Fabrication and Assembly Integration of the Orbiting Carbon Observatory Instrument

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ABSTRACT

Final assembly and integration of the Orbiting Carbon Observatory instrument at the Jet Propulsion Laboratory in Pasadena, California is now complete. The instrument was shipped to Orbital Sciences Corporation in March of this year for integration with the spacecraft. This observatory will measure carbon dioxide and molecular oxygen absorption to retrieve the total column carbon dioxide from a low Earth orbit. An overview of the design-driving science requirements is presented. This paper then reviews some of the key challenges encountered in the development of the sensor. Diffraction grating technology, lens assembly performance assessment, optical bench design for manufacture, optical alignment and other issues specific to scene-coupled high-resolution grating spectrometers for this difficult science retrieval are discussed.

Keywords: Carbon dioxide, global warming, grating spectrometer, hyperspectral sensor

1. INTRODUCTION

The Orbiting Carbon Observatory (OCO) is a NASA Earth System Science Pathfinder (ESSP) mission that will measure the distribution of carbon dioxide (CO_2), the principal man-made greenhouse gas. OCO will do this with high accuracy and precision to improve our understanding of the sources and sinks of CO_2. The Jet Propulsion Laboratory (JPL) is leading the mission. Orbital Sciences Corporation (OSC) is supplying the spacecraft and the launch vehicle. Hamilton Sundstrand is responsible for the design of the Primary Instrument Assembly (PIA) and delivery of the instrument flight hardware. Delivery of the flight hardware to JPL started in the fourth quarter of 2006 and continued through the end of the second quarter of 2007. Hamilton Sundstrand developed a unique optical system design and alignment methodology for the OCO instrument and built an optical breadboard for demonstration in the second quarter of 2002. The demonstration results of the Oxygen A-Band spectrometer breadboard were presented in the SPIE conference on Infrared Spaceborne Remote Sensing X in Seattle, Washington, 10-11 July 2002[1]. At present, the Hamilton Sundstrand instrument team continues to support the instrument during spacecraft integration and test. The instrument, delivered to OSC in March of 2008 for integration with the spacecraft, is scheduled for a January 2009 launch from Vandenburg AFB, California atop a Taurus XL launch vehicle.

An overview of the mission requirements is discussed along with several highlights during the development, design and manufacture of the instrument.

2. MISSION OVERVIEW

Carbon dioxide (CO_2) is the principal human-made greenhouse gas and the primary atmospheric component of the global carbon cycle. Precise ground-based measurements of CO_2 made since the late 1950s indicate that the atmospheric CO_2 concentration has increased from ~310 to over 380 parts per million (ppm) over this period. Interestingly, comparisons of these data with CO_2 emission rates from fossil fuel combustion, biomass burning, and other human activities indicate that only about half of the CO_2 that has been emitted into the atmosphere during this period has remained there. The rest has apparently been absorbed by surface "sinks" in the land biosphere or oceans[2]. These measurements also show that despite the steady long-term growth in atmospheric CO_2 abundance, the atmospheric CO_2 buildup varies dramatically from year to year in response to smoothly increasing emission rates. The ground-based CO_2 monitoring network does not have the spatial resolution, coverage or sampling rates needed to identify the natural CO_2 sinks, nor the processes and conditions that control how their efficiency changes from year to year.

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NASA's OCO is currently being developed to address these issues[3]; it will make space-based measurements of atmospheric CO_2 with the precision, resolution and coverage needed to characterize the geographic distribution of CO_2 sources and sinks and quantify their variability over the seasonal cycle**.** The Observatory is scheduled for a January 2009 launch from Vandenberg Air Force Base in California on a Taurus XL launch vehicle. During its two-year nominal mission, OCO will fly in a circular, 705 km-altitude, near-polar, sun synchronous orbit providing global coverage of the sunlit hemisphere with a 16-day ground-track repeat cycle. The observatory carries a single instrument designed to measure the absorption of reflected sunlight by CO_2 and molecular oxygen (O_2) at near infrared wavelengths. Bore-sighted spectroscopic measurements of the CO_2 and O_2 column abundance will be analyzed to retrieve spatial variations in the column-averaged CO_2 dry air mole fraction, X_{CO2}. Because X_{CO2} typically varies by only ~2% from pole to pole, CO_2 sources and sinks must be inferred from subtle spatial variations in this quantity. A sensitive, stable instrument and a comprehensive ground-based validation network are therefore being implemented to ensure that the X_{CO2} measurements have random errors and systematic biases no larger than 0.3-0.5% on regional scales. These measurements are expected to improve our understanding of the nature and processes that regulate atmospheric $CO_{2;}$ enabling more reliable forecasts of CO_2 buildup and its impact on climate change.

