

PRE-LAUNCH ANALYSIS AND TEST OF THE OCEAN COLOR INSTRUMENT MODULATION TRANSFER FUNCTION

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ABSTRACT

Launched in February 2024, the Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) mission represents NASA's next investment in ocean biology, clouds, and aerosol data records. The Ocean Color Instrument (OCI) is the primary instrument supporting PACE by collecting accurate radiometric data of the Earth by observing the top of atmosphere reflectance and is a combination hyperspectral (ultra-violet to near infrared) / multiband imager (shortwave infrared). An important aspect of the radiometry is the ability of OCI to resolve contrast from scene to scene to achieve data accuracy requirements. This paper reviews the analysis that was performed to verify the modulation transfer function (MTF) requirement levied against the instrument and presents the supportive test data collected during pre-launch instrument testing to supplement the analysis.

The requirements levied against OCI drove to a 1.2 km² ground resolution leading to a Nyquist period of 2.4 km (0.417 cycles / km). The analysis is comprehensive with incorporation of as many contributors as practical to provide the clearest possible picture of the margin against requirements. The analysis provided input for additional design trade studies and insight into the aspects of the design that required the most attention during the implementation phase. We describe four separate MTF contributor networks based on the instrument design and mutual exclusivity of contributing factors. The various networks represent the hyperspectral and multiband detection systems separately as well as the along track and cross track imaging dimensions. Ground-test was performed against the MTF primary contributors and the results were used to validate the analysis as will be presented here.

1. INTRODUCTION

The Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) mission represents NASA's next investment in ocean biology, clouds, and aerosol data records [8]. The development of the Ocean Color Instrument (OCI), the primary instrument on PACE, took many years and provides a significant technological leap in collecting accurate radiometric data on ocean leaving reflectance [9]. During the development of OCI it was important to track MTF performance and provide an allocation of the system level requirement to each design element in accordance with their expected contribution. Having a detailed and credible analysis of the design enabled efficient distribution of these allocations in order to avoid insurmountable engineering feats to satisfy an unrealistic expectation. Allocations could then be re-evaluated and adjusted accordingly as development progressed and actual performance was better understood. Identification of the primary contributors facilitated insight into where the most effort should be made during development.

The OCI specification defines imaging performance based on data collected with the primary aperture facing nadir (or perfectly straight down), with the ground resolution specified as 1 square km ± 0.05 km. During operations, however; the entire imaging platform is tilted from 20 degrees aft to 20 degrees forward while taking data on the day side of the orbit. This tilting avoids sun glint reflection, but as a result, increased distance to the Earth's surface causes ground resolution changes. Therefore, the resolution that is used for much of the design

implementation is roughly 1.2 km^2 which may explain discrepancies in some of the papers/literature published on OCI. The MTF requirement levied against OCI, which was driven by heritage instruments, is shown in Table 1 below. The requirement is defined in terms of fractions of the Nyquist frequency, which for the as-built OCI was $0.417 \text{ km}^{-1} \left(\frac{1}{2 * \text{ground resolution}} \right)$. Analytical models of MTF performance were derived in terms of cycles per km and then conversions could be made as the ground resolution changed with as built components. Once instrument integration was completed, the test campaign confirmed that MTF performance was consistent with estimates.

Table 1. OCI MTF Requirement

Fraction of Nyquist	0.25	0.5	0.75	1.0
MTF Performance	0.9	0.7	0.5	0.3

2. MODULATION TRANSFER FUNCTION DESCRIPTION

The modulation transfer function of an imaging system is a comprehensive performance characteristic of the system's ability to resolve contrast of a given input signal. MTF performance is often included in the requirement set for space-borne remote sensing systems and can be challenging to completely verify. It augments signal to noise requirements which could drive toward sacrificing imaging performance in an effort to boost signal and decrease noise.

Mathematically, the Fourier Transform of an image response is the Optical Transfer Function (OTF)

- $OTF \equiv H(\xi, \eta)$ where $H(\xi, \eta)$ is the impulse response function
 - ξ and η are the spatial frequencies of the source image in two-dimensional space (cross-track and along-track respectively)
 - Different system components have different OTFs or other image modification aspects
 - $MTF \equiv |OTF| \equiv |H(\xi, \eta)|$
 - While OTF can go negative and represents a phase shift or aliasing, MTF is always positive
 - The sum (Σ) of the MTF effects is the product of all of the Fourier transforms
- $$MTF_{sys} = MTF_{optics} \bullet MTF_1 \bullet MTF_2 \bullet MTF_3 \bullet MTF_4 \dots \dots \bullet MTF_N$$

3. OCI SYSTEM MTF CONTRIBUTORS

MTF performance can be impacted by a large range of design implementation decisions including but not limited to optics, electronics, timing, detector size, vibration and image motion, etc. OCI utilizes a single primary telescope aperture that provides top of atmosphere reflectance to three imaging sub-systems after passing through a polarization scrambler, slit field stop, dichroic elements and focusing optics. Two charge-coupled device (CCD) based sub-systems and a photodiode (PD) based sub-system provide radiometric data over the wavelengths 315 nm to 2260 nm. The two CCDs (referred to as the UVNIR system) cover the wavelength ranges 315-607 nm and 597-887 nm. The PDs (included as part of the short-wave infrared [SWIR] system) longer wavelengths are measured in discrete bands centered at 940, 1038, 1250, 1378, 1615, 2130, and 2260nm with varying bandwidths (there are two repeated bands at 1250 and 1615 that have much higher signal gain for low ocean signals). While the UVNIR focusing optics project the slit image directly onto the CCDs themselves, the photodiode sub-system incorporates optical fibers to transmit light to the detectors making the microlens array essentially the imaging plane or effective "pixel", the remaining optics are considered a light bucket and not included in the optical MTF contribution. A diagram of the OCI optical system can be seen in Figure 1; additional details of it, and the detector architecture, can be found in reference [1].

