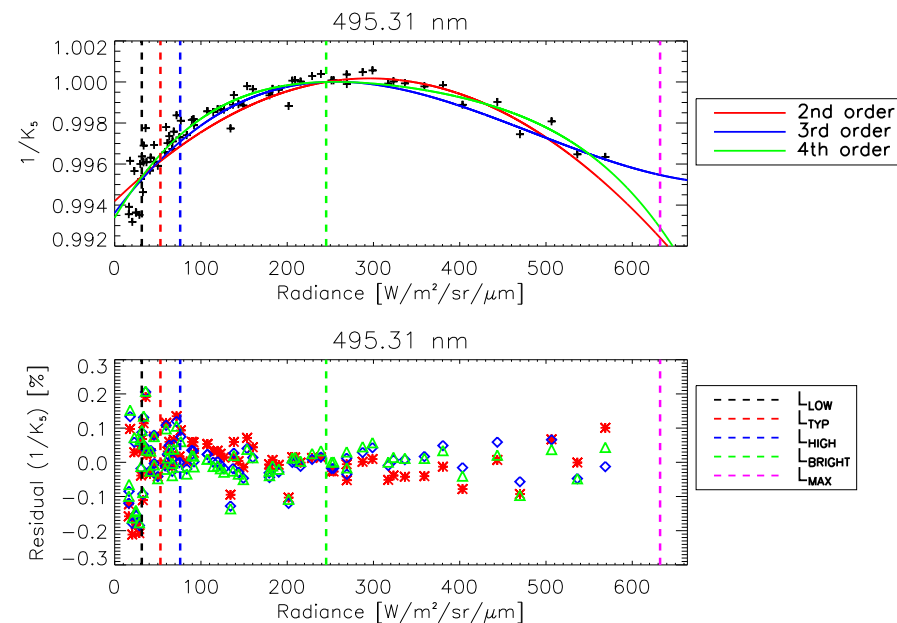


Figure 4. Comparison of different order polynomial fits to the pTDI data (upper plot) and corresponding residuals (lower plot).

For bands below 340 nm, radiance data were not available and, as a result, fitting was not possible during sensor level testing. Fortunately, some limited linearity testing

was performed at the component level. As the non-linearity in the system is expected to result from limitations in the electronics, the component level results were used where system level results could not be measured. For the component level, one wavelength was measured for every tap on the CCD. As the taps are fairly uniform in terms of linearity, these values were used for the lowest two taps on the blue CCD.

The fits acquired from pre-launch pTDI were compared to more traditional methods of linearity assessment using a source that was cycled through a series of power levels to cover the dynamic range. The source used was GLAMR [7,10], a monochromatic source consisting of a series of tunable lasers coupled to an integrating sphere. Due to time constraints, only a subset of OCI bands were compared in this manner (about one per tap). An example of a comparison is shown in Figure 5, where the upper and lower plots show the comparison of the fits and residuals, respectively. Note that fits agree well, except at the upper end of the dynamic range where pTDI data were not available and, as a result, the fit is not well constrained. In general, there is also good agreement for the other bands measured with GLAMR, giving confidence that the pTDI method can accurately characterize the non-linearity of OCI.

