

PACE OCI Short-Wave Infrared Detection Assembly optical system design, alignment, and environmental test

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ABSTRACT

The Ocean Color Instrument (OCI), which will be integrated with the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) satellite, will collect science data that will be used to monitor the health of Earth's oceans and atmosphere. The Short-Wave Infrared (SWIR) Detection Assembly (SDA), built and characterized by Utah State University Space Dynamics Laboratory (SDL), is a subsystem of OCI consisting of 32 channels covering seven discrete optical bands of interest. A total of 16 SWIR Detection Subassemblies (SDSs) compose the SDA and house the cold optical system. The science data optical input for each SDS is supplied by a 0.22 NA multimode fiber interfacing with a fiber adapter. The diverging light from the fiber is collimated, split by a dichroic beamsplitter to two separate channels, filtered by the science filter, and then reimaged onto the single-element detectors with a final 0.76 NA. Aspheric, diamond-turned powered elements are used throughout the optical design. Fabrication and alignment tolerance analysis/budgets are balanced to ensure the optical system meets throughput requirements. All systems are aligned at ambient temperature using an InSb camera and an in-line illumination microscope system to directly image the active detector area through the science filters. Compensators used during alignment are detector focus and decenter, which are adjusted via photo-etched shims in increments of 25 μm . Average focus and centering errors were less than 8 μm among all 32 flight and 10 flight spare detectors. Each SDS spectral response and conversion gain was verified at operational temperature of -65°C in vacuum.

Keywords: OCI, PACE, GSFC, SDL, SWIR, Optical Design, Alignment, Environmental Test

1. INTRODUCTION

This paper details the optical design, alignment, and thermal vacuum test verification of the Goddard Space Flight Center (GSFC) Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Ocean Color Instrument (OCI) Short-Wave Infrared (SWIR) Detection Assembly (SDA). The PACE mission is a strategic data continuity mission that will extend the high-quality ocean ecological, ocean biogeochemical, cloud, and aerosol particle data records begun by NASA in the 1990s. The mission will be capable of collecting radiometric and polarimetry measurements of the ocean and atmosphere, from which these biological, biogeochemical, and physical properties will be determined. PACE data products will not only add to existing critical Earth system records, but also answer new and emerging advanced science questions related to Earth's changing climate ocean and atmosphere interface. The primary instrument on the PACE observatory is the OCI, which is being developed at GSFC. The OCI is a hyper-spectral scanning (HSS) radiometer designed to measure spectral radiances from the ultraviolet to SWIR to enable advanced ocean color and heritage cloud and aerosol particle science. The PACE satellite is planned for launch in January 2024. The PACE project office at NASA GSFC is responsible for the satellite development, launch, and operations.

The SDA, designed, built, and characterized by the Utah State University Space Dynamics Laboratory (SDL), is a subsystem of OCI consisting of 32 channels of science data covering seven discrete optical bands from 940 nm to 2260 nm. The SDA consists of the Aft Optics Box (AOB) that is comprised of sixteen SWIR Detection Subassemblies (SDSs), where each SDS consists of one cold optics assembly and two detector assemblies. Each SDS receives SWIR light from the OCI optical module via a fiber optic within the Micro Lens Assembly (MLA). The main functions of the SDSs are to receive light from the MLA via 16 fiber optic cables, split light from 16 fibers into 32 optical channels, filter the light from the 32 optical channels to isolate the desired wavelength bands, and detect the intensity of light from each of the filtered optical bands (convert photons to electrical signal).

2. OPTICAL DESIGN

Optical system overview

The optical design consists of eight optical elements that collimate, split, filter, and reimage light from a multi-mode optical fiber to a detector. Four optical variants were designed, with a variant covering two science channels. Table 1 provides optical variant information and Figure 1 gives the optical layout. All optical variants are identical except for the optical coatings, the front focal length of the collimator lens, and the back focal length of the last re-imaging optic before the detector.

Table 1. Optical Variants

Optical Variant Number	Center Wavelength (nm)	
	Short Wavelength Band	Long Wavelength Band
1	940	1378
2	1250	1615
3	1038	2130
4	1038	2260