3. PRIMARY INSTRUMENT ASSEMBLY

The science instrument for OCO is imbedded inside, rather than bolted on, the spacecraft. Structural and thermal considerations led to the decision to separate various parts of the instrument into subassemblies with different mechanical and thermal interfaces to the spacecraft. For instance, the analog electronics enjoy tight thermal control provided by variable conductance heat-pipes, while the digital electronics are mounted directly to a spacecraft panel and see much wider temperature variations. The largest part of the instrument is named the Primary Instrument Assembly (PIA), shown in figures 1 and 2. This assembly contains the majority of the instrument mass. Sitting in the heart of the PIA is the Optical Bench Assembly (OBA). The OBA is suspended inside a hole in a large deck that forms the structural interface between the spacecraft and instrument. The OBA is mounted on three titanium flexures to provide a kinematic mount and thermal isolation. Also mounted on the deck is a thermal shroud that surrounds the OBA. This shroud is also connected to variable conductance heat pipes that are regulated to provide a constant -5^{o} C optics temperature throughout the mission life.

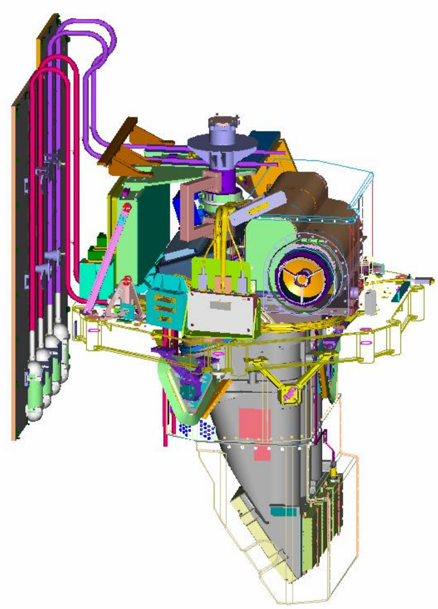

Fig. 1.The OCO Primary Instrument Assembly (PIA). The thermal shroud and instrument deck are transparent to view the internal optical bench. The heat rejection radiators and connecting heat pipes on the left of the view are the only PIA components external to the spacecraft. The telescope views the Earth through an opening in the side of the spacecraft.

Fig. 2. The OCO Instrument Assembly in the JPL High Bay. The complete Optical Bench Assembly, with mid-thermal shroud section attached, is shown. The entrance telescope is pointing toward the control room window (left). Image credit NASA/JPL.

4. OPTICAL BENCH ASSEMBLY

The OBA design incorporates three high-resolution grating spectrometers to measure two carbon dioxide absorption bands centered at 1.61 μm and 2.06 μm in the near infrared region of the spectrum and the oxygen a-band centered at 0.76 μm. Only a brief description of the optical design is given here since it has already been reported in the literature [4]. The three spectrometers share a common view of the scene through a single all-reflective telescope re-collimator assembly coupled with a dichroic relay system. The collimated light passing through the relay is thus separated and then re-imaged onto the spectrometer entrance slits using a novel inverse Newtonian re-imager. The Optical Bench Assembly and alignment was completed in July of 2007. Figure 3 shows the assembly in its handling fixture. Assembly work then started on the integrated optical bench, which adds the focal plane assemblies (part of the cryogenic subsystem or CSS), the thermal control system for the optical bench, a remote electronics assembly, and other subsystem hardware. Alignment and focus of the detectors was performed during thermal vacuum alignment in August 2007.