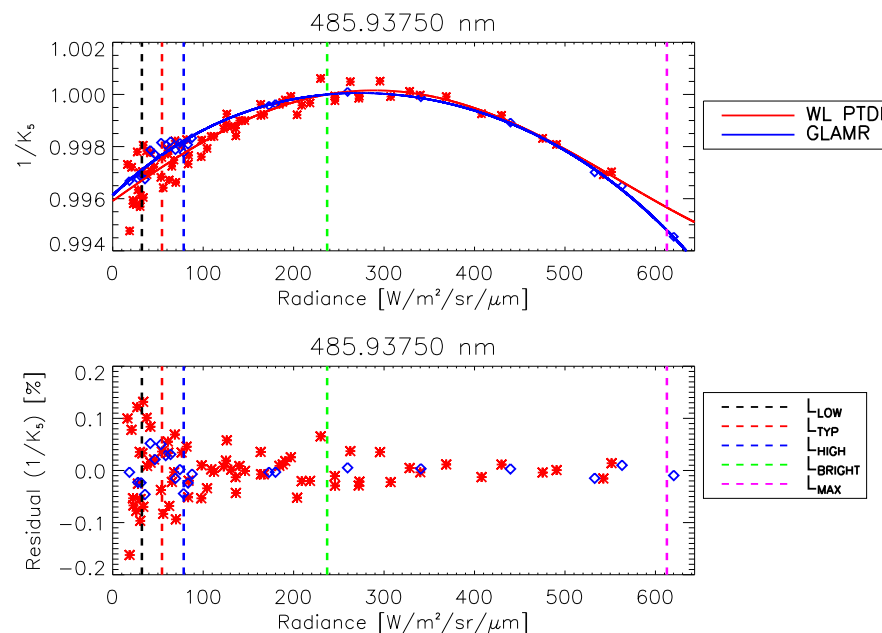


Figure 5. Comparison of fits to pTDI data and GLAMR power stepping data (upper plot) and residuals (lower plot).

Now that OCI is on orbit, the pre-launch and on-orbit measurements using pTDI can be compared. A comparison of the pre-launch measurements to the first two on-orbit pTDI data collections is shown in Figure 6. The two on-orbit data collections were performed successfully on 4 March 2024 and 11 March 2024 (for reference, the first light was acquired on 1 March 2024). The plot shows the data points and fits for both on-orbit data collections and the fit derived from pre-launch (dashed black line). Note that the curves are all normalized to L_{BRIGHT} , which is the fixed calibration point for on-orbit calibration. The two on-orbit data collections agree very well and also generally agree with the pre-launch measurements. On-orbit the highest radiance level is usually below L_{MAX} , which causes some discrepancy in the fits at the highest radiances as the on-orbit fits are not well constrained. The uploadable tables are in the process of being updated to rectify this by changing the pixel aggregation sequence to include higher levels.

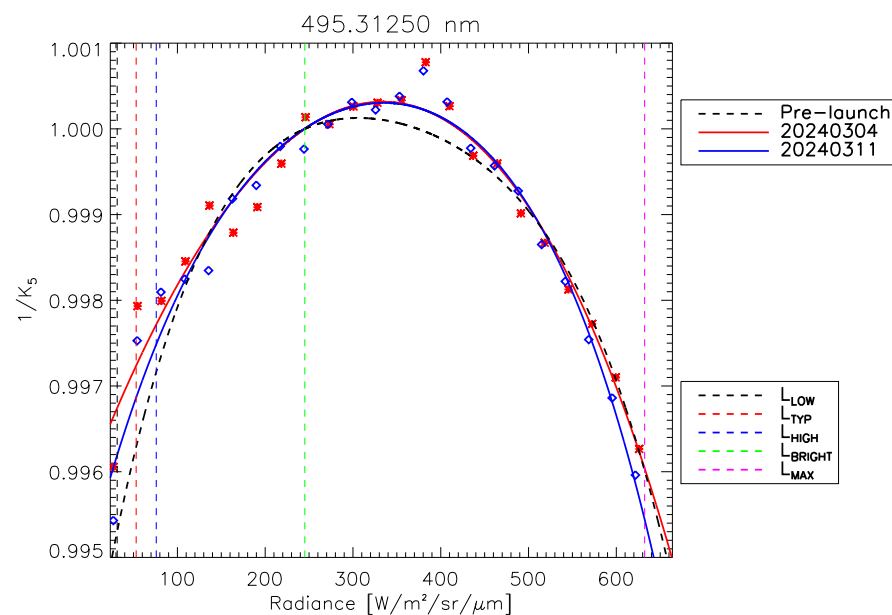


Figure 6. Comparison of pre-launch fits to the first two on-orbit data collections. Symbols represent on-orbit data and lines represent the corresponding fits.

4.3. Linearity Assessment

The non-linearity of OCI was assessed as part of the larger uncertainty assessment, and also in terms of design requirements. Using the fits performed for all bands, the maximum change in linearity over the dynamic range was estimated and plotted in Figure 7. The upper and lower plots show the results for bands in the blue and red CCDs. For most bands, the total non-linearity is less than 1%. However, there are regions where the non-linearity is as high as 6%, typically in the medium or high gain taps on the CCDs: below ~ 430 nm and above ~ 580 nm on the blue CCD; and between ~ 655 nm and 720 nm and above 880 nm on the red CCD. This is understood to be a feature of the electronics. In addition, the signal monotonically increased with radiance; this is no longer true when saturation occurs, but OCI saturation generally occurs well above the specified dynamic range. The exceptions to this are in the spectral ranges 400 nm– 430 nm and 580 nm– 600 nm on the blue CCD.