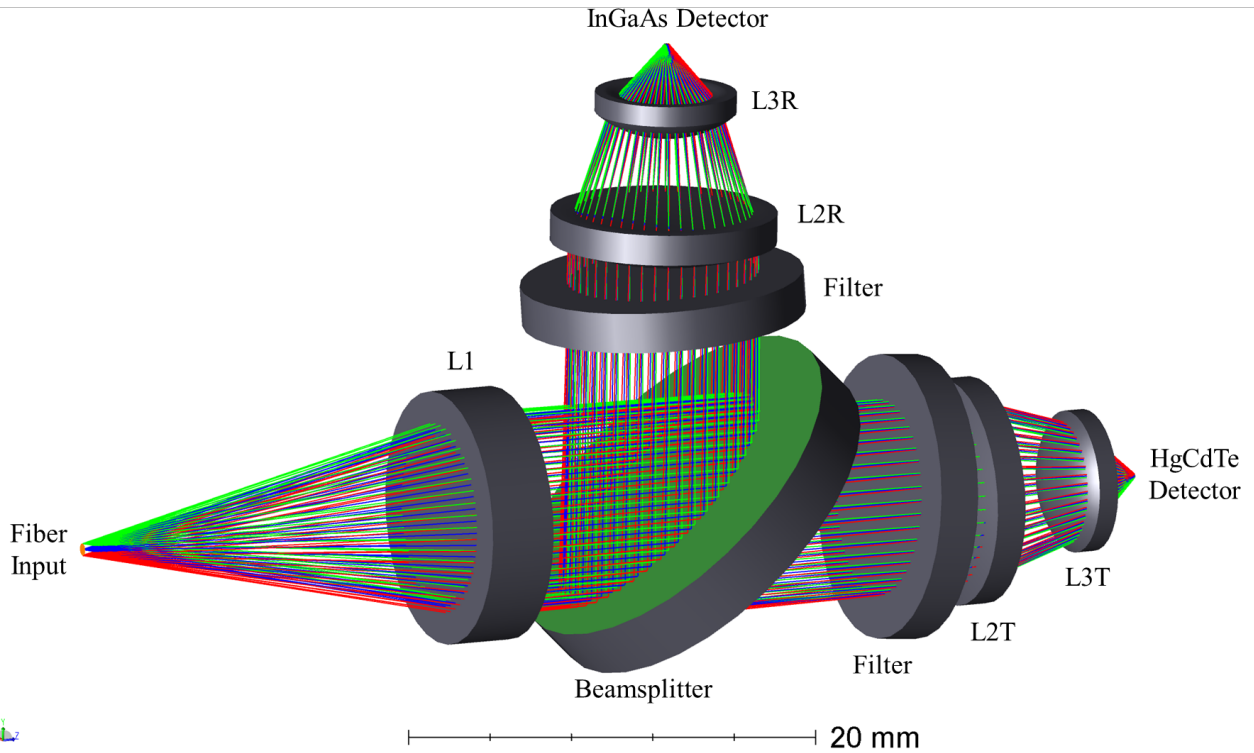


Figure 1. Cold Optics Assembly layout with light propagating left-to-right.

The input multi-mode fiber core diameter of 600 μm is reimaged to a nominal image diameter of 200 μm at the detector, within a total optical path length of less than 58 mm in each channel. The short wavelength band is reflected at the dichroic beamsplitter, while the long wavelength band is transmitted through the dichroic beamsplitter. The multi-layer dielectric bandpass science filters located in collimated space function to pass the bands of interest and block out-of-band light the detectors are sensitive to. Out-of-band rejection ratios requirements range from 0.005 to 0.0075 for the

seven different center wavelengths. A small tilt of the science filter ensures the reflected out-of-band light does not get coupled back into the input fiber. Science filter bandpass full-width half max values range from a low of 15 nm to a high of 75 nm. Zinc sulfide (ZnS) Multispectral and fused silica materials are used in the design, both which have high resistance to radiation darkening². The powered elements are diamond turned aspherical elements while the plano elements are pitch polished. The working F/# at the detector is a fast F/0.76. Specialized photodiodes of indium gallium arsenide (InGaAs) and mercury cadmium telluride (HgCdTe) are used in the system.

Driving requirements

Table 2 gives the driving requirements for the optical design.

Table 2. Driving requirements

Requirement Description	Requirement
Operational Temperature	-65°C +/- 5°C
Hot Survival Temperature	55°C
Cold Survival Temperature	-90°C
Minimum Center Wavelength Transmission	90%
Encircled Energy Diameter	<290 μ m
Pressure	Vacuum

Tolerance analysis

Table 3 gives the most sensitive tolerances of the optical design, where encircled energy diameter is the tolerance analysis criterion. Encircled energy diameter of less than 290 μ m is driven by the physical diameter of the detector active area. Detector defocus and centering were used as compensators during the optical tolerancing process. These same compensators are used during the alignment phase as described in Section 3.

Table 3. Optical design most sensitive tolerances.

Most Sensitive Tolerances			
Tolerance Description	Ranking	Value	Units
Spacing between 1st and 2nd Reimaging Lens	1	± 0.050	mm
Wedge in 2nd Reimaging Lens (ETD)	2	± 0.010	mm
Thickness of 2nd Reimaging Lens	3	± 0.050	mm
Decentering of 1st and 2nd Reimaging Lenses	4	± 0.0127	mm
Thickness of 1st Reimaging Lens	5	± 0.050	mm
Wedge in 1st Reimaging Lens (ETD)	6	± 0.010	mm
Surface Power	7	3.0	fringes ($\lambda = 633$ nm)
Surface Irregularity	8	1.0	fringes ($\lambda = 633$ nm)
Wedge in Collimator Lens (ETD)	9	± 0.010	mm
Thickness of Collimator Lens	10	± 0.050	mm

A full tolerance list was used to construct 1000 Monte Carlo (MC) builds for each center wavelength channel. Figures 2 and 3 show the worst-case encircled energy diameter at the detector from these MC builds. The reflected 1038 nm

channel gave the worst 99.9% encircled energy diameter of 230 μm . This worst-case error still provides 30 μm of radial margin before the focused energy starts to fall off the detector active area. Worst-case transmitted channel 99.9% encircled energy diameter of 216 μm was found on the 1615 nm channel.

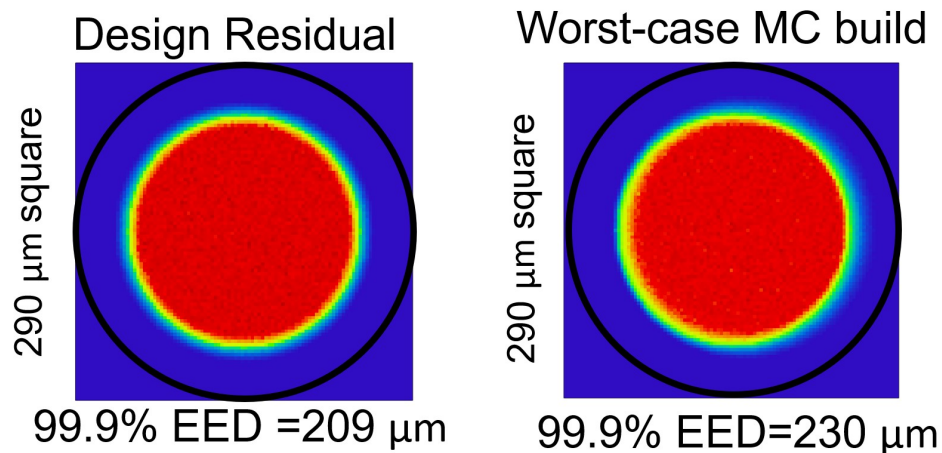


Figure 2. Worst-case encircled energy diameter reflected channel 1038 nm.