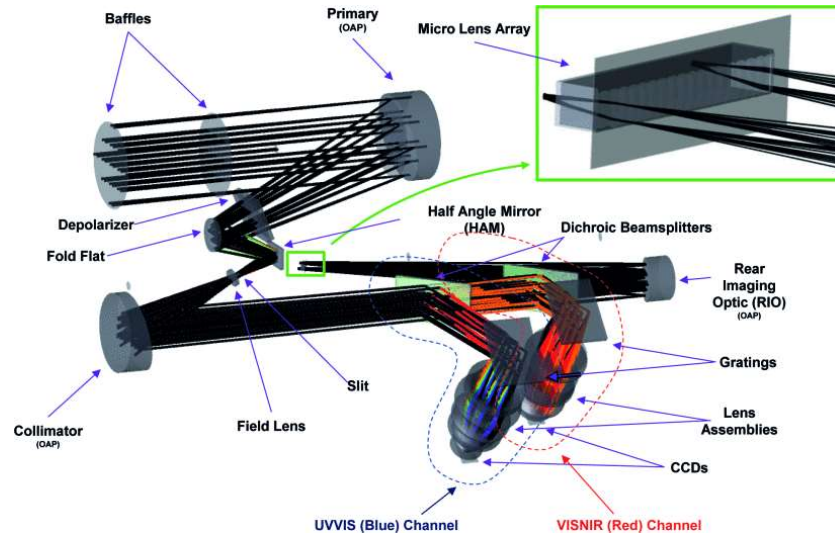


Figure 1. OCI Optical Architecture. Figure taken from [1].

3.1. MTF Network Assumptions and Discretization

The MTF analysis for OCI was discretized between imaging sub-system types and image dimensions. There were clear demarcation points for this separation among the contributor types due to the fact that they are largely mutually exclusive. There was no significant interaction across these two categories (detector types and image dimensions) which resulted in four separate analysis networks, all of which had to meet the defined requirement independently for the requirement to be considered verified.

Discretization developed for the OCI imaging system MTF are as follows:

- ► Cross -Orbit Track MTF (along scan) UVNIR
- ▲ Along-Orbit Track MTF UVNIR
- ▷ Cross-Orbit Track MTF (along scan) Photodiode Sensor Chain
- △ Along-Orbit Track MTF Photodiode Sensor Chain

3.2. Listing of OCI MTF Contributors Included in Analysis

Contributors included in the OCI MTF analysis (related discretization referenced):

1. Model based optical MTF ►▲▷△; Acquired using Z-max optical modeling software and ultimately as-built component placement
2. Assembly imperfections ►▲▷△; Bessel-function estimation, later removed when as-built Z-max model was complete
3. Stray light ►▲▷△; Bessel-function estimation
4. Ghosting ►▲▷△; Bessel-function estimation
5. Atmospheric scattering ►▲▷△; Insignificant based on ground resolution
6. Environment (Launch Dynamics) ►▲▷△; Estimated as a fraction of Optical MTF
7. Jitter (Observatory Platform) ►▲▷△; Supported by observatory jitter analysis
8. Mechanism motion ►▲▷△; Bearing runout assumed as equivalent displacement as a CCD pixel
9. Orbit Velocity ▲△; Displacement calculated based on ground velocity at equator
10. Optics to detector distortion ►▲▷△; Treated as an additional aperture
11. Bi-refringement Filter (Polarization scrambler) ▲△; Dedicated ghost image contribution
12. Slit Size (Along-track pixel size) ▲△; Rectangular aperture for the spectrograph
13. Pixel footprint ►; Individual CCD pixel rectangular aperture
14. Pixel pitch ►; Contiguous pixel pitch
15. Charge transfer efficiency ►; CTE performance inputs were based on vendor test data

16. Carrier diffusion ►; Estimated carrier diffusion factor
17. Image velocity ►; CCD charge transfer period fraction
18. TDI velocity mismatch ►△; Average CCD charge well velocity vs the scan image velocity
19. Detector response ►▷; Detectors have high response frequency compared to spatial frequency (>1MHz, equivalent, based on vendor data)
20. MLA (“pixel size”) ▷; Effective PD pixel imaging plane
21. Effective Electronic Filter ▷ Accumulation of all electronic signal conditioning impacts
22. Sampling Frequency Filter ▷ Clock stability between PD samples