To assess the quality of the correction, the maximum and average fit residuals were calculated over the dynamic range (excluding saturation). Figure 8 shows these residuals based on pre-launch testing for the blue and red CCDs in the upper and lower plots. The maximum residuals, shown by the red curve, are generally in the order of 0.2% or less, except for wavelengths above 800 nm, where it can be as high as 0.4%. The highest residuals mostly occur at the lowest radiance levels where the uncertainty is highest. The blue lines represent the average residual over the dynamic range, which are consistently in the order of 0.05% for all bands.

For comparison, the same analysis was performed on the residuals derived from on-orbit fitting, as shown in Figure 9, where, again, the upper and lower plots show the blue and red CCD results. For most bands, the maximum residuals are around 0.2% or less, and the average residuals are again in the order of 0.05%. As described earlier, the on-orbit fits generally have fewer data points within the dynamic range, particularly at the lower radiance levels; nonetheless, the residuals show comparable levels of fitting for both pre-launch and on-orbit. The quality of the fits, as shown by the residuals, indicates that the linearity is well characterized for the CCDs, and can be monitored on orbit for any variations over time.

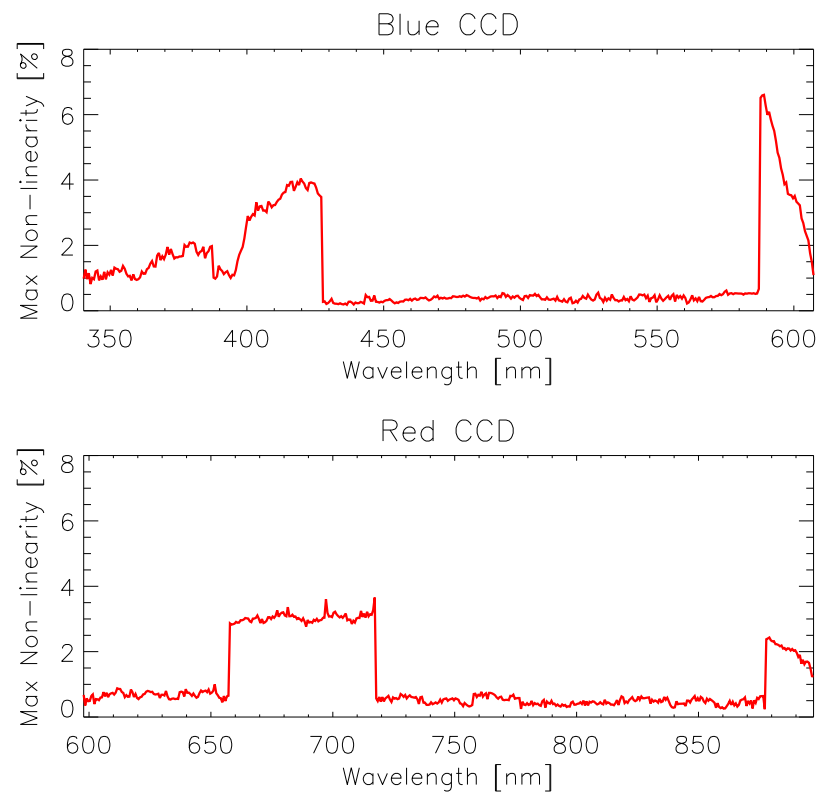


Figure 7. The maximum non-linearity from L_{LOW} to L_{MAX} for all bands on the blue CCD (**upper** plot) and red CCD (**lower** plot).