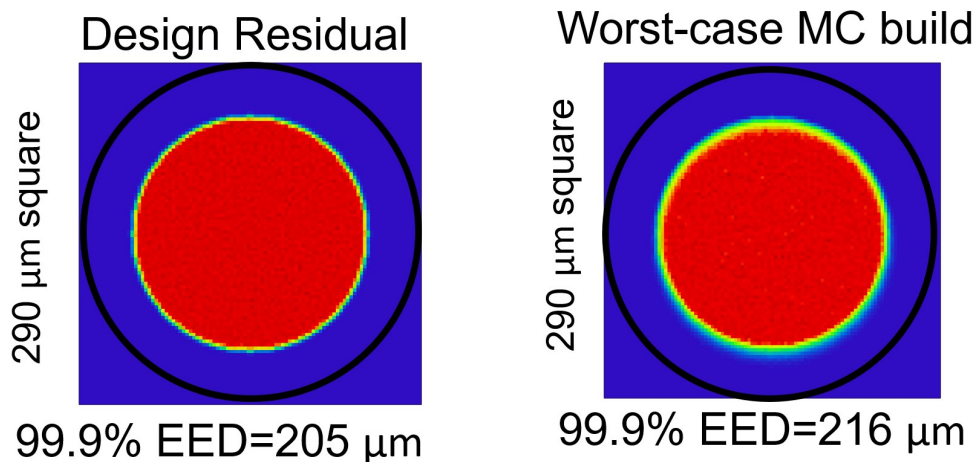


Figure 3. Worst-case encircled energy diameter transmitted channel 1615 nm.

Detector alignment sensitivity

The fast F/0.76 fiber image at the detector makes the optical system sensitive to detector focus position. Centering of the detector to the fiber image is also critical. Large focus and centering errors will cause the fiber image to fall off the detector active area and cause a loss in detected signal. Figure 4 is an analysis of detector defocus combined with a centering error of 8 μm and 15 μm for the worst Monte Carlo build on the 1038 nm channel. A defocus tolerance of ± 40 μm coupled with a 15 μm centering tolerance produces a 0.5% loss in detected signal. The loss in detected signal can be reduced to 0.2% by keeping detector centering errors below 8 μm .

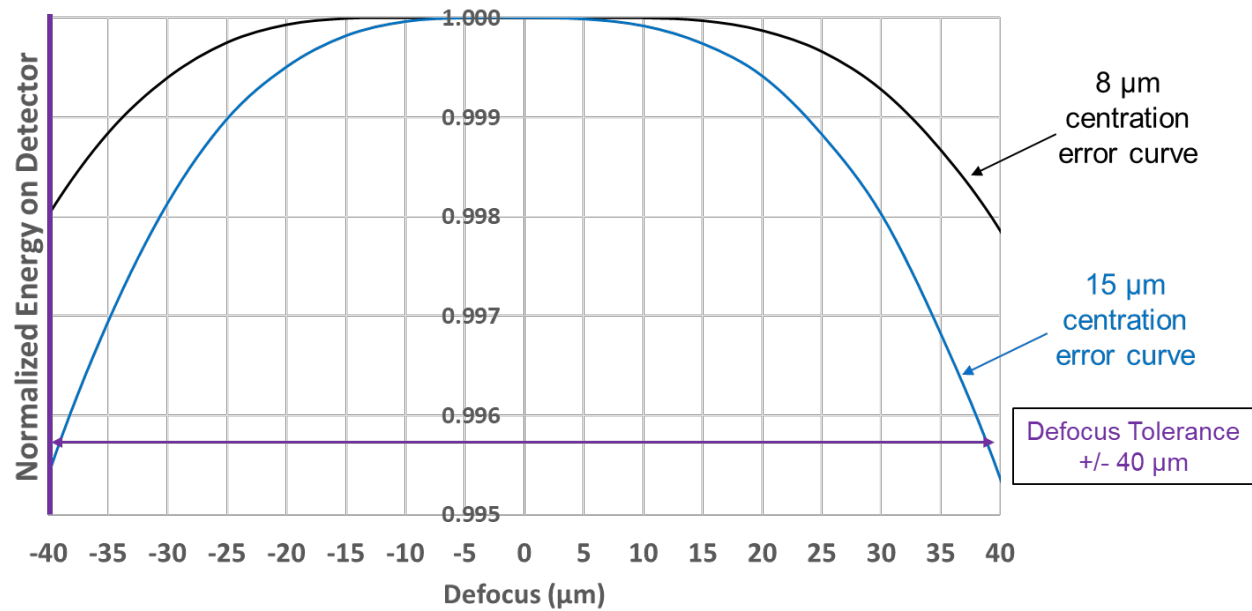


Figure 4. 1038 nm channel MC build detector focus and centering sensitivity.

Environmental focus shift compensation

The optical system operates at -65°C under vacuum but must be aligned at room temperature and ambient pressure. Thermal opto-mechanical modeling indicates the back focus of the optical system increases due to changes in metal lens mount, vacuum air index of refraction, optical element index of refraction, and optical element thickness/radius as the system is subjected to colder temperatures. The longer back focus at colder temperatures is driven by the index of refraction change of the ZnS powered lens elements with temperature (dn/dT). Tables 4 and 5 give the predicted focus shift of each channel over the operational temperature range. These focus shifts are compensated for by defocusing each detector during ambient alignment, using a focus shim 25 μm thicker than the ambient best focus shim.

Table 4. Short wavelength bands focus shift with temperature.

Optical Variant Number	Center Wavelength (nm)	Focus Shift at -70°C (mm)	Focus Shift at -65°C (mm)	Focus Shift at -60°C (mm)
1	940	0.026	0.025	0.023
2	1250	0.025	0.024	0.022
3	1038	0.026	0.024	0.023
4	1038	0.026	0.024	0.023

Table 5. Long wavelength bands focus shift with temperature.

Optical Variant Number	Center Wavelength (nm)	Focus Shift at -70°C (mm)	Focus Shift at -65°C (mm)	Focus Shift at -60°C (mm)
1	1378	0.025	0.023	0.022
2	1615	0.025	0.023	0.022
3	2130	0.024	0.023	0.021
4	2260	0.024	0.023	0.021

Optical performance budget

An optical performance budget was created early in the design phase to ensure that the 90% system transmission could be achieved at each channel center wavelength. The budget includes the following fabrication and alignment parameters:

- Lens transmission
- Dichroic beamsplitter reflectance/transmission
- Bandpass filter transmission
- Scattering due to optic surface roughness
- Detector alignment (focus and centration)
- Contamination

Lens, beamsplitter, and bandpass filter transmission are controlled via thin film coatings. Scatter loss is largest for the shortest wavelength channel at 940 nm. Using the well-known total integrated scatter (TIS) equation¹ ($TIS \approx (4\pi\sigma/\lambda)^2$), the estimated total integrated scatter loss for a single diamond-turned surface with roughness of $\sigma = 30 \text{ \AA}$ RMS at 940 nm is 0.16%. After propagating through six diamond turned surfaces, worst-case scattered light loss at 940 nm could approach 1%. Table 6 gives the optical performance budget for each channel, where each parameter is allocated a transmission value. Peak transmission is calculated by multiplying all the parameters together for a single channel. The budget shows that the requirement can be met but will be challenging at the shorter wavelengths.

