Current development status of the Orbiting Carbon Observatory Instrument Optical Design

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ABSTRACT

The Orbiting Carbon Observatory, OCO, is a NASA Earth System Science Pathfinder (ESSP) mission to measure the distribution of total column carbon dioxide in the earth's atmosphere from an earth orbiting satellite. NASA Headquarters confirmed this mission on May 12, 2005. The California Institute of Technology's Jet Propulsion Laboratory is leading the mission. Hamilton Sundstrand is responsible for providing the OCO instrument. Orbital Sciences Corporation is supplying the spacecraft and the launch vehicle. The optical design of the OCO[1] is now in the detail design phase and efforts are focused on the Critical Design Review (CDR) of the instrument to be held in the 4th quarter of this year. OCO will be launched in September of 2008. It will orbit at the head of what is known as the Afternoon Constellation or A-Train (OCO, EOS-Aqua, CloudSat, CALIPSO, PARASOL and EOS-Aura). From a near polar sun synchronous (~1:18 PM equator crossing) orbit, OCO will provide the first space-based measurements of carbon dioxide on a scale and with the accuracy and precision to quantify terrestrial sources and sinks of CO_2. The status of the OCO instrument optical design is presented in this paper. The optical bench assembly comprises three cooled grating spectrometers coupled to an all-reflective telescope/relay system. Dichroic beam splitters are used to separate the light from a common telescope into three spectral bands. The three bore-sighted spectrometers allow the total column CO_2 absorption path to be corrected for optical path and surface pressure uncertainties, aerosols, and water vapor. The design of the instrument is based on classic flight proven technologies.

Keywords: Infrared spectrometer, greenhouse gases, carbon dioxide, oxygen A-band, HgCdTe detector

1. INTRODUCTION

The Orbiting Carbon Observatory is a NASA sponsored Earth System Science Pathfinder (ESSP) mission that will make space based measurements of column CO_2 to monitor sources and sinks of this principal greenhouse gas. The mission is lead by the Jet Propulsion Laboratory. Hamilton Sundstrand Space Land and Sea will provide the instrument, figure 1. Orbital Sciences Corporation will provide the spacecraft and launch vehicle. Launch is scheduled for September of 2008 from facilities at Vandenburg, California. The preliminary design of the instrument was completed last year and many long lead items are now in the procurement process. As the detailed design of the optical bench continues, several important changes are being implemented to the optomechanical system prior to creation of the detailed fabrication documents. Other improvements include the construction and test of a qualification grating assembly. The potential to perform lens sub-assembly thermal/vacuum alignment and focus verification prior to integration into the optical bench assembly housing with the diffraction gratings is under consideration. These improvements are not discussed in detail. What are presented in overview are the key hardware elements that comprise the optical bench assembly. Updates of the current status of the ongoing detail design are reported.

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1.1 The Orbiting Carbon Observatory mission

OCO will be launched into a sun-synchronous near polar orbit that provides near global coverage at monthly intervals to make space-based measurements of atmospheric carbon dioxide with the precision, resolution, and coverage needed to characterize the geographic distribution of CO_2 sources and sinks and to quantify CO_2 variability over the annual cycle. The mission will record, calibrate, validate, publish, and archive science data records and calibrated geophysical data products in the NASA Distributed Active Archive Center for use by the scientific community.

1.2 Carbon Dioxide measurements from space

High-resolution spectra of reflected sunlight in the near infrared at the CO_2 bands at 1.61 μm and 2.06 μm and the oxygen A-band at 0.760 μm are used to retrieve the column average CO_2 dry mole fraction, X_{CO2}. The 1.61 μm CO_2 band provides the maximum sensitivity near the surface while the O_2 A-band and the 2.06 μm CO_2 bands provide information needed to determine surface pressure, albedo, atmospheric temperature, water vapor, clouds, and aerosols. The need for high spectral resolution, from a minimum of 17,000 for the A-band to 20,000 for the two CO_2 bands is driven by both sensitivity requirements and the need to minimize systematic errors in the retrieval. Figure 2 shows the typical spectral radiance profile of the spectra to be measured by the optical system.

1.3 Observing modes

OCO cycles between Nadir and Glint modes on 16-day intervals to cross calibrate observations. In the Nadir mode, the instrument will collect footprints directly beneath the spacecraft with an area of less than 3 km^2. The glint mode observes the solar radiance reflected specularly from the Earth's surface to improve the signal to noise ratio from the low albedo of the water's surface in these measurements bands. Additionally, a target mode points the instrument at specific well instrumented ground sites and is provided for in-flight validation of the space-based measurements.. A 10.3 km wide swath at nadir is measured from a nominal orbit height of 705 km. The swath includes 8 cross-track samples of 20 pixels per sample. A rolling readout is incorporated resulting in parallelogram-shaped ground footprints.