5. CHALLENGES

5.1 Optical bench housing manufacture

The finished machined optical bench housing, pictured in figure 4, is mounted in the so-called “bear cage” handling fixture at Hamilton Sundstrand’s Long Beach, California facility. The bear cage functions as the primary metering structure for the instrument optics, maintaining the spectrometer collimator, grating and camera subassemblies in precise alignment with the relay optics. The optical bench housing serves as the metrology base from which the relay and telescope sub-assemblies are assembled and aligned. The optical bench structure must maintain this critical alignment for proper co-registration of the telescopic scene view onto the spectrometer entrance slits, throughout all environments including ground environmental test, integration with the spacecraft, the launch phase and on-orbit operation.

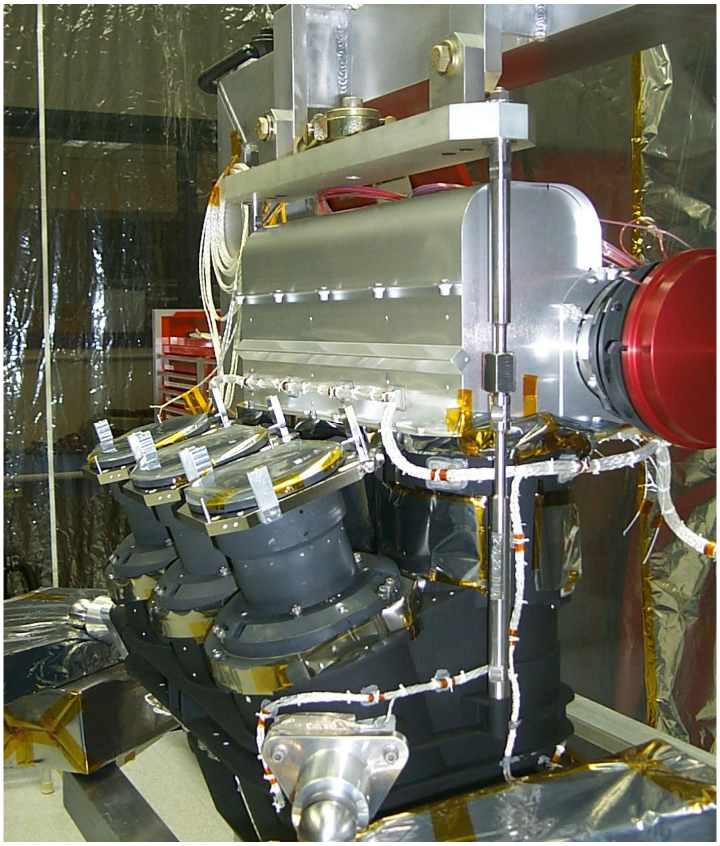

Fig. 3. Showing assembled optical bench in the area of the telescope. A tooling cover (red) is covering the telescope aperture at the right center of the picture. A temporary relay shroud (bright aluminum piece behind the telescope) will be replaced with flight hardware after the focal planes are aligned and focused. The flight detector assemblies attach to the three-camera lens exit flanges at the lower left. Image credit NASA/JPL.