Table 6. Optical performance budget

Parameter	940 nm Channel Budget	1038 nm Channel Budget	1250 nm Channel Budget	1378 nm Channel Budget	1615 nm Channel Budget	2130 nm Channel Budget	2260 nm Channel Budget
Thin Film Coatings	0.920	0.920	0.920	0.920	0.920	0.920	0.920
Scatter Loss	0.990	0.992	0.995	0.996	0.997	0.998	0.998
Detector Alignment	0.998	0.998	0.998	0.998	0.998	0.998	0.998
Contamination	0.995	0.995	0.995	0.995	0.995	0.995	0.995
Peak Transmission	0.905	0.906	0.909	0.909	0.911	0.912	0.912

The 0.998 transmission allocation for the detector alignment can be used in conjunction with Figure 4 to determine the allowable combined detector focus and centering errors. For example, a 15 μm centering error allows for a defocus error of up to 30 μm before the 0.998 detector alignment allocation is consumed.

3. OPTICAL ALIGNMENT

SDS opto-mechanics description

Four separate opto-mechanical cells make up the SDS. The lenses, beamsplitter, and filters are centered in their respective cells and then bonded into place using a low outgassing compliant polymeric adhesive. Each cell is bolted to a cubic mechanical housing, which contains the beamsplitter, and then liquid pinned at the interfaces after alignment is complete. Figure 5 shows the opto-mechanical internals of a single SDS.

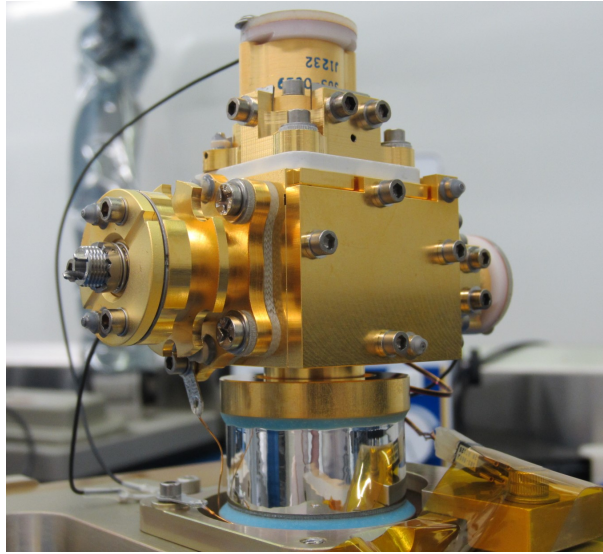


Figure 5. Internals of an SDS.

Compensators

Detector focus and centering is adjusted via five metal shims placed between the detector package and the mechanical cell it bolts to via a semi-kinematic interface. Three shims control detector focus along the optical axis. Two shims at the edges of the detector package control centering in two orthogonal axes. Figures 6 and 7 give detail of the detector shim interface.

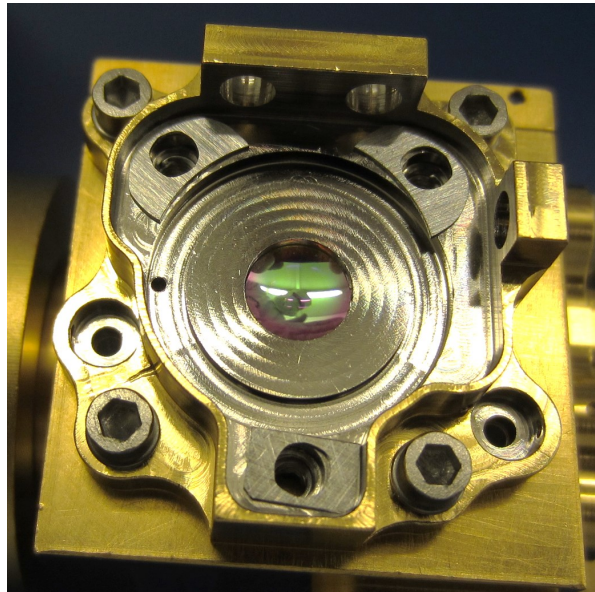


Figure 6. Focus shims installed before detector integration to the opto-mechanical cell.

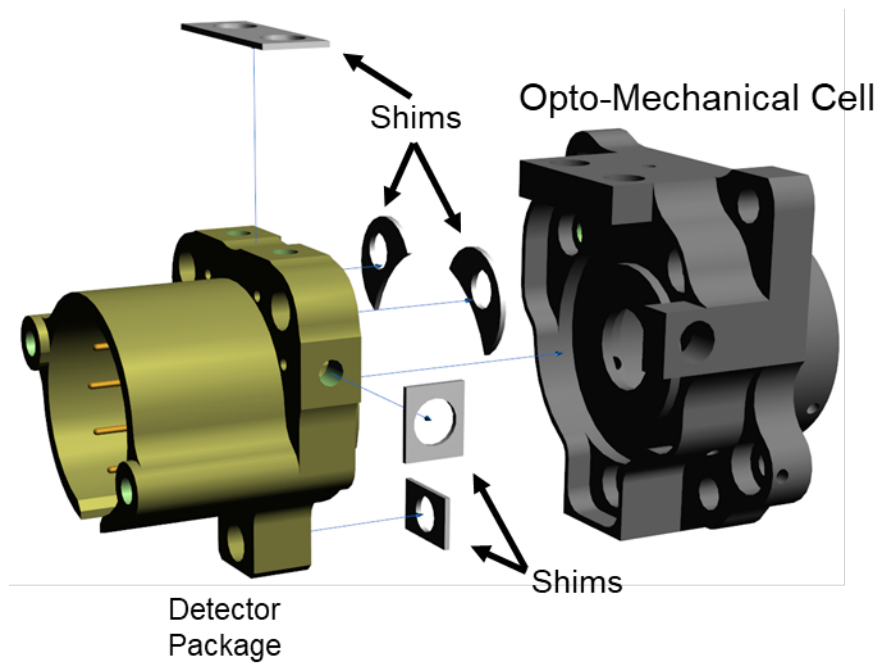


Figure 7. Detector focus and centering shims exploded view.