2. OPTICAL BENCH ASSEMBLY DESIGN

The design of the optics is driven by a set of critical requirements, most of which remain unchanged since presented at the instruments preliminary design review. The requirements flowed down from higher-level mission science requirements are summarized in table 1. Chief among these requirements is the relatively high spectral resolution specified, >17,000 for the oxygen A-band spectrometer and >20,000 for both the carbon dioxide spectrometers. These requirements are unusual for a dispersive spectrometer and usually left to the domain of Fourier transform spectrometers. The high throughput and low focal ratio requirements are driven by minimum signal to noise requirements needed for the mission science. The instrument acquires 8 cross-track samples of a minimum of 19 pixels each. The detector chosen for each CO_2 channel spectrometer is based on the HAWAII-IRG device produced by Rockwell Scientific Corporation. It consists of a 1024 by 1024 array of 18 μm-square pixels. The A-band spectrometer uses a silicon version known as the HyViSi detector. The detector size, the minimum spectral sampling requirement, and the field of view establish the system focal length and spectrometer slit size. A shaded ray trace view of the complete optical design is pictured in the figure 3.

2.1 Design implementation

The OCO optical bench assembly, shown in figure 4, is an updated version of the preliminary design. The assembly contains three classic grating spectrometers sharing a common housing. Relay assemblies consisting (in order) of a dichroic relay, a band isolation filter, a linear polarizer, and an inverse Newtonian re-imager are fixed at the entrance of each spectrometer. The three relays share common hardware and the order of band separation is 2.06 μm CO_2, 1.61 μm CO_2, and 0.760 μm A-band. The A-band uses a fold mirror instead of the dichroic element since it is the last element in the relay optical path. The telescope/collimator assembly is attached to the first relay housing using a titanium isolator tube. Except for the isolator, which is located in a collimated section of the beam path, all metering structures with powered reflective elements in the optical path are made of aluminum alloy to achieve an athermalized design. The telescope and the collimator function to compress the beam to allow room to package the relay optics and most importantly allow a field baffle at the telescope focus to limit the amount of unwanted radiation entering the optical system – needed for stray light management. The complete optical bench assembly is thermally isolated and suspended inside an aluminum shroud. The shroud is actively cooled to maintain a uniform and constant –5° C optical bench assembly temperature in all operational modes of the instrument.

2.2 Spectrometer design

The relatively narrow spectral range of each spectrometer channel, 25 to 40 nm, allows a very simple refractive based spectrometer solution consisting of a slit, refractive collimator, a plano reflection diffraction grating, and a refractive camera to re-image the spectral by spatial image. A scaled breadboard of the OCO A-band spectrometer was constructed and tested in 2002[2]. It demonstrated that very high spectral resolution, greater than 17,000, can be achieved using the simple design approach chosen for the OCO instrument spectrometers. An important goal maintained since the preliminary design phase has always been to keep the design simple by keeping the number of optical elements to a minimum, using optical glasses that are readily available, maintaining the geometry of the optical path of the three spectrometers similar if not identical (if practical), and by designing to requirements. Today, the maturing “simple” optical design is shown to meet or exceed all requirements flowed from the OCO mission level requirements. The design approache yields a synergy not only in parts design but also in the tools and techniques to sub-assemble, align/focus, and test the optical bench assembly hardware through out the build process.

2.3 Telescope/relay design

The OCO instrument optical design is shown in figure 4. Light enters a single telescope, a classic f/1.8 Cassegrain design, and images the scene at the field baffle. The light is then collimated with a similar Cassegrain collimator with a shorter focal length to compress the pupil to a diameter that can be packaged within the volume constraints. This entrance optics design provides a common field of view for the three spectrometers. Since the telescope and re-collimator must work over the much broader spectral range, 0.76μm to 2.06 μm, the all-reflective implementation is chosen to avoid complexities associated with refractive designs. The collimated beam passes the scene irradiance through a series of dichroic beam splitters to separate the two CO_2 bands from the oxygen A-band. Each band thus separated is re-imaged onto the entrance slit of a spectrometer. Figure 5 shows a close up section view of the telescope/collimator design.

2.4 Entrance Baffle/Calibration assembly design.

The OCO instrument has several provisions for spectral-radiometric calibration on orbit. These provisions are incorporated in the entrance baffle/calibration assembly, shown in figure 6. Depending on the particular mode of operation, a paddle shaped device is rotated into view of the instrument via a simple motor driven mechanism. The three functional modes provided are; 1) covered or stowed; 2) science; and 3) solar calibration. In the covered mode, as the name implies, the instrument’s field of view of view is completely obscured. The instrument is to be launched in the covered mode (the paddle is rotated 90° counter clockwise as pictured in figure 6) to protect the optics from contamination. The inside of the aperture cover is coated with a gold surface that can be illuminated by three redundant lamps to produce an on-orbit “flat field” calibration. In the science mode the “paddle” is positioned as shown in the figure to provide the instrument an un-obscured view of the scene for science retrievals. In the third mode, the mechanism rotates 90° clockwise so that the diffuser covers the entrance baffle for direct views of the sun to record the solar spectrum and provide on board radiometric calibrations. When clocked into this position the instrument is in the radiometric calibration mode. The entrance baffle is a classic straight vane design that serves several functions. First, attenuation of unwanted scattered light into the instruments optical path. Second, it provides a mount for a three-vane spider supported calibration lamp assembly. Finally, it provides thermal isolation since the entrance baffle/calibration assembly will see the full solar irradiance. This assembly is not mechanically attached to the cooled optical bench assembly. Instead, it is mounted to the spacecraft and aligned to the instrument optical path at integration with the spacecraft. Redundant methods to verify the baffle assembly’s alignment with the telescope are provided in the design.