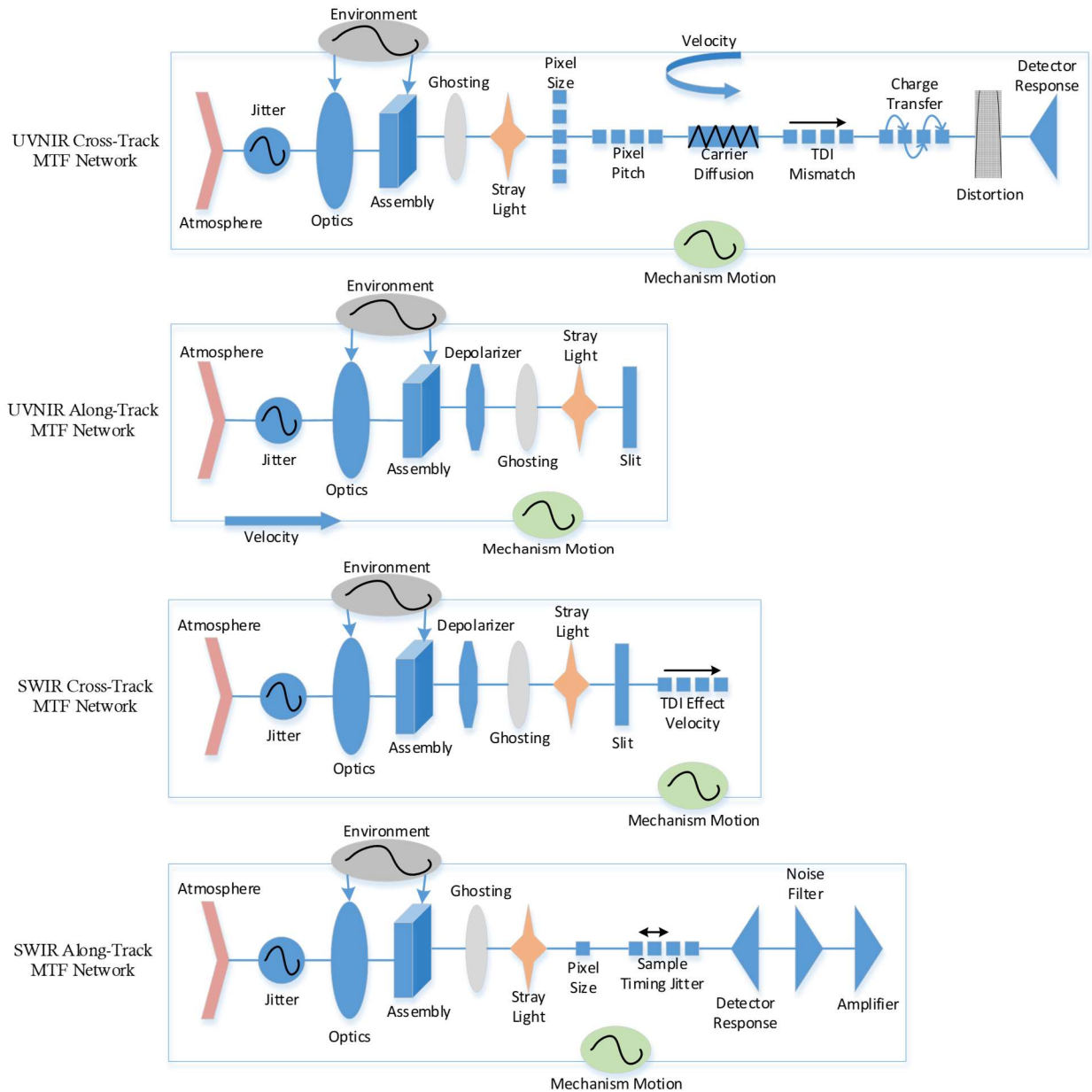


Figure 2. OCI MTF Contributor Networks

3.3. Primary MTF Contributors

3.3.1. Cross Orbit Track UVNIR System MTF (along scan)

The cross-track MTF performance for OCI is quite good, this is primarily due to over sampling that is done at the CCD level (8:1 over sampling of ground resolution). The primary contributors to MTF were therefore found to be image velocity combined with stepwise time-delayed integration (TDI) followed closely by on-orbit jitter.

The MTF impact caused by image velocity over a pixel integration period, can be analytically represented by the following:

$$MTF_{ImageVel} = \left| \frac{\sin(\pi \cdot \xi \cdot v_{image} \cdot t_{integration})}{\pi \cdot \xi \cdot v_{image} \cdot t_{integration}} \right| \quad (1)$$

Specific applicability to OCI of this velocity contributor is as follows:

- Conservatively, CCD charge transfer is assumed instantaneous with an integration period roughly seven times the transfer period
- Ultimately two different velocities occur for different durations (the image moves continuously while the accumulated electrons move in a stepwise manner) to give the same overall displacement ($t \cdot v$)
- Typically, this MTF reduction would occur for every pixel on the CCD in the TDI direction (x128 pixels)
- The 128 CCD pixels are aggregated into groups of 8 to form a science pixel, therefore the velocity displacement that occurs at boundaries between science pixels is the only relevant MTF impact.

Total image velocity MTF impact for OCI was then represented by:

$$MTF_{ImageVel} = \left| \frac{\sin(\pi \cdot \xi \cdot v_{image} \cdot t_{integration})}{\pi \cdot \xi \cdot v_{image} \cdot t_{integration}} \right|^{128/8} \quad (2)$$

$$v_{image} = \frac{w_{Pixel}}{t_{integration}} \rightarrow v_{image} \cdot t_{integration} = w_{Pixel} = D_{Image}$$

$$MTF_{ImageVel} = \left| \frac{\sin(\pi \cdot \xi \cdot D_{Image})}{\pi \cdot \xi \cdot D_{Image}} \right|^{128/8} \quad (3)$$

The second largest contributor in this network was platform (observatory) jitter. Unlike astronomical imaging platforms OCI is a relatively fast imager so only high frequency jitter contributes to MTF degradation and other spacecraft motion results in a pointing error. Observatory jitter analysis provided a conservative expected random displacement of 1/16th of the ground resolution (σ_r) at these higher frequencies. The jitter impact is analytically represented by the following equation:

$$MTF_{jitter} = e^{-2(\pi \cdot \sigma_r \cdot \xi)^2} \quad (4)$$

$$\sigma_r = \text{random image displacement}$$

Other notable contributors include optics, straylight, and ghosting, which together do degrade imaging performance noticeably. As mentioned previously, the optics MTF is provided by the as-built Z-max model (including assembly imperfections). The other two contributions were modeled as Bessel function based estimations and supported by supplemental analysis showing minimal effects to overall imaging performance.