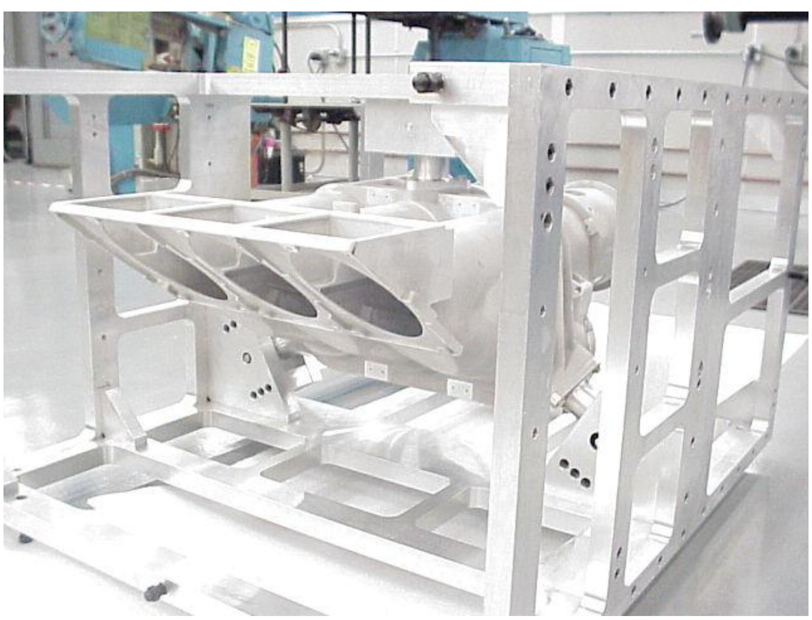

Fig. 4. The flight spare optical bench housing mounted in the bench assembly/alignment fixture during a check fit at the Hamilton Sundstrand facility in Long Beach, CA.

The optical bench is uniformly cooled to limit excessive thermal radiation to meet stringent scattered light and signal-to-noise requirements. These and other requirements, combined with the very limited space in the interior of the spacecraft, resulted in the selection of a lightweight complex monolithic aluminum structure. The approach for manufacturing the complex bench structure and the events that followed proved to be quite challenging. A detailed trade study performed during the preliminary design effort considered machining the monolithic housing out of a solid aluminum billet or as a machined investment casting. The latter approach was chosen because it appeared to pose the least schedule risk. During the detailed design phase, the team worked closely with the investment casting vendor’s engineering staff to achieve the original design intent. This process was iterative and when the final revision to the casting drawing was incorporated and production started, the allocated schedule reserve was exhausted. In hindsight the expected improvement in turnaround time for the casting technique versus machining a massive bullet would have been nil. The lesson learned is that investment castings can pose significant schedule and cost risk even when things go correctly. One might expect some guarantee from the vendor that the delivered part would be to print. However, in practice, every failed casting attempt along the way is still a cost to the project. Paying close attention to the vendor's engineering staff led to delays in getting the documentation finalized, it was the right decision because two acceptable castings were produced on the first attempt. The first casting was used as a setup part for subsequent machining operations, fixture check fits, and acted as a flight spare. The second casting is now part of the flight assembly, figure 5.

Fig. 5. Flight optical bench housing with collimator and camera lens assemblies aligned and pinned in place. The spectrometer diffraction gratings are under the black cover at the bottom of the bench. Image credit NASA/JPL.

5.2 Baffle calibration subsystem

The baffle/calibration subsystem, figure 6, provides three modes of operation for the OCO instrument: direct scene viewing through a stray light baffle, viewing through a solar diffuser that is rotated in place, or viewing internal calibration lamps when a cover in rotated in place. It was apparent that no single ground test would be sufficient to verify the baffle performance in all modes of operation, and alternate methods were pursued, including qualification by analysis. Figure 6 is a screen dump of the baffle/calibration model, developed for this purpose, to simulate the stray light performance of the baffle/calibration subsystem. The TracePro program, (Lambda Research Corporation) uses a Monte Carlo algorithm to trace many rays. In these simulations, typically over half a million rays were traced from the source to get an acceptable number of scatter rays reaching the telescope field baffle. Each run took four-to-six hours of computer time. The simulations were repeated many times at different solar angles to the instrument boresight. In most cases Bi-Directional Reflectance Distribution (BRDF) measurements of the manufactured flight hardware, or coupons finished per the flight hardware processes, were incorporated in the simulation models. This is the qualification approach taken for the OCO baffle calibration assembly.