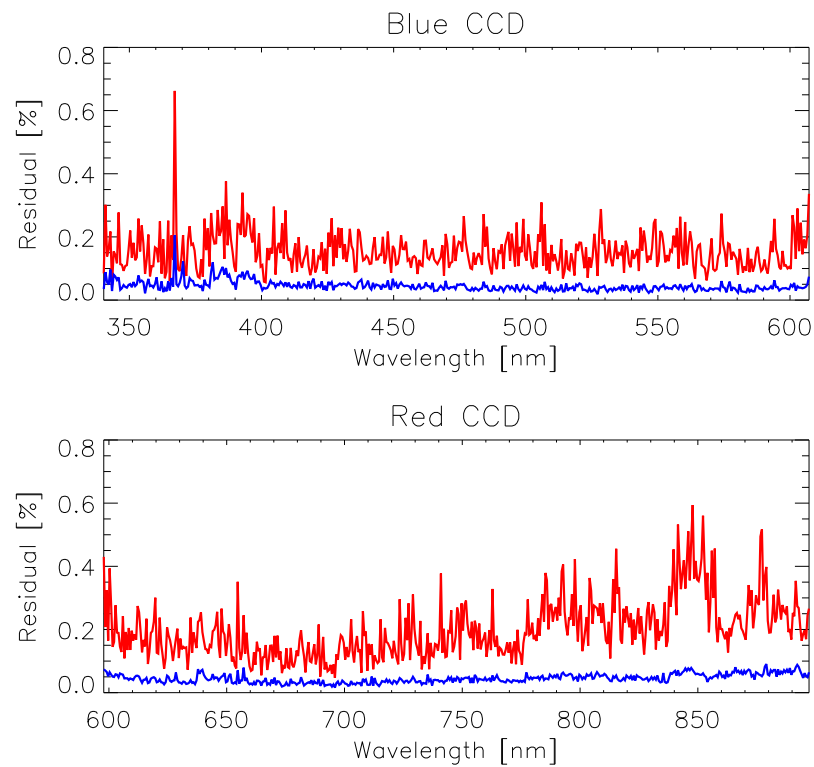


Figure 8. Maximum and average residuals (red and blue lines) for linearity fits derived pre-launch for the blue CCD (**upper** plot) and red CCD (**lower** plot).