3.3.2. Along Orbit Track UVNIR System MTF

The optical architecture of OCI results in an along track image plane located at the hyperspectral slit for the broadband image source of top of atmosphere reflectance. The along track MTF would remain relevant beyond the slit, for an input source of monochromatic light, however broadband light spreads the slit image over the CCD such that all spatial information is lost, and only spectral information is retained. This effectively makes the slit behave as a rectangular aperture and the sub-sampling (8:1) performed at the CCD does not provide any improvement to the system MTF. This slit is not included as part of the cross-track chain as it is much larger

than the science pixel area in this dimension (x16). This slit aperture is by far the largest contributor to MTF reduction in this detection chain, followed by similar contributors for cross-track imaging (jitter, straylight, ghosting and assembly imperfections).

The OCI slit can be analytically represented by the following equation:

$$MTF_{Slit} = \left| \frac{\sin(\pi \cdot \eta \cdot w_{Slit})}{\pi \cdot \eta \cdot w_{Slit}} \right| \quad (5)$$

$$w_{Slit} = \text{OCI Slit Width projection to the ground}$$

3.3.3. Cross Orbit Track SWIR System MTF (along scan)

The SWIR photodiode detection system for OCI does not sub sample the ground resolution; there is a single photodiode for each ground scene. Additionally, signal in the short-wave infrared range of the ocean reflectance is much lower resulting in more noise filtering electronics present in the SWIR system to increase the signal to noise ratio. The larger pixel size and electronic filtering are the largest contributors to the cross-track PD chain MTF degradation. The digital TDI that is performed as part of SWIR data collection does not contribute to the SWIR MTF outside of timing errors, this is due to the sampling nature of the PD front-end electronics operating in a linear fashion and does not perform any integration (the image is not moving during an “integration” period as it does for the CCD). During the development effort, there was a tradeoff analysis performed for the PD detection chain to set the filtering bandwidth. The MTF analysis was instrumental for this effort providing a lower bound of allowable filtering impact informing the design of the filtering circuits. The primary contributors of this chain are analytically represented by the following equations:

- MTF_{MLA}
 - SWIR MLA element treated as a rectangular aperture
 - $p(\xi, \eta) = \text{rect}(x, y)$
 - $\hat{p}(\xi, \eta) = \text{sinc}(\xi \cdot w_{Pixel}, \eta \cdot w_{Pixel}) = \text{OTF}(\xi, \eta)$
 - One dimensional $\rightarrow \hat{p}(\xi) = \text{sinc}(\xi \cdot w_{MLA})$
 - $MTF(\xi) \equiv |\text{OTF}| = |\text{sinc}(\xi \cdot w_{Pixel})|$

$$MTF_{MLA} = \left| \frac{\sin(\pi \cdot \xi \cdot w_{MLA})}{\pi \cdot \xi \cdot w_{MLA}} \right| \quad (6)$$

- MTF_{Filter}
 - Scan velocity is used to translate electrical frequency (f_e) to spatial frequency ξ .
 - $f_e = V_{image} \cdot \xi$
 - $MTF_{Filter}(f_e) = \frac{1}{\sqrt{1 + \left(\frac{V_{image} \cdot \xi}{f_{3dB}}\right)^2}}; \quad MTF_{LPF}(f_e) = \frac{1}{\sqrt{1 + \left(\frac{V_{image} \cdot \xi}{f_{e3dB}}\right)^{2N}}}$
 - Each effective filter in the electronics chain its own MTF contribution (a total of 4 were evaluated for this analysis)
 - Detector 3dB frequency (f_{3dB}) = $\frac{1}{2\pi\tau_d}$
 - $N = \text{Number of Filter Nodes}$
 - Effective 3dB frequency performance of filters and amplifiers = f_{e3dB}
 - Insignificant change in MTF for the OCI system at 3dB frequencies above 25kHz

3.3.4. Along Orbit Track SWIR System MTF

Outside of the optical MTF performance variation over the wavelength range, the along-track MTF performance for the SWIR system has the same primary contributors as the along-track UVNIR system. The OCI optical system has lower MTF performance in the SWIR wavelength range which is what drives the bulk of the difference between the UVNIR and SWIR overall MTF performance. The effect of orbit velocity on the SWIR system does happen to be less of an MTF reduction than the UVNIR as the scene does not need to translate the

same distance but both impacts are so small (due to relatively fast scan speed) that neither has a noticeable impact on system MTF.