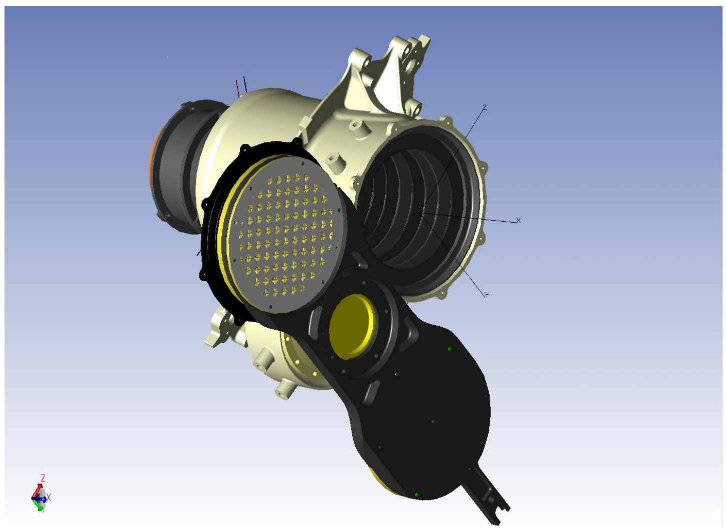

Fig 6. The OCO instrument baffle calibration assembly stray light analysis model. The calibration paddle is shown in the normal science mode with the aperture open. Rotation of the paddle 90 degrees clockwise places the instrument in the solar calibration mode.

The primary baffle design selected for the OCO baffle is a classic straight-vane design. More complex baffle designs were considered, such as designs that use ellipsoidal surfaces to reflect the entrance pupil, but in order to reduce cost and minimize schedule impact, only the simplest design was chosen to move forward. The results of several runs of the simulation model of the OCO baffle/calibration system quantifies the scattered irradiance at the telescope focus (the field baffle aperture) is at least four orders of magnitude down at all angles outside of the field of view as is shown in the figure 7 plot. When the relay optics are added to the simulation model the stray radiation incident to the spectrometer entrance slit at 0.1 degrees outside the field of view is predicted to be 1×10^{-7}.

Similar analyses of the OCO all-reflective transmission diffuser for in-flight solar calibration were performed. These results and a transmission test of the flight diffuser were compared. The simulations predict a lower-that-optimal transmission in agreement with the transmission tests preformed at JPL. However, rather than re-manufacture the hardware the project is going forward and accepting the as-built performance.

The third mode of operation involves rotating an opaque cover over the telescope aperture. This cover protects the optical system during launch and during on-orbit propulsion maneuvers. It is also closed to support two on-orbit calibration operations. First, dark frames taken with the cover closed are used to take dark frames to estimate the instrument bias. Second, a set of three calibration lamps in the shadow of the telescope secondary can be used to illuminate a diffuse surface on the inside of the cover to provide "flat fields" that are used to monitor optical throughput and detector gain variations.. This cover surface was roughened by vapor grit blasting technique to achieve a diffuse but adjustable surface. Measurements showed that the combination of the lamps and the diffuse surface provided only about half the optimal light level, but once again, this performance was accepted, rather than modifying the lamps or diffuse surface.