Alignment measurement and adjustment

Alignment starts with a set of nominal shims installed between the detector and the opto-mechanical cell. The assembly is then mounted to an XYZ translation stage in front of a InSb camera with a microscope objective. The stage allows the SDS fiber adapter port to be centered and focused to the microscope objectives fixed focus. A real-time video display of the InSb output is used during this alignment. Focus and centering errors are measured relative to the fiber adapter port aperture. Focus sensitivity of the test is $2.8\text{ }\mu\text{m}$. For every $25\text{ }\mu\text{m}$ of axial motion of the SDS, the focus at the detector changes by $2.8\text{ }\mu\text{m}$ (nine to one object-to-image space motion). Centering sensitivity of the test is $2.4\text{ }\mu\text{m}$. A total of 140 pixels of the InSb camera cover the fiber adapter port diameter of 1 mm. This 1 mm diameter is mapped to $333\text{ }\mu\text{m}$ at the detector. Dividing that dimension by the 140 pixels gives an InSb camera single pixel dimension of $2.4\text{ }\mu\text{m}$ at the SDS detector. Filtered in-line illumination light is injected into the InSb camera path via a fiber collimator and beamsplitter, allowing a single detector channel to be aligned at a time. Figure 8 shows the alignment test setup in one of SDL's ISO 5 cleanrooms, where humidity and electrostatic discharge controls are also in place.

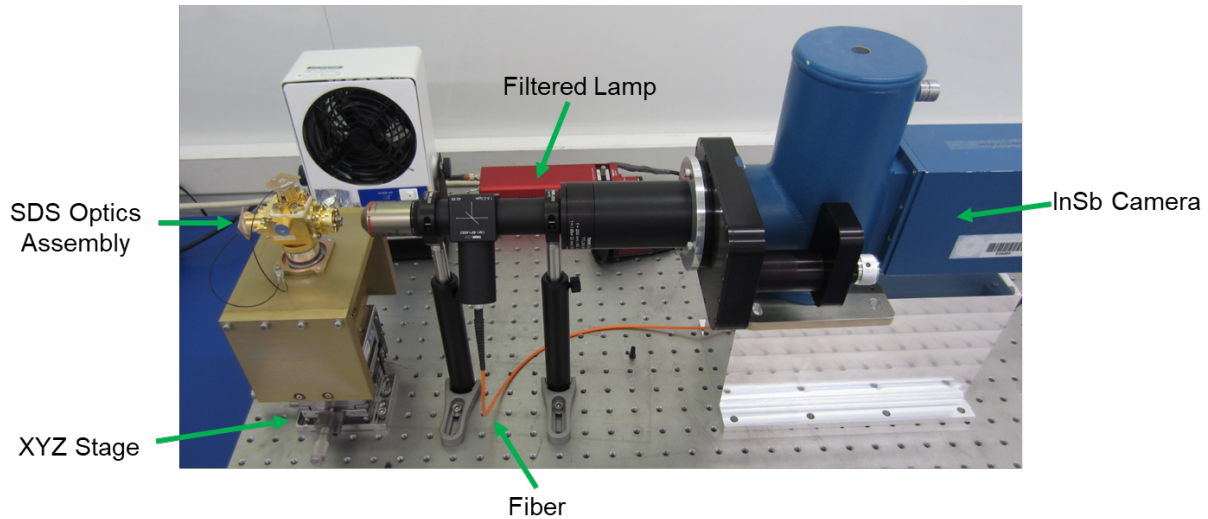


Figure 8. SDS optical assembly alignment test setup.

The initial detector alignments using nominal shim values often showed a misaligned detector. Figure 9 shows a large initial decenter error of $77\text{ }\mu\text{m}$ with the alignment camera focused on the fiber adapter port. Detector focus error was measured to be $31\text{ }\mu\text{m}$ in this case.

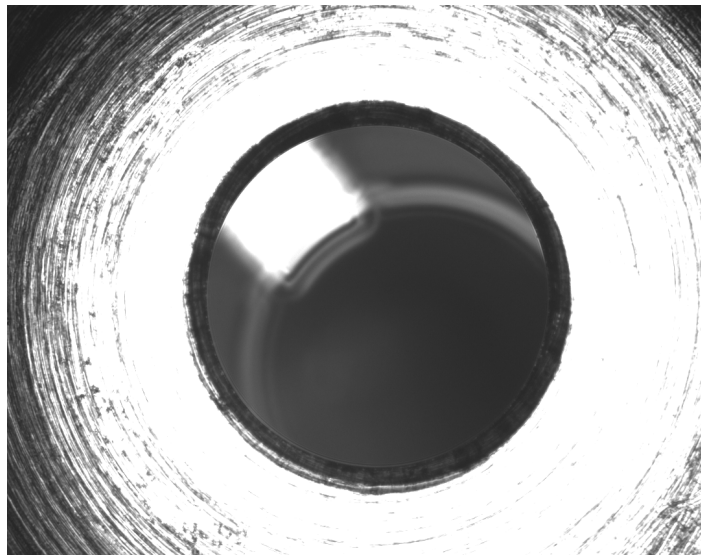


Figure 9. Large initial decenter error of $77\text{ }\mu\text{m}$ and focus error of $31\text{ }\mu\text{m}$ with alignment camera focused on fiber interface.

After determining the detector focus and centering errors, the alignment shims were swapped out for ones to bring the detector into alignment. A few iterations were often necessary to find the optimal focus. Ambient best focus would have the detector and fiber port adapter images both in focus. Due to the environmental focus shift, a $25\text{ }\mu\text{m}$ thicker focus shim is installed at this point to ensure optimal focus under vacuum and operational temperatures. Figure 10 shows a final aligned detector centered to within $3\text{ }\mu\text{m}$ of the fiber port adapter. Focus error was measured to be $12\text{ }\mu\text{m}$ in this case.