2.5 All reflective transmission diffuser design

OCO uses a unique solar diffuser, called an all-reflective transmission diffuser. Although sunlight is intended to enter the diffuser on one side and exit on the opposing side as it would in a ground glass transmission diffuser functionally this is instead accomplished by a single specular reflection and a single diffuse reflection. The details of the optical design and theory of operation are beyond the scope of this paper. However, this stacked array of apertures, shaped mirrors and reflective diffusers allows the irradiance profile filling the telescope entrance pupil to be tailored to perform solar calibration of the OCO spectrometers over their full dynamic range when in this mode and the instrument is oriented to view the sun directly. This proved impossible to achieve using traditional reflective or transmission diffuser designs. All surfaces in the all-reflective transmission diffuser are coated with gold.

2.6 Optical design performance

The spectrometer optical design produces long narrow spots diagrams with an aspect consistent with the detector pixel sampling in both spatial and spectral directions, approximately 20 pixels per spatial sample by 2 pixels in the spectral direction, the minimum requirement per sample. An updated y-enclosed (y being the dispersion direction) energy plot, figure 7, of the 0.760 μm spectrometer optimized design shows 100% of the energy in the dispersion direction is contained within a distance of less than 4.5 um from image centroid. At 2.06 μm this is less than the diffraction limit. Each spectrometer, the A-band, and two CO_2 bands, was optimized using this technique. The predicted resolution of the A-band spectrometer is over 20,000, similar to the CO_2 channels. The spectrometer slit has been widened to improve the throughput since the minimum resolution required in lower, 17,000 for the A-band verses 20,000 for the CO_2 bands.

2.7 Spectral stray light

Simulations of the stray light performance of the OCO instrument are being performed using TracePro (Lambda Research Corporation). The expert version of the program is being put to use because it allows the use of tabulated BRDF (Bi-directional Reflectance Distribution Function) measurement data. Samples of several optical path materials including those for the diffuser, focal planes, and types of painted aluminum, have been prepared and measured. Figure 8 is an example of the measured BRDF of a representative HgCdTe detector. These data are now being input into a complete model of the 0.760 μm A-band optical path. Figure 9 shows a view of the model, created from the current Pro-Engineer CAD model database. The specified RMS surface roughness for the spectrometer lenses and the grating scatter specification is included in the model. Although some initial stray light modeling of the optical path was performed to supported the preliminary design, the higher fidelity and accuracy of the updated model is intended to provide assurance that the materials, surfaces finishes, and the processes to produce them will result in an instrument that will exceed requirements. In addition, the quantitative nature of the simulation results will provide the science team expected OCO instrument optical performance. The results of the analysis will apply directly to the prediction of the as built instrument line shape function.

2.8 Instrument line shape

The requirements for instrument line shape are based on the W (x) function. The integral function used to numerically calculate this parameter for each spectrometer is shown in equation 1.

$$w(x) = \frac{\int_{\lambda_0 - x\cdot\Delta\lambda}^{\lambda_0 + x\cdot\Delta\lambda} ILS\, d\lambda}{\int_0^{\infty} ILS\, d\lambda} \qquad (1)$$

In this expression, the limits of the instrument normalized line shape function, ILS, are enumerated for x= 0.5, 1.0, and 6.0 where x is the number of multiples of full width at half maximum response, $\Delta\lambda$. For example, for x=6.0 the requirement is that a fraction of > 0.99 of the total integrated line shape be enclosed within 6 full widths at half maximum from the line peak. Updated stray/scattered light contributions reaching the focal plane will be added to the model. However, preliminary design predictions indicate requirements are exceed and provide ample margin for the stray/scattered light contribution.