4. OCI MTF ANALYSIS

After the development of the four MTF networks to cover the complete OCI imaging system, each contributor was analyzed or modeled over a spatial frequency range twice that of the requirement definition to get a more complete MTF picture. As only a few MTF contributors are affected by the wavelength of the signal, the analysis was simplified by identifying the worst performing wavelengths for input into the analysis. The analysis results are presented as simply MTF versus spatial frequency that has been normalized to the science pixel-based Nyquist frequency. Model uncertainty factors were used to augment the analysis to reduce MTF performance accordingly for contributors that were pure estimations versus well established and understood analytics. Once the baseline analysis was completed, each contributor was assigned a model uncertainty factor based on its maturity and available supporting data. This boosted confidence in the amount of margin that existed against the requirement during instrument development. The final analysis results are shown in the figures below. As instrument development progressed, the analysis was updated accordingly with as-built data to drive Nyquist changes and design parameter-based modeling. Model uncertainty factors were also updated if deemed necessary.

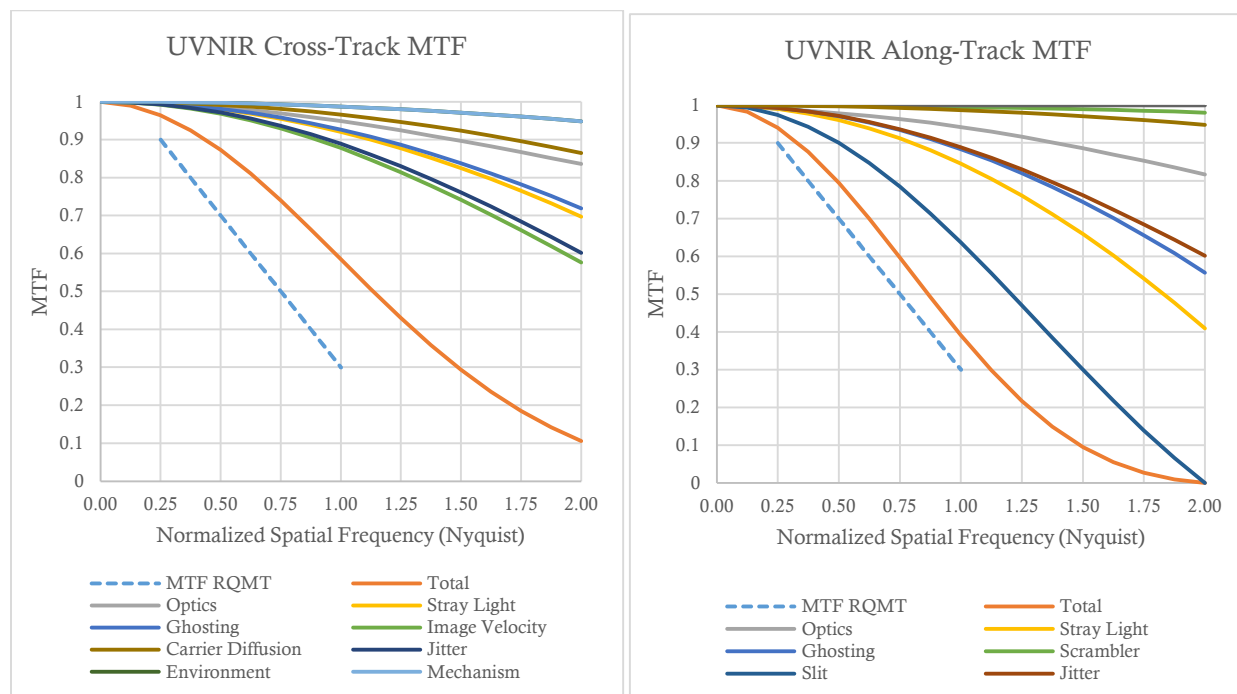


Figure 3. OCI UVNIR MTF Analysis Results

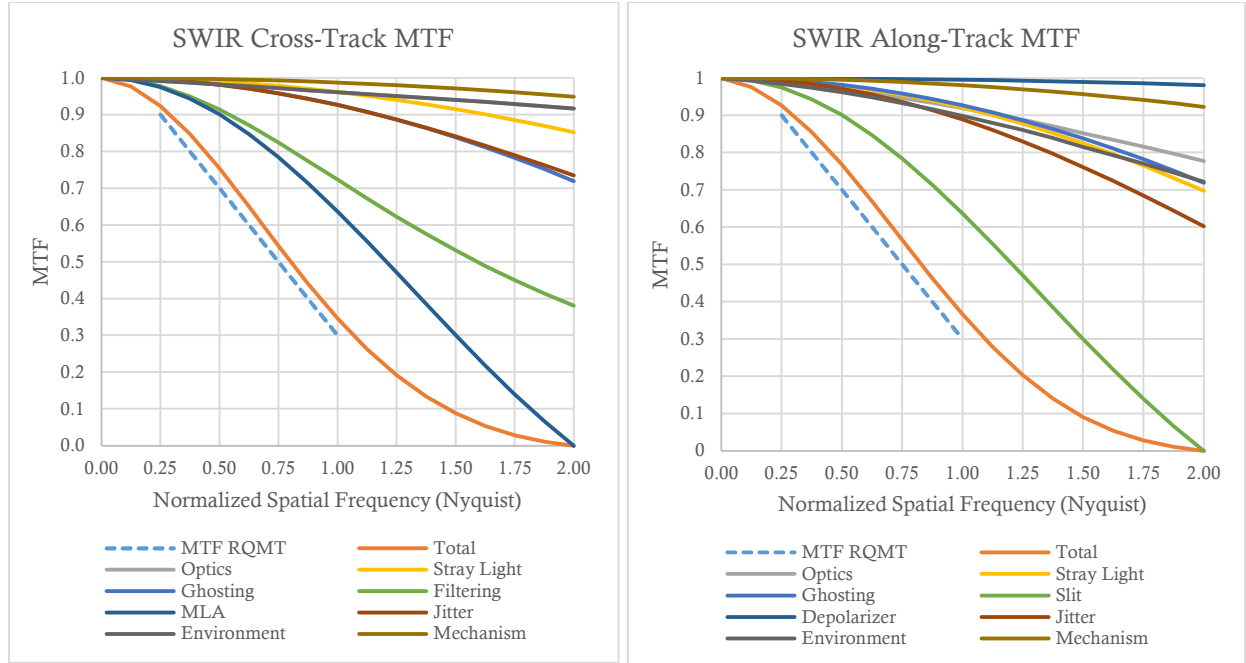


Figure 4. OCI Photodiode Sensor Chain MTF Analysis Results

5. PRE-LAUNCH OCI MTF TESTING RESULTS

Prior to the launch of the PACE mission, OCI went through a comprehensive test campaign including measurement of its line spread function (LSF). Utilizing a collimated image scene and a specialized delay-stepping operational mode (eliminates phase errors between the scene and the detectors, see reference [2]), data was successfully collected to produce an accurate LSF of the instrument. The projected images used during testing are illustrated in Figure 