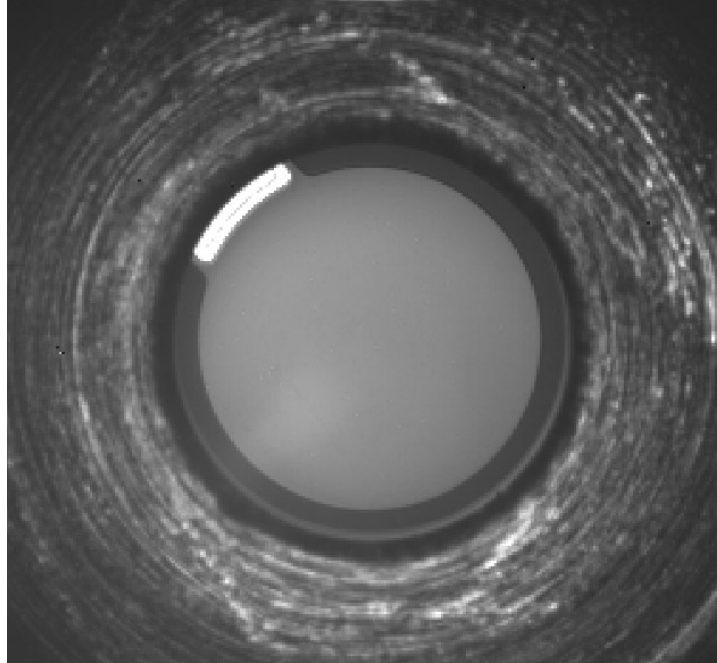


Figure 10. Detector focused within 12 μm and centered within 3 μm with alignment camera focused on the detector.

Figure 11 gives the ambient focus errors measured for the 21 SDSs (42 channels) aligned at SDL. Average detector focus error was 7 μm . These focus errors are relative to the predicted vacuum focus (25 μm offset from ambient best focus). Average centration error among the 42 channels was 10 μm .

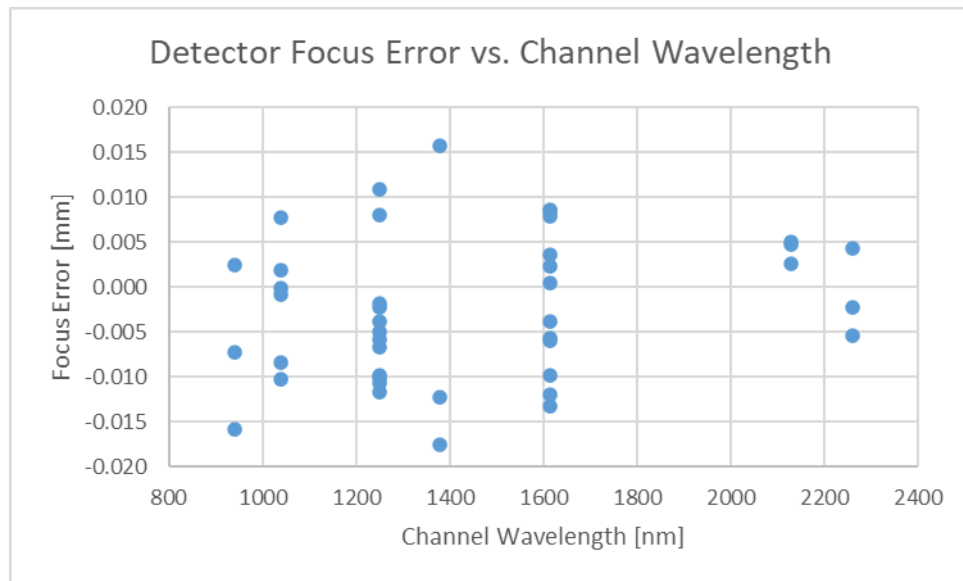


Figure 11. As-aligned ambient detector focus errors.

4. THERMAL VACUUM TEST ALIGNMENT VERIFICATION

Thermal vacuum test equipment description

After integration of the front-end electronics with the cold optics and detector assemblies, each SDS was tested at operational temperature and vacuum pressure in a small vacuum chamber. A vacuum fiber feedthrough attached to the chamber allows for light to be injected into each unit under test. The fiber optic interfaces with an ambient calibrated integrating sphere, allowing for known radiances to be input into the fiber and to the unit under test. Each SDS spectral response and conversion gain was verified at operational temperature of -65°C in vacuum. Figure 12 shows the thermal vacuum test chamber developed specifically for the program. Figure 13 shows the integrating sphere and external components used for relative spectral response (RSR) and conversion gain/absolute responsivity measurements. The setup includes a calibrated quartz tungsten halogen (QTH) lamp with a variable aperture attenuator (VAA) for adjusting light levels. A Fourier transform spectrometer (FTS) is input into the integrating sphere for RSR testing. Other light sources are also shown attached to the integrating sphere for linearity and frequency response testing.

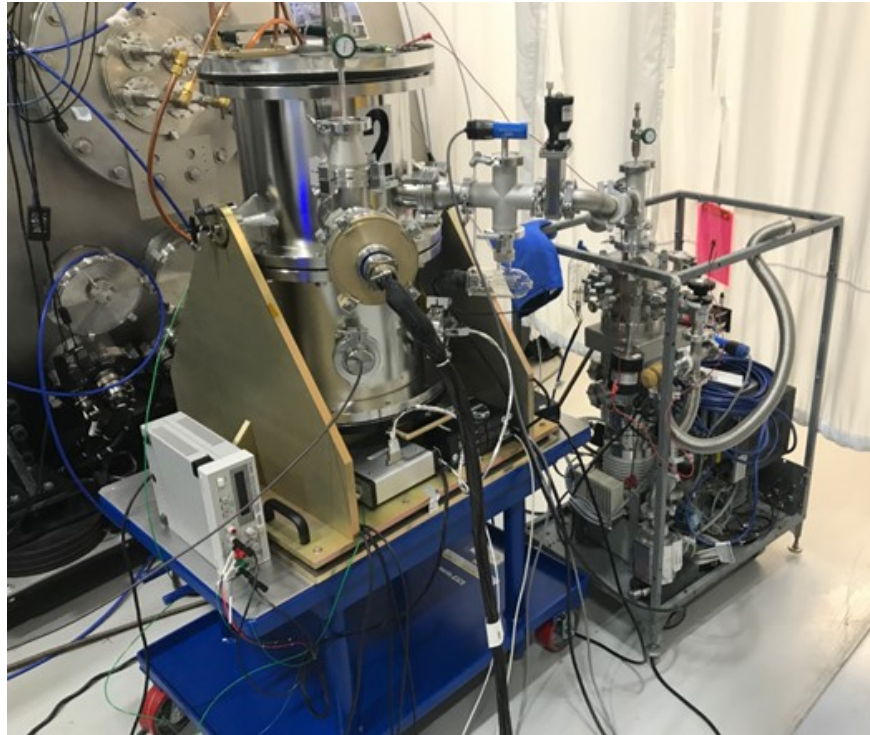


Figure 12. SDS thermal vacuum test chamber.