Figure 1: The OCO Instrument

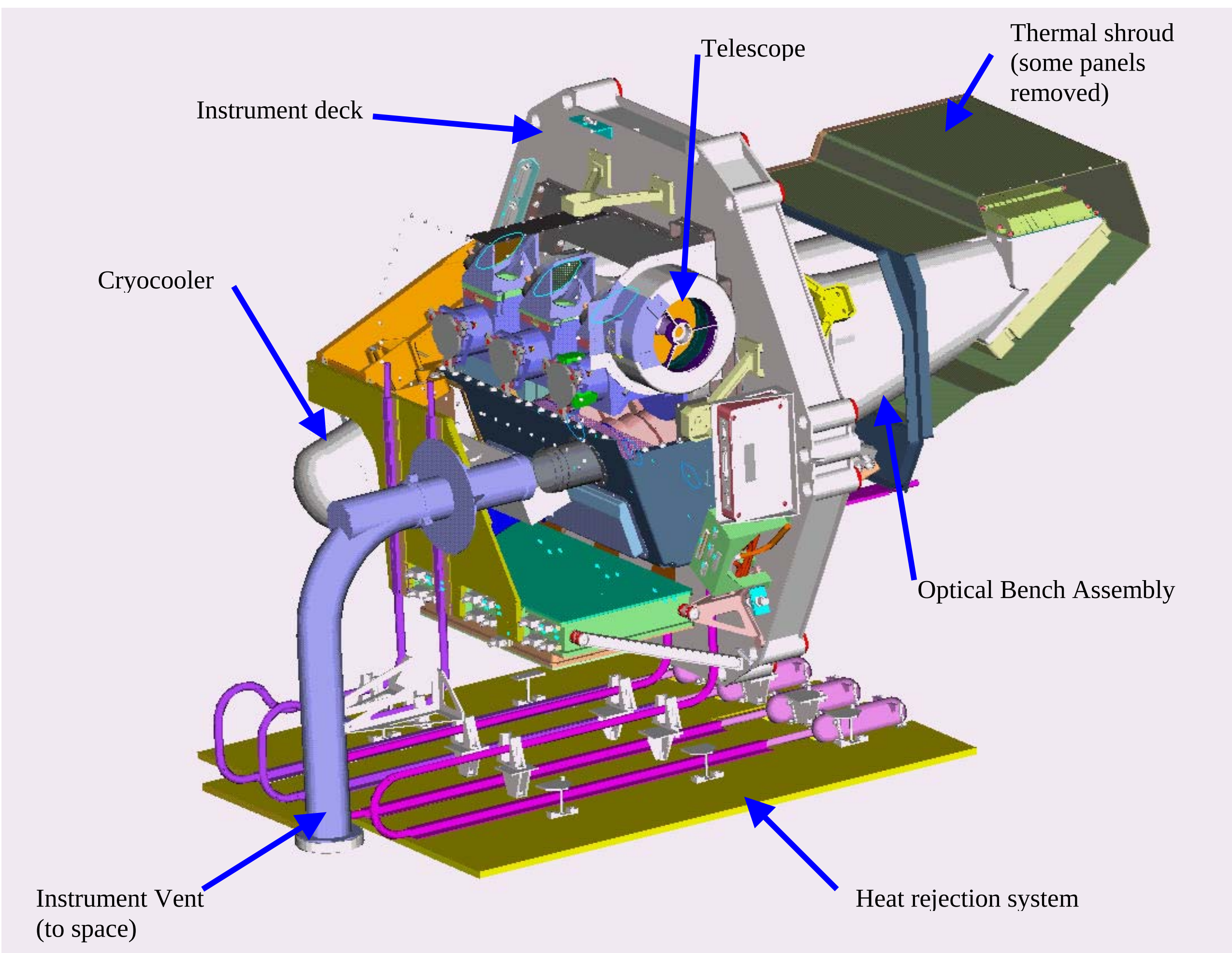


Figure 2: typical spectral radiance profiles

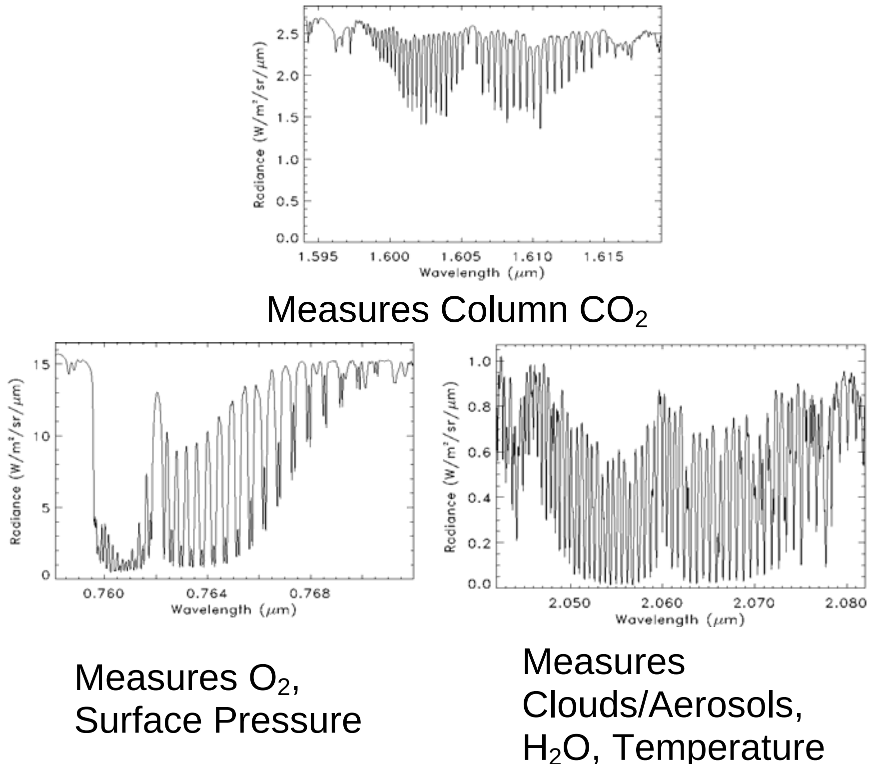


Table: 1 OCO instrument optical requirements

			0.76 µm O_2		1.61 µm CO_2		2.06 µm CO_2	
ID	**Requirement**	**Unit**	**Specification**	**Prediction**	**Specification**	**Prediction**	**Specification**	**Prediction**
L0514	Focal Ratio	-	≤ 1.9	1.8	≤ 1.9	1.8	≤ 1.9	1.8
L5016	Field of view	mrad	14.2 - 15.1	14.6	14.2 - 15.1	14.6	14.2 - 15.1	14.6
L5017	Samples	-	8	8	8	8	8	8
L5018	Pixels per Sample	-	≥ 19	20	≥ 19	20	≥ 19	20
L5019	Minimum Wavelength	µm	0.758	0.758	1.591	1.591	2.042	2.042
L5049	Maximum Wavelength	µm	0.772	0.772	1.621	1.621	2.081	2.081
L5020	Spectral Resolution	-	≥ 17,000	17,842 - 18,199	≥ 20,000	20,990 - 21,410	≥ 20,000	20,990 - 21,410
L5052	Spectral Sampling	pixels / sample	≥ 2	2.45 - 3.34	≥ 2	2.08 - 2.84	≥ 2	2.08 - 2.84
L5039	Optical Throughput TM(s) polarization	-	> 35%	35.5%	> 40%	41.5%	> 45%	46.3%