5, cross track MTF was acquired using the Physical Slit Mask and along-track MTF was acquired using the Jitter Evaluation Mask. As seen in the figure, the projected image extends beyond view of the OCI slit which reduces potential issues with manufacturing exact dimension of the mask slit bank on the instrument slit and and/or aligning the image in the along-track direction (any errors may introduce an MTF reduction). The OCI cross-track MTF performance was then derived from the Fourier transform of the straightforward acquisition of the cross-track LSF (for each wavelength band) in this dimension. The along-track LSF was a bit more challenging to acquire as it is difficult to simulate orbit motion accurately in a test environment. The along-track LSF was calculated by evaluating the relationship between the vertical slit and a slanted one of a known angular rotation that were cut into the jitter mask. More complete details on the OCI pre-launch test campaign and setup can be found in reference [3].

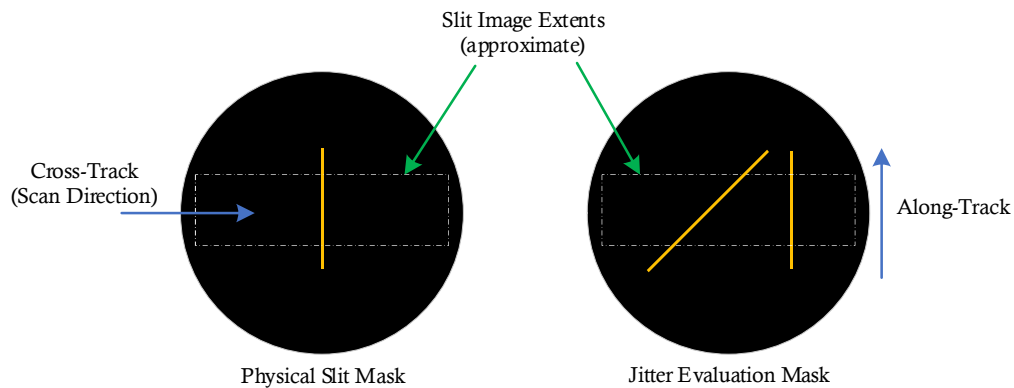


Figure 5. LSF Testing Image Mask Illustrations (not to scale)

During testing, a white light broadband source was the primary light used to produce the scene image, however, there was no significant energy in the lowest wavelength region. This is the reason the performance falls off in the region below 400nm, see Figure 6. These white light tests were augmented by additional testing performed with the Goddard Laser for Absolute Measurement of Radiance (GLAMR) system [10]. Monochromatic light at the wavelengths of 340 nm and 620 nm were used to illuminate the same scene mask to acquire MTF results specific to those wavelengths. The GLAMR results confirm white light results at 620 nm and show that OCI MTF performance below 400 nm is much better than the white light testing would indicate, thus the requirement was met.

LSF testing results are shown for the full wavelength range at the varied Nyquist frequency fractions in Figures 6 and 7.