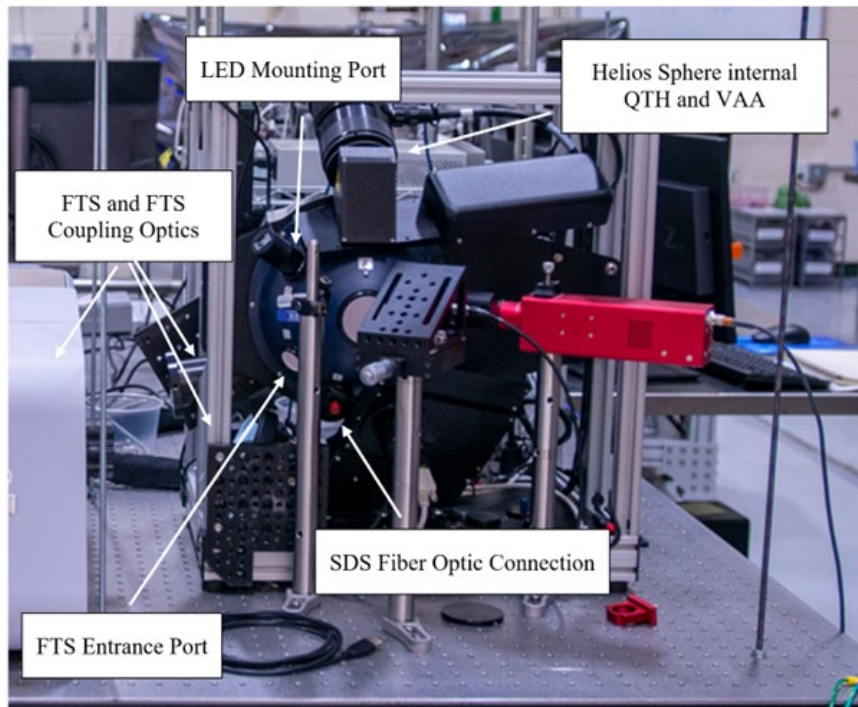


Figure 13. Integrating sphere and external components for spectral response and conversion gain measurements.

Figures 14 and 15 show sample RSR measurement data for a 940 nm detector channel.

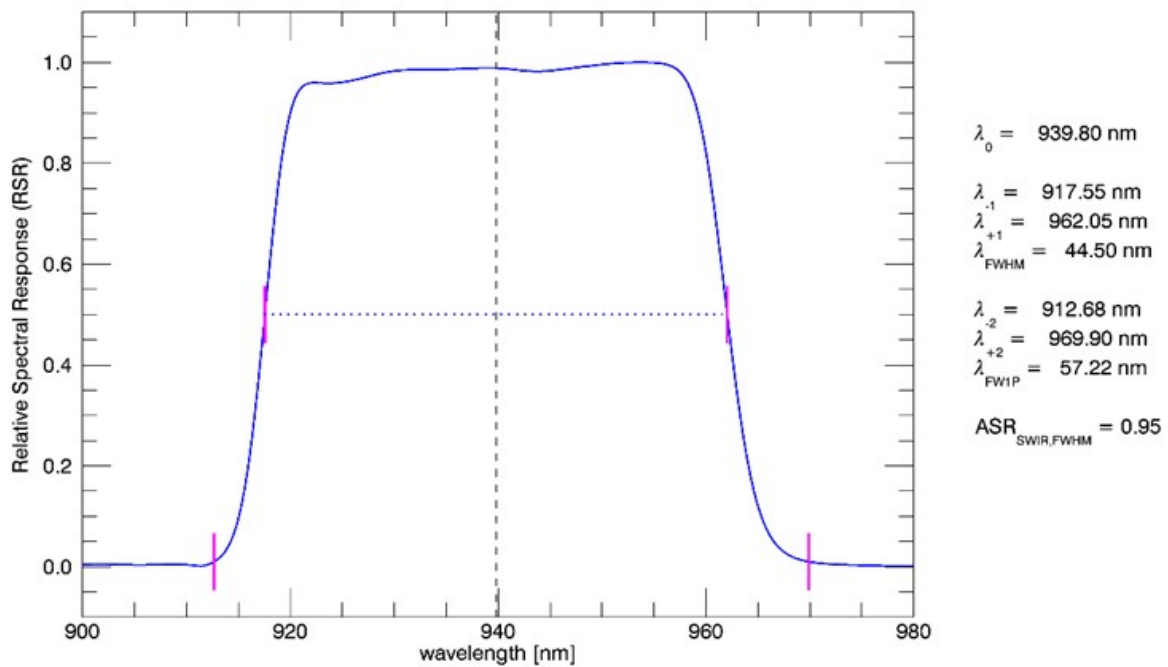


Figure 14. In-band RSR measurement results demonstrate system-level requirements compliance.