Figure 3: The OCO optical system

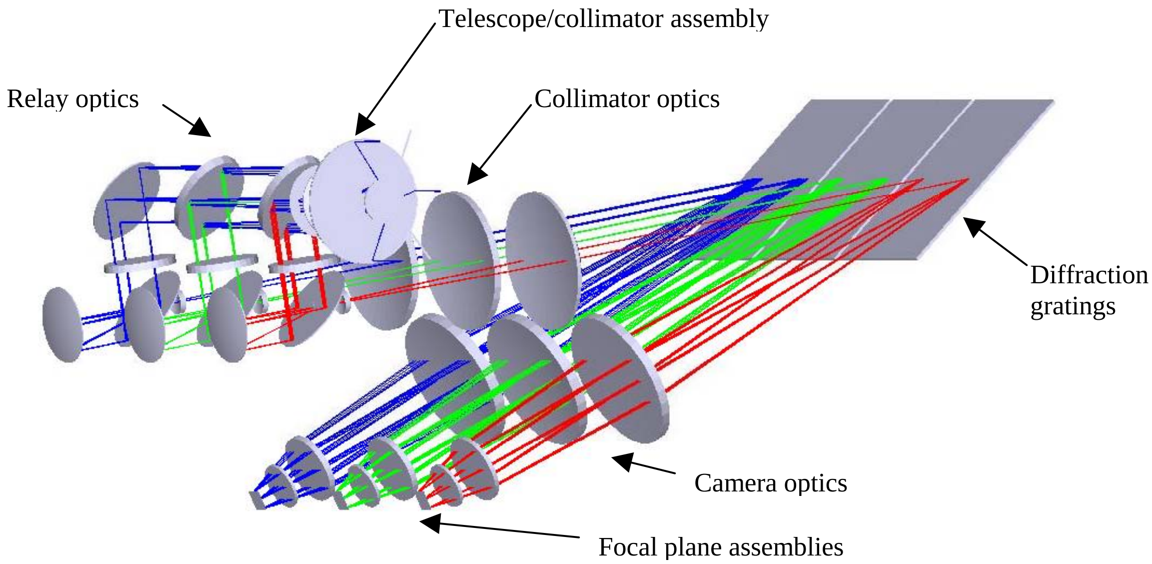


Figure 4: OCO Optical Bench Assembly

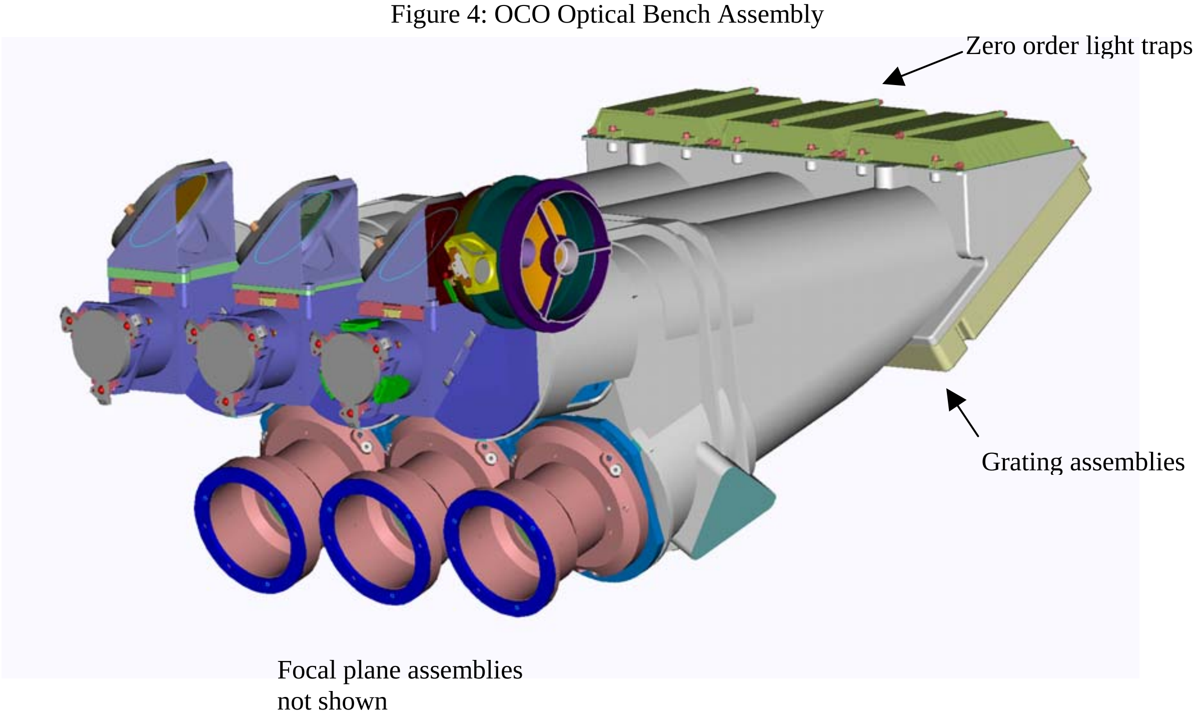


Figure 5: F/1.8 telescope and collimator section view

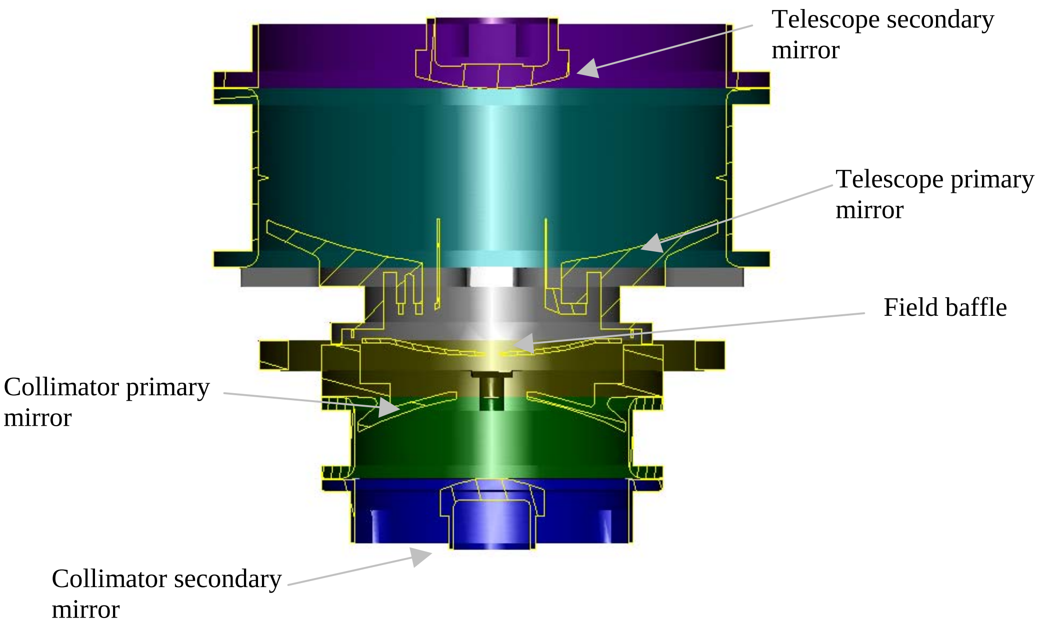


Figure 6: Entrance baffle/calibration sub assembly (science mode shown)