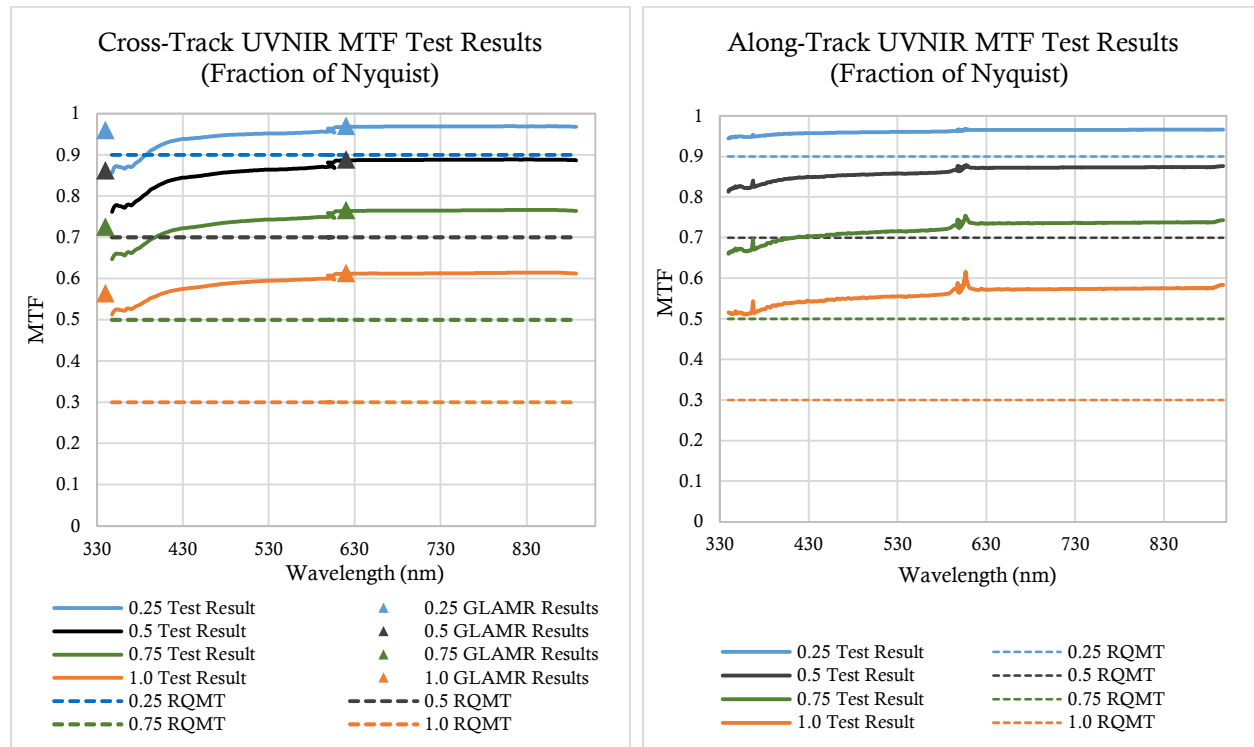


Figure 6. Pre-Launch OCI MTF UVNIR Test Results

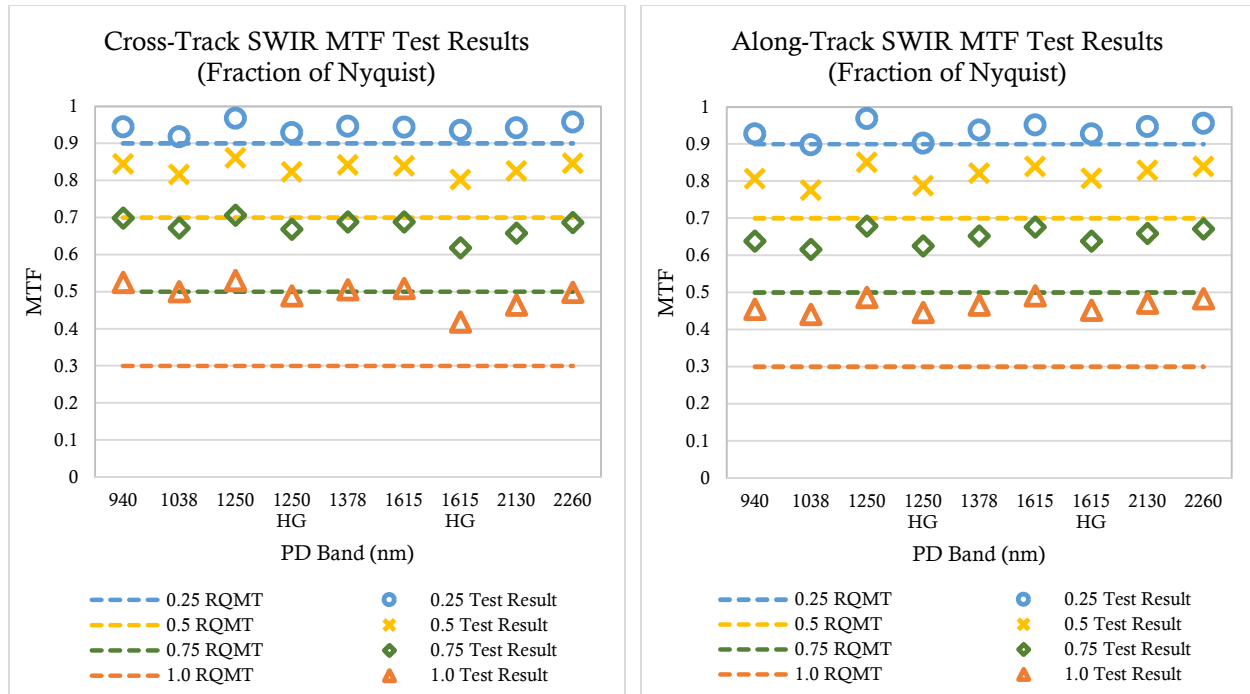


Figure 7. Pre-Launch OCI MTF Photodiode Sensor Chain Test Results

6. COMPARISON OF MTF ANALYSIS AND TEST

In comparing the analysis results with the test results, performance differences are observed primarily in the rate of the reduction as Nyquist is approached. In the case of UVNIR cross-track MTF, the performance is very similar and has a comparable roll off as seen in Figure 8. The UVNIR along-track MTF performance on the other hand shows a much larger disparity between the expected performance and actual performance. Early in development, it was established that MTF requirement verification would be based on an ideal phasing with spatial frequency. This made testing easier and more streamlined, and the specialized mode discussed earlier could be used to remove phase and some alignment sensitivity. A side effect of this is that MTF performance is far less sensitive to apertures in the system as the source and aperture are effectively coaligned. If the analytical pixel (or slit for along-track) MTF is combined with the test result MTF, then the modified value is much closer to the performance predicted by the analysis, see Table 2. This works especially well for the UVNIR system. Looking at the SWIR system performance, it is closer to the analysis but shows more degradation than even the analysis suggests, some wavelength bands end up lower than the specification.