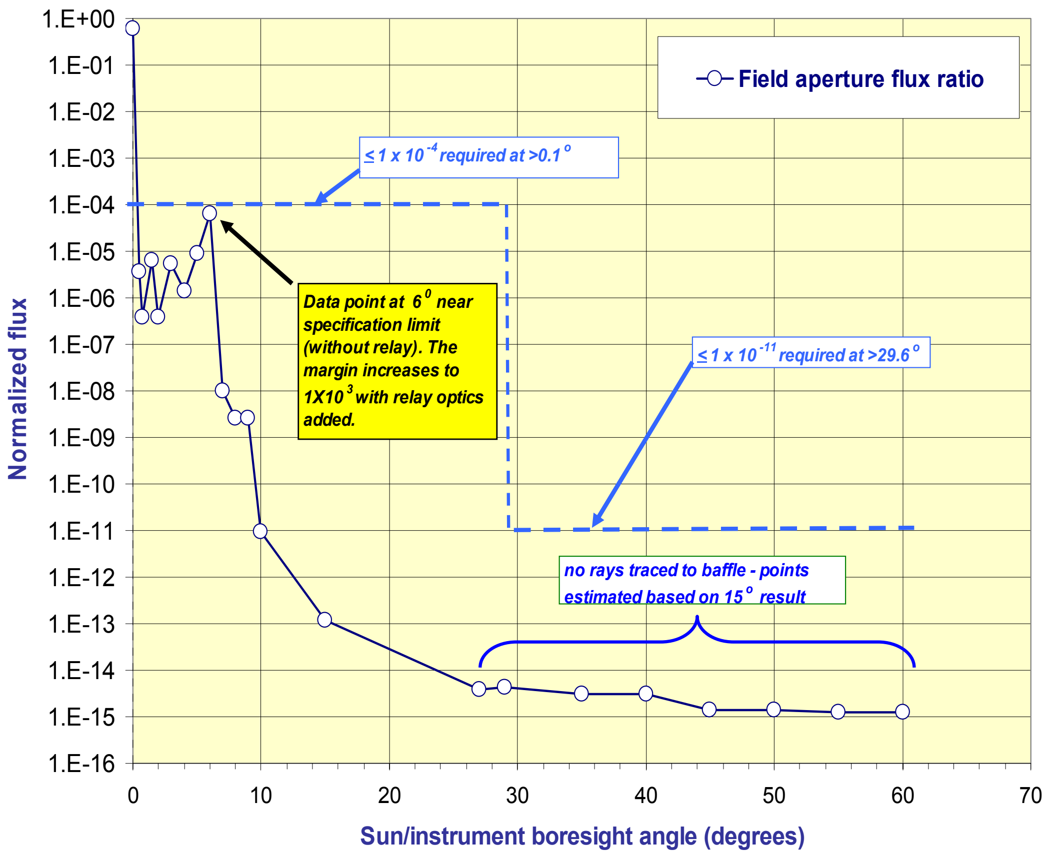

Fig. 7. Simulated stray/scattered light reaching the a-band spectrometer entrance slit as a function of instrument/sun angles. The specification is that less than 1×10^{-4} of the scene radiance 0.1 degree outside the instrument field of view reaches the detector. At angles greater than 29.6 degrees the requirement becomes less than 1×10^{-11}.

5.3 Telescope and relay system optical design

At the focus of the telescope is a baffle that contains a 150-micron wide slit. In the region of the slit, the baffle thickness diminishes to approximately a knife edge. After the assembled telescope/recollimator was received, a computer scatter analysis revealed that the telescope focus fell at the wrong location with respect to the slit and that some vignetting would occur unless the baffle were shimmed by about half of the "knife" thickness away from the baffle's support. The interface between the telescope and recollimator had been designed to be self-centering to within the necessary tolerance, and so the tightened and secured fasteners were removed to allow the baffle shift. The team at JPL was able to insert the required shim, center the baffle properly (since the shim negated the baffle's self-centering feature), and reassemble the telescope and recollimator using their self-centering features so that the result was satisfactory. This maintained the excellent ¼-wave performance that telescope manufacturer, Axsys, Inc. had measured after their manufacture and assembly of the telescope and recollimator. We had earlier assumed that the preparation for the scatter analysis would provide a verification of fine details like this baffle location (since this wasn't obvious viewing the mechanical models at the usual resolution), but the effort to save time nearly led us to miss this important consideration.

Early concerns for the relay assembly's final weight and center of gravity had driven making the relay parts as light as possible based on first-order analyses. Obtaining any kind of reliable figure for the vibrational response using a first-order analysis for a trimmed or complex part is nearly impossible, so the team assumed that analytical finite-element verification would be necessary. Schedule-driven decisions to fabricate the flight parts before these analyses were available left the flat diagonal mirror in the reversed Newtonian re-imager with fatigue stresses in the contiguous flexures that support it. JPL fabricated a yoke to support the flat to reduce these stresses under vibration while allowing the original flexures to locate the flat and mount it as designed without inducing unacceptable fastener loads into the mirror's surface.

"Liquid-pin" joints were used in the various interfaces for re-mating major component assemblies that had been disassembled for various reasons during the alignment process. These joints consist of stainless steel dowel-pin aligners that cantilevered out of one surface into aluminum bushings with venturi-shaped bores than had been epoxied into the adjacent surface after the assembly had been aligned and clamped. This approach worked well, and the relay and telescope assemblies went together rather efficiently, providing some time savings.