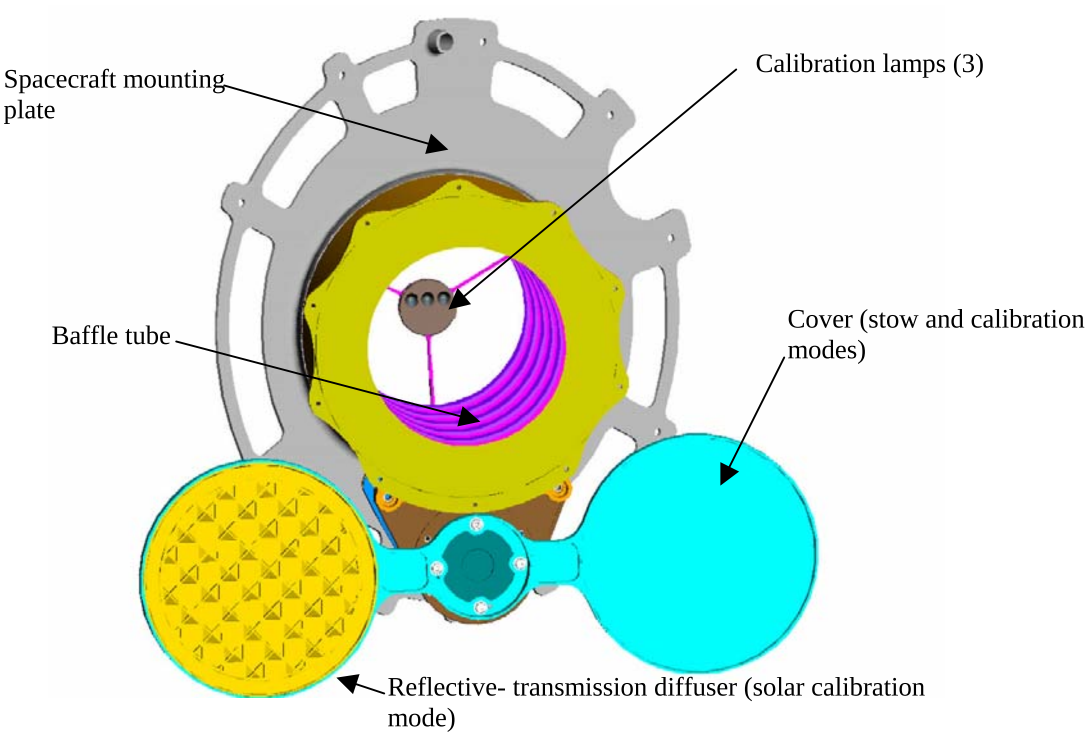


Figure 7: A-band spectrometer Y-enclosed energy plot

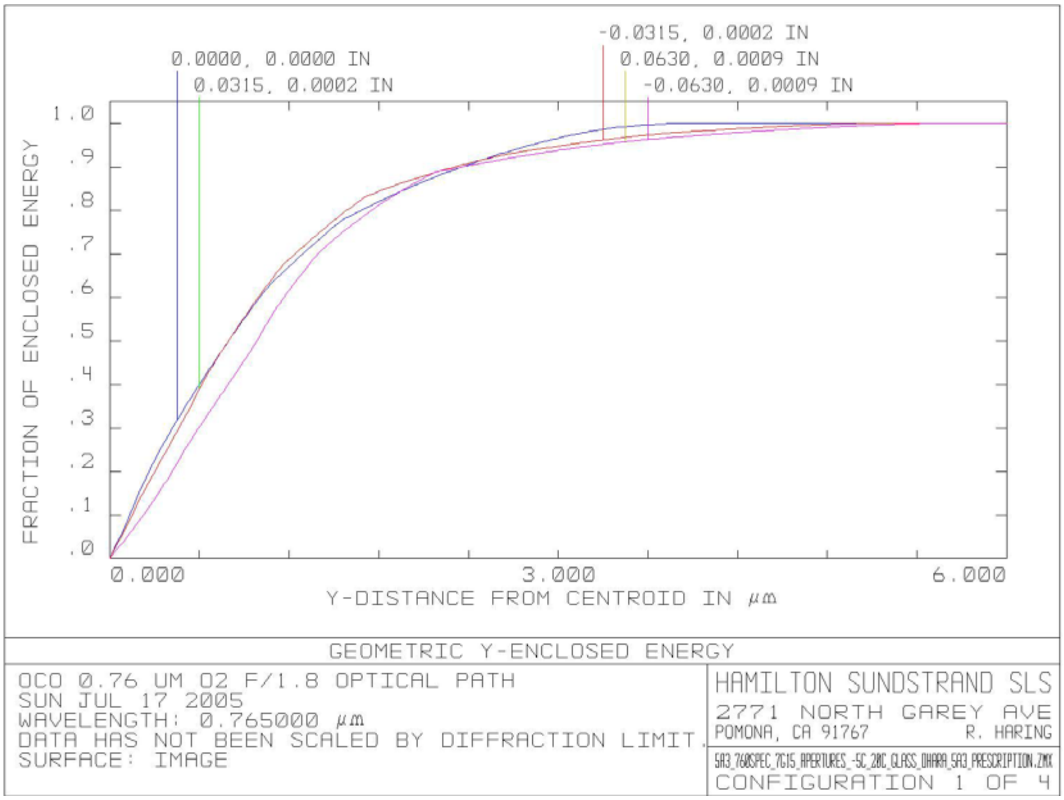


Figure 8: Mercury Cadmium Telluride Detector Bi-Reflectance Disruption Function at 1.55 microns