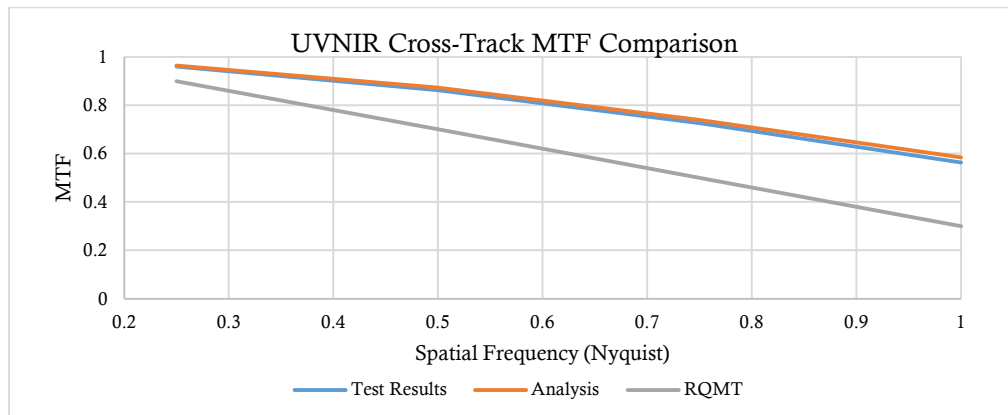


Figure 8. UVNIR Cross-track Comparison Test to Analysis (wavelength average).

Table 2. UVNIR Along-Track MTF Analysis to Test Comparison

		UVNIR Along-Track (Wavelength average)		SWIR Cross-Track (Wavelength average)		SWIR Along-Track (Wavelength average)	
		MTF	% Difference from Analysis	MTF	% Difference from Analysis	MTF	% Difference from Analysis
0.25 Nyquist	Analysis	0.92	-	0.92	-	0.93	-
	Test Results	0.95	3%	0.94	2%	0.94	1%
	Test Results w/ Analytical Pixel Aperture Added	0.94	2%	0.92	-1%	0.91	-2%
0.5 Nyquist	Analysis	0.76	-	0.75	-	0.77	-
	Test Results	0.84	10%	0.83	11%	0.82	7%
	Test Results w/ Analytical Pixel Aperture Added	0.78	2%	0.75	-0.4%	0.74	-4%
0.75 Nyquist	Analysis	0.55	-	0.54	-	0.57	-
	Test Results	0.69	24%	0.68	24%	0.65	15%
	Test Results w/ Analytical Pixel Aperture Added	0.57	2%	0.53	-2%	0.51	-10%
1.0 Nyquist	Analysis	0.35	-	0.35	-	0.37	-
	Test Results	0.53	34%	0.49	43%	0.47	27%
	Test Results w/ Analytical Pixel Aperture Added	0.36	3%	0.31	-9%	0.30	-19%

During instrument testing, the SWIR system exhibited a slow decay response. A detailed description of this behavior is document in reference [4]. Also explained in the aforementioned reference, there is a correction that has been developed to reduce the impact of this response; both the slow decay and the corrected signal are shown in Figure 9. The correction was not yet available during the pre-launch testing effort so the data that was used to produce the MTF values have this error included. This effect is the likely cause for the lower-than-expected values shown in Table 2 (results modified with analytical pixel) but does not impact the on-orbit performance as the correction is now in use for the SWIR bands.

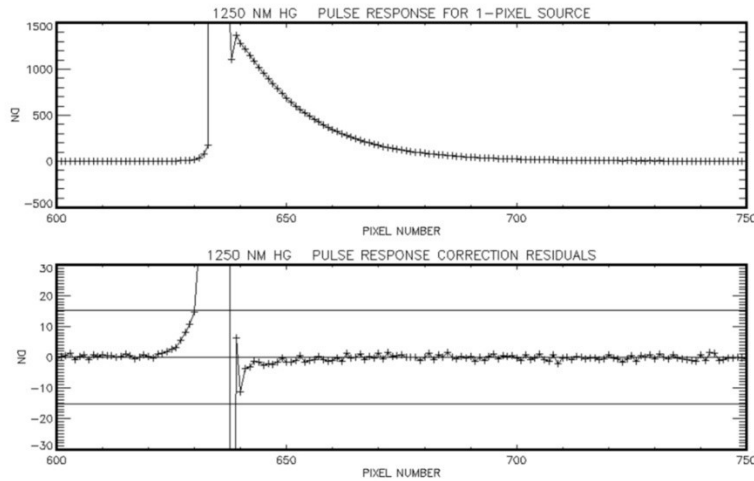


Figure 9. SWIR Long Decay Period and Correction. Figure taken from [4].

7. CONCLUSION

The development of complex instruments can benefit from taking the time to produce an MTF model in the early stages to assist in implementation decisions as the design matures. The identification of primary contributors can help to focus resources and ensure overall system performance. If possible, the execution of

system testing at the conclusion of development provides confidence in the original model and a more robust verification of requirements. Evaluation of the analysis compared with test results can provide insight into the adequacy of test setups and exposure of nuances in instrument data collection.

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