5.4 Spectrometer lens design for manufacture

To relax tight lens tolerances, as-built spectrometer ray trace modeling was used to specify assembly shims and alignment parameters for the as-built hardware.

For example, Optimax, the lens fabricator, measured asphere lens transmitted wavefront error (TWE) Zernike coefficients for delta wavefront error (WFE) between the prescription Zygo lens test and the as-built lens. This was modeled by inserting a Zernike phase surface after each lens in our spectrometer ray trace. The Optimax Zernike coefficients were put on the Zernike phase surface.

Collimator TWE interferograms during assembly were compared to the ray trace model, including as-built Optimax lens fabrication data, aluminum barrel dimensions, and shim dimensions. If they did not agree, then dimensions and model were re-examined. In one case the team found a 0.007" difference in spacing due to lens mount tooling. Ray trace and measured interferogram agreed after correcting for this de-space.

For our asphere lenses, Optimax TWE Zygo measurement layouts were much simpler than asphere surface interferogram layouts. Adding delta TWE Zernike phase surfaces allowed successful as-built ray trace modeling. Ray trace tolerancing tools are not yet automated for TWE through-lens elements. The tools need to be developed if the TWE approach is more widely used.

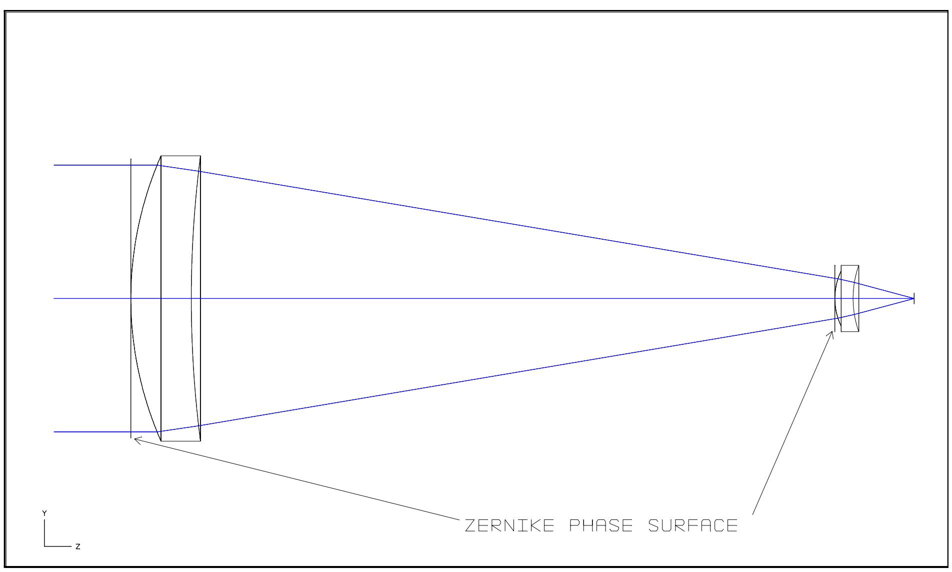

Fig. 8. Zernike phase surfaces were inserted into the nominal prescription allowing as-built performance assessment.