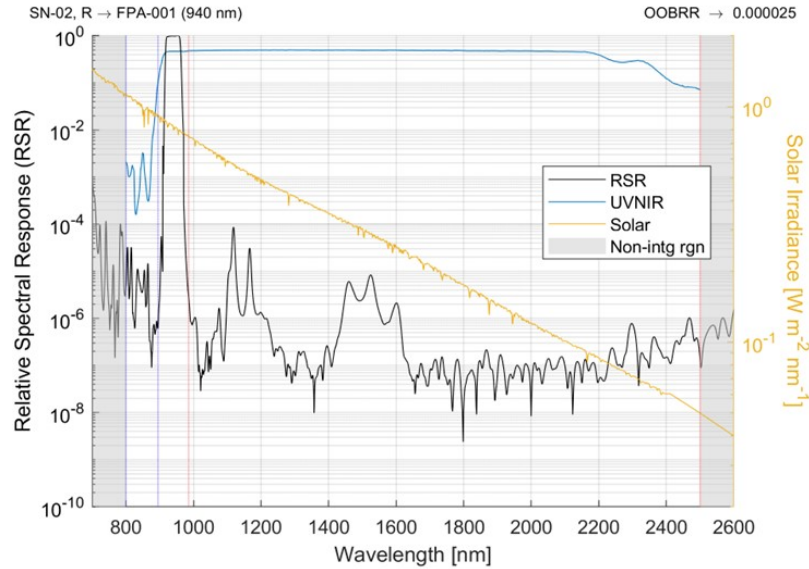


Figure 15. Out-of-band RSR data used for out-of-band rejection ratio calculations.

Conversion gain verification

Each SDS has a range of conversion gain requirements the final assembled unit must meet at operational temperature and vacuum pressure. Conversion gain is sensitive to detector focus and centering errors. If light is lost due to misalignments at operational temperature, the conversion gain measured will come in lower than expected. The 940 nm channel has a conversion gain requirement range from 26.87 V/ μW to 39.75 V/ μW . RSR measurement data along with test fiber optic transmission and integrating sphere spectral radiance was used to calculate in-band power injected into an SDS. The integrating sphere light source was ramped through the dynamic range of the detector, and the detector output response was measured. Figures 16 and 17 show sample data measured on a 940 nm detector channel. An average conversion gain of 30.08 V/ μW was measured, which meets requirements. Similar tests were completed for all the flight SDS units and were shown to meet conversion gain requirements and thus verified the optical alignments.

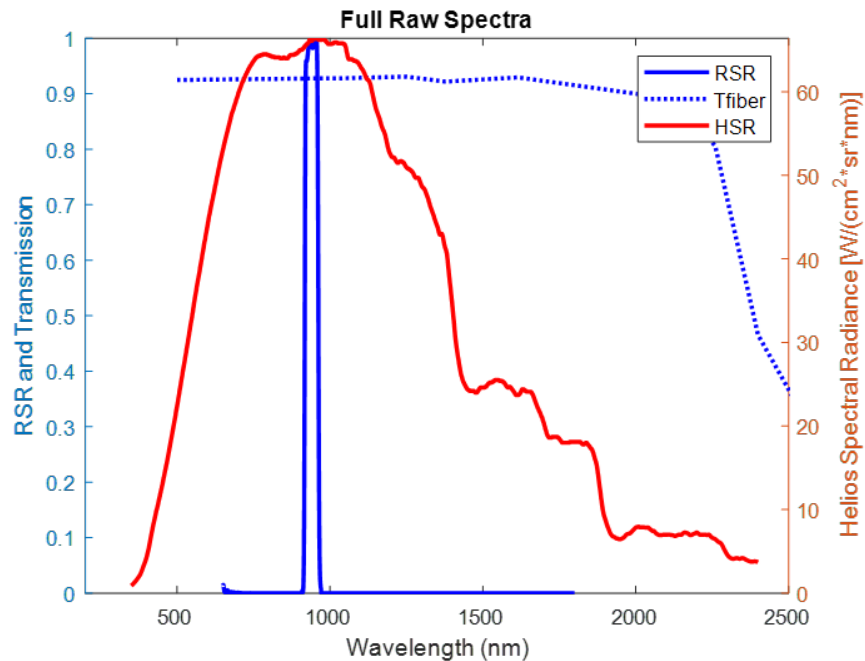


Figure 16. 940 nm SDS in-band power computed from RSR data, test fiber transmission, and Helios integrating sphere spectral radiance (HSR).

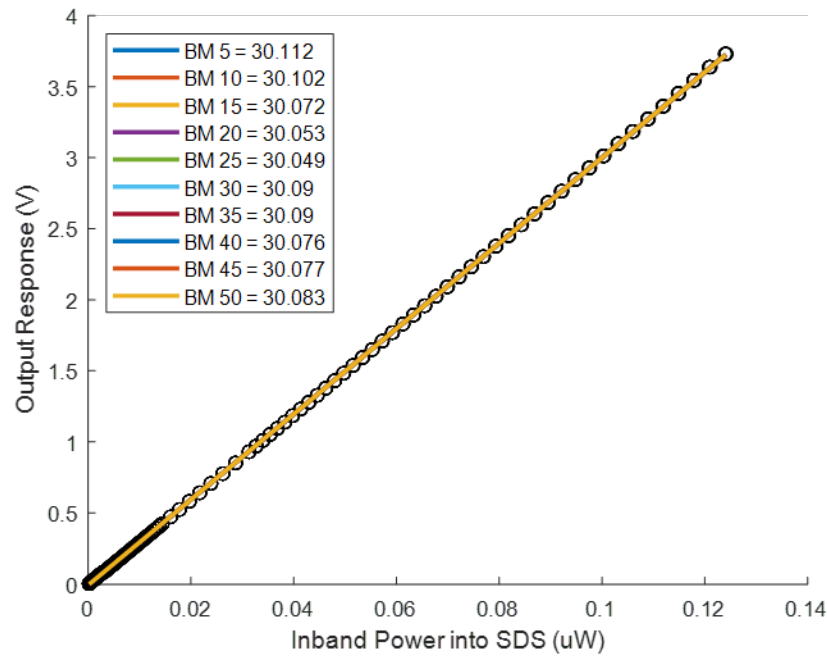


Figure 17. 940 nm conversion gain computed from slope of output response vs. SDS in-band input power.

5. CONCLUSION

Upon completion of the individual SDS thermal vacuum alignment verifications, the units were integrated into the top-level SDA at SDL. A full environmental test campaign was successfully completed at SDL before delivery to GSFC in July 2021. The SDA was integrated with the OCI instrument December 2021 and has been performing nominally.

6. ACKNOWLEDGEMENTS

The design, assembly, integration, and test of the SWIR SDA was a collaborative effort between SDL and GSFC. The SDL team would like to thank the NASA GSFC OCI team for their knowledge and support through the entire program.

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