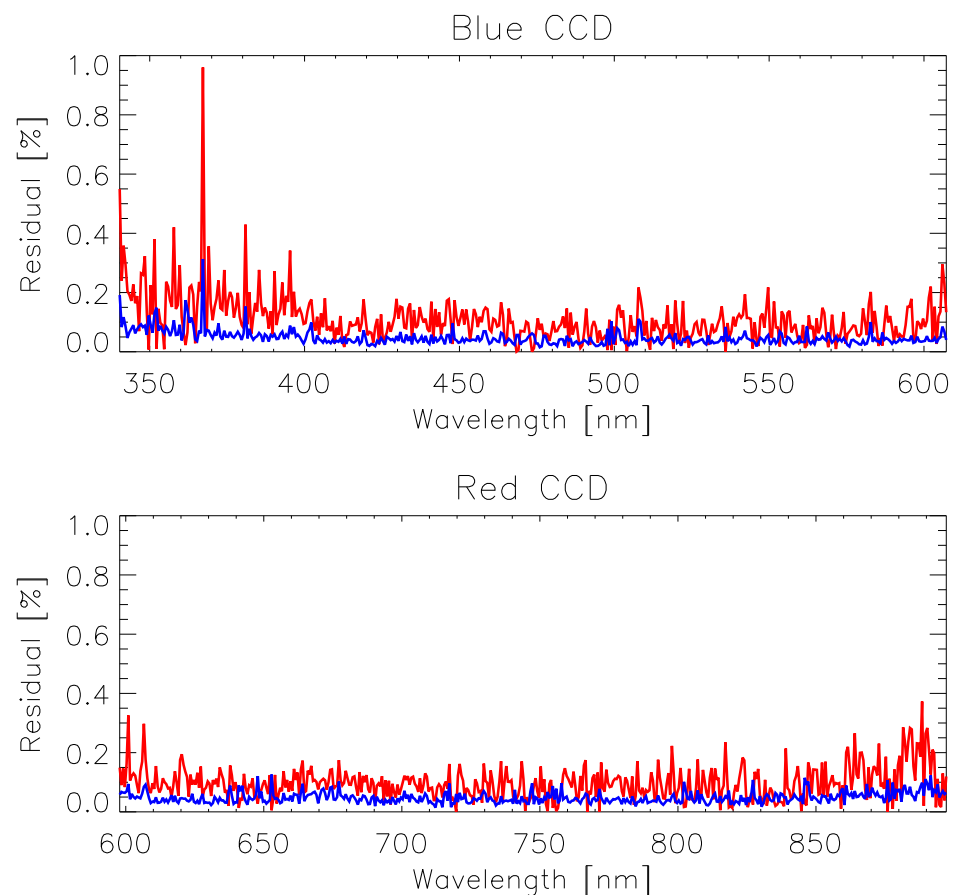


Figure 9. Maximum and average residuals (red and blue lines) for linearity fits derived on-orbit for the blue CCD (**upper** plot) and red CCD (**lower** plot).

4.4. SWIR Linearity

Figure 10 shows in the upper plot an example the linearity fitting for a SWIR band (1615 nm single gain) using the GLAMR data. The data are generally well described by the polynomial fit inside the dynamic range. This is true for the other bands as well, with the exception of 1615 nm high gain. In that case, the data at the lowest radiance levels was not well described, and resulted in higher residuals, although the linearity was well characterized over most of the dynamic range. In the lower plot of Figure 10, the maximum and average residuals are shown for all SWIR bands. The maximum residual for 1615 nm high gain is $\sim 2\%$, while the average residual is only about 0.2% , due to the reasons described above. All of the other SWIR bands have maximum residuals under 0.5% and average residuals under 0.1% . This indicates that overall, the linearity is well characterized for the SWIR bands.

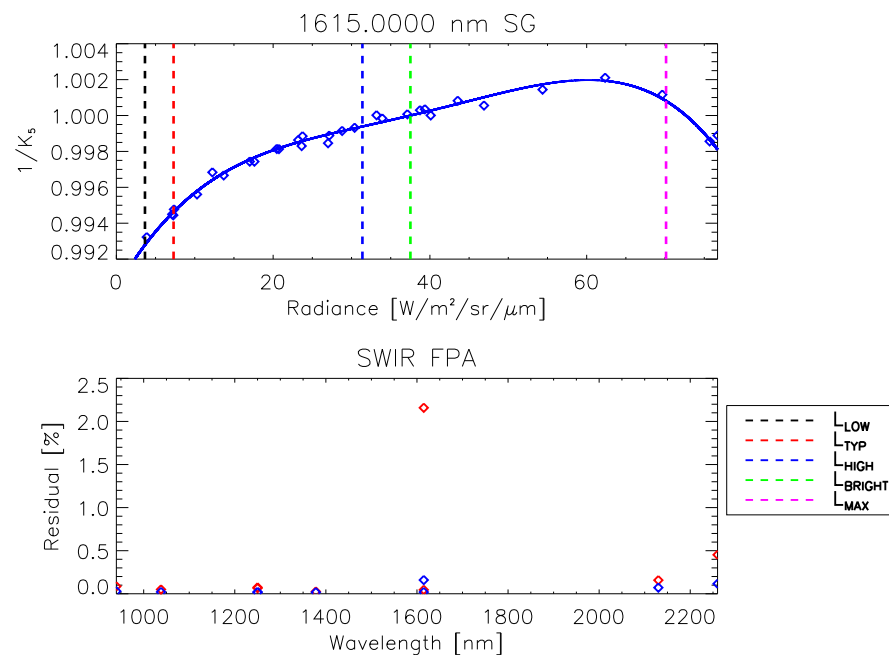


Figure 10. The fit of $1/K_5$ for the 1615 nm single gain band (**upper** plot) using GLAMR data. Maximum and average residuals (red and blue symbols) for linearity fits derived from pre-launch SWIR band data (**lower** plot).

5. Conclusions

OCI is the primary sensor onboard the recently launched PACE platform, and is the next generation sensor for ocean and atmospheric science remote sensing. One of the design improvements made for OCI relative to heritage sensors is a special operating mode, referred to as progressive TDI (or pTDI). This mode allows OCI to change the integration time within a scan line, producing the equivalent of multiple radiance levels when viewing a uniform source (such as the Sun reflected off a dim diffuser). The multiple radiance levels can be used to assess the linearity of OCI bands on-orbit. Results have shown that the non-linearity of OCI is generally small and was well characterized. The pTDI method was also validated by comparison to more traditional measurements using GLAMR. Comparisons of pre-launch measurements to on-orbit observations also show good agreement.