5.5 Flight diffraction gratings

The diffraction gratings were identified early in the program as a key risk area. Grating substrates had to be lightened because their location at the extreme end of the optical bench resulted in higher dynamic loads during launch (over 100 G RMS at 3σ). Lowering grating mass raised the frequency of the optical bench and reduced stress in the mounted optic in the specified dynamic launch environment. The substrates had to be made out of a near zero coefficient-of-expansion material to achieve a better than 1 part in 10,000 requirement on the accuracy of the grating dispersion constant. The scattered/stray light specifications were near the demonstrated limit for this type of grating and required independent verification measurements, figure 9, to provide assurance the vendor's test configuration was providing the required performance. The schedule was tight and it was known the typical lead times for custom gratings of this quality were very long and in series with the procurement of the highly sculpted grating substrates. Therefore, the procurement process was initiated well before the instrument critical design review. To address these issues a dual procurement path was initiated with two different grating manufacturers, one domestic, the Spectrum Scientific Corporation located in Irvine, CA, and the other European, Horiba Jobin Yvon located in Longjumeau Cedex, France. Initially, a special a-band test/setup grating was manufactured by Spectrum Scientific and independently tested to verify that the accuracy, efficiency and low-stray/scattered light requirements were achievable prior to any flight grating procurement. The test grating was a complete success and was in fact used as a dispersion recording setup/check tool for all flight a-band flight gratings. A total of 6 flight parts were ordered from Horiba, a flight and a flight spare for each of the three spectrometer channels with the CO^2 channel gratings to be delivered first. A parallel effort was initiated with Spectrum Scientific for a flight and a flight spare a-band grating. Concerns over the high projected vibration levels led to a decision to qualify a mounted grating in its mount prior to completing the flight grating assemblies. One of the first flight gratings delivered from Horiba was selected for qualification testing. All the delivered flight gratings from both vendors met or exceeded specifications. However, since a Horiba manufactured grating underwent the qualification test the decision was made to build the flight hardware using the Horiba manufactured gratings, holding the Spectrum Scientific flight gratings in reserve.

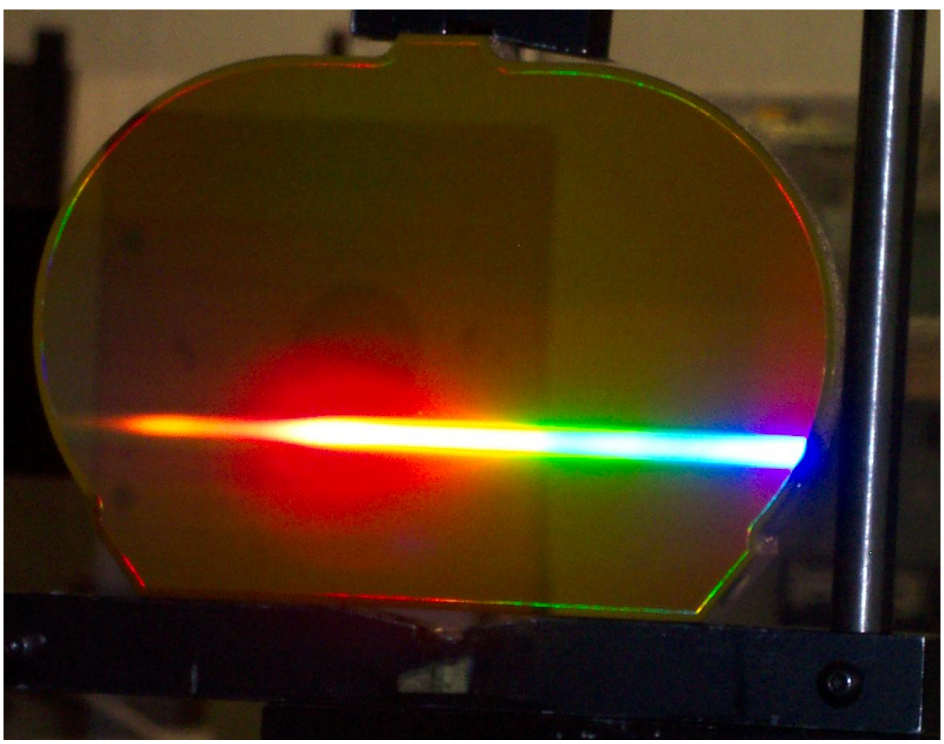

Fig. 9. A flight diffraction grating mounted for Bi-Direction Reflectance Distribution (BRDF) measurements to independently verify the parts scattered light properties.

6. CONCLUSION

The Orbiting Carbon Observatory will make precise measurements of the global abundance and distribution of carbon dioxide, the principal man-made greenhouse gas affecting global climate. Scientists will use this data to increase our understanding of the complex, and not well understood, mechanisms involved in the carbon cycle. Development of the new OCO instrument to make this measurement often pushed existing technologies to their limits and provided several challenges for the teams responsible for making it a reality.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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