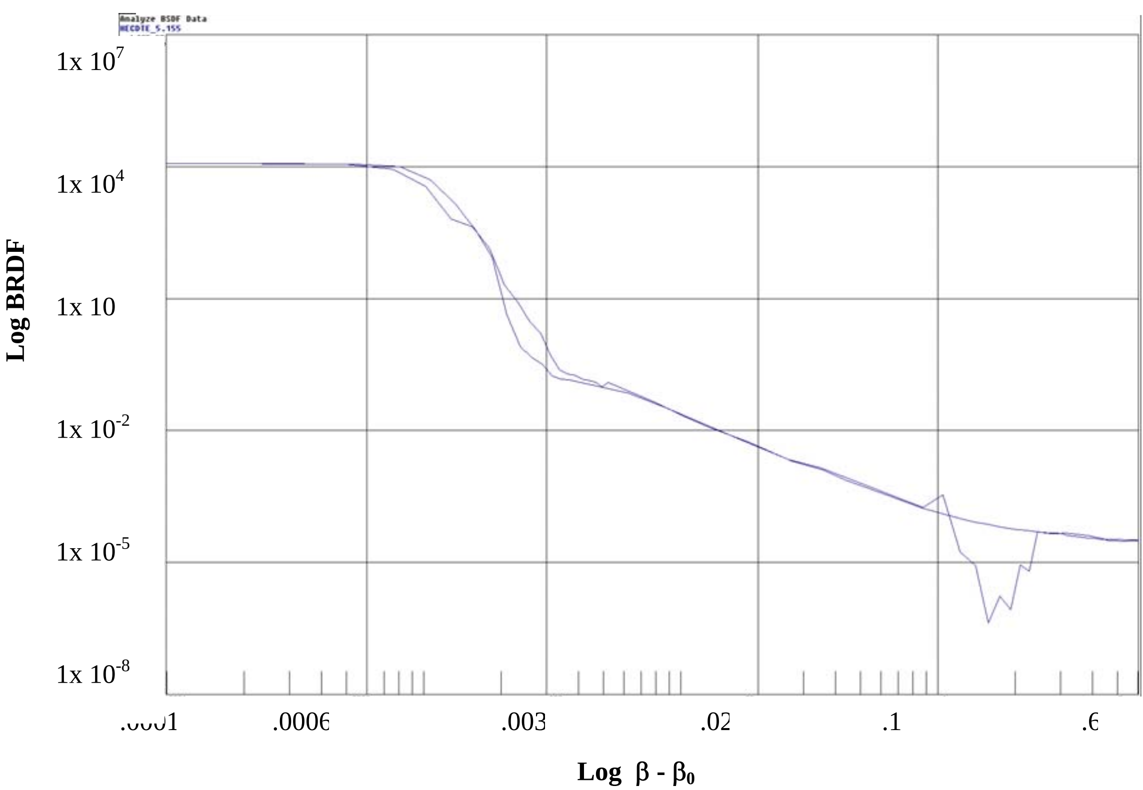
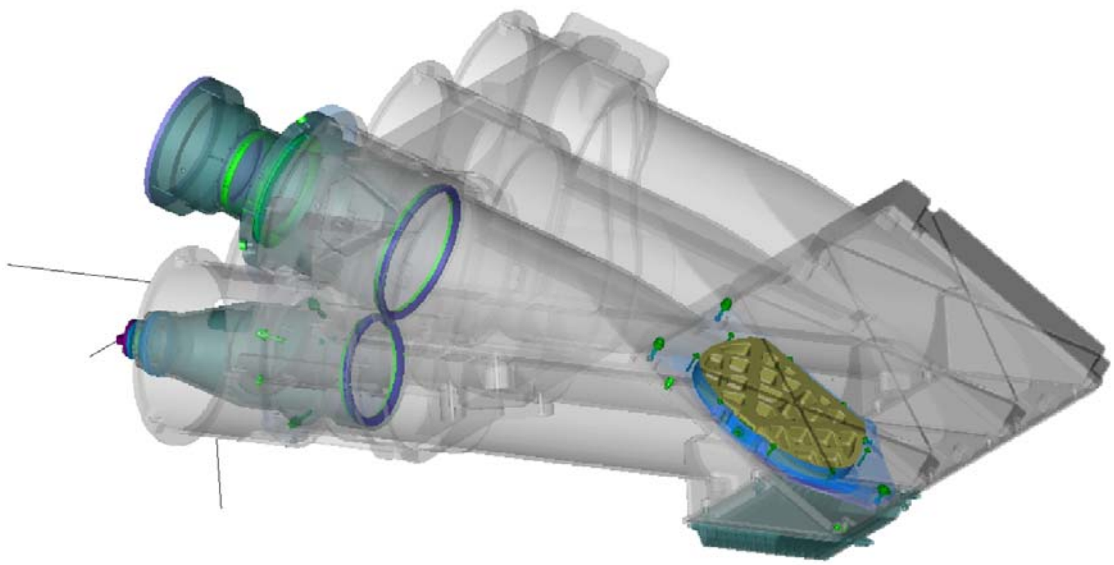


Figure 9: OCO A-band spectrometer stray light model



SUMMARY

The development status of the optical design of the Orbiting Carbon Observatory instrument is presented. The cooled optical bench assembly is comprised of three substantially similar refractive spectrometer designs coupled to an all-reflective unitary telescope/re-collimator entrance optic via a simple dichroic relay system. The instrument is now in the detail design phase. Critical Design Review (CDR) is scheduled for the forth quarter 2005. Challenges lay ahead to fabricate, assemble, align, and test the OCO instrument. However, the simple optical design approach chosen for this instrument should make the effort manageable.

ACKNOWLEDGEMENTS

The Jet Propulsion Laboratory, California Institute of Technology manages the Orbiting Carbon Observatory, under a contract with the National