Author Contributions: J.M. wrote the article and performed the analysis. G.M. oversaw the testing and analysis. J.A.B. and S.K.-M. provided the GLAMR data and processing. K.J. and U.G. conducted the pre-launch experiments and performed analysis on the component data. S.L. performed analysis. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data is available at <https://oceancolor.gsfc.nasa.gov> accessed on 3 October 2024.

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Conflicts of Interest: Authors Jeff McIntire, Kim Jepsen and Samuel Kitchen-McKinley were employed by the company Science Systems and Applications. Ulrik Gliese was employed by the company KBR. Shihyan Lee was employed by the company Science Applications International Corporation. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Werdell, P.J.; Behrenfeld, M.J.; Bontempi, P.S.; Boss, E.; Cairns, B.; Davis, G.T.; Franz, B.A.; Gliese, U.B.; Gorman, E.T.; Hasekamp, O.; et al. The Plankton, Aerosol, Cloud, ocean Ecosystem mission: Status, science, advances. *Bull. Am. Meteorol. Soc.* **2019**, *100*, 1775–1794. [\[CrossRef\]](#)
2. Gorman, E.T.; Kubalak, D.A.; Patel, D.; 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. In Proceedings of the Sensors, Systems, and Next-Generation Satellites XXIII, Strasbourg, France, 9–12 September 2019; SPIE: Washington, DC, USA, 2019; Volume 11151, pp. 78–84.
3. Meister, G.; Knuble, J.J.; Gliese, U.; Bousquet, R.; Chemerys, L.H.; Choi, H.; Eplee, R.E.; Estep, R.H.; Gorman, E.T.; Kitchen-McKinley, S.; et al. The Ocean Color Instrument (OCI) on the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission: System Design and Prelaunch Radiometric Performance. *IEEE Trans. Geosci. Remote Sens.* **2024**, *62*, 5517418. [\[CrossRef\]](#)
4. Xiong, X.; Butler, J.; Chiang, K.; Efremova, B.; Fulbright, J.; Lei, N.; McIntire, J.; Oudrari, H.; Sun, J.; Wang, Z.; et al. VIIRS on-orbit calibration methodology and performance. *J. Geophys. Res. Atmos.* **2014**, *119*, 5065–5078. [\[CrossRef\]](#)
5. McClain, C.R.; Feldman, G.C.; Hooker, S.B. An overview of the SeaWiFS project and strategies for producing a climate research quality global ocean bio-optical time series. *Deep. Sea Res. Part II Top. Stud. Oceanogr.* **2004**, *51*, 5–42. [\[CrossRef\]](#)
6. McIntire, J.; Kitchen-McKinley, S.; Choi, H.; Meister, G. Progressive TDI measurements with the PACE OCI ETU. In Proceedings of the Earth Observing Systems XXVI, San Diego, CA, USA, 1–5 August 2021; SPIE: Washington, DC, USA, 2021; Volume 11829, pp. 214–220.
7. Barsi, J.A.; Donley, E.; Goldman, M.; Kampe, T.; Markham, B.L.; McAndrew, B.; McCorkel, J.; Morland, E.; Pedelty, J.A.; Pharr, J.; et al. Prelaunch Spectral Characterization of the Operational Land Imager-2. *Remote Sens.* **2024**, *16*, 981. [\[CrossRef\]](#)
8. Available online: <https://acktar.com/product/fractal-black/> (accessed on 1 January 2022).
9. Coddington, O.; Richard, E.; Harber, D.; Pilewskie, P.; Woods, T.; Snow, M.; Chance, K.; Liu, X.; Sun, K. Version 2 of the TSIS-1 Hybrid solar reference spectrum and extension to the full spectrum. *Earth Space Sci.* **2023**, *10*, e2022EA002637. [\[CrossRef\]](#)
10. Wang, Z.; Barsi, J.; Thome, K.; Wenny, B.N.; McAndrew, B.; Efremova, B.; McCorkel, J. Uncertainty budget for detector-based absolute radiometric calibration with GLAMR. *Appl. Opt.* **2024**, *63*, 3015–3028. [\[CrossRef\]](#) [\[PubMed\]](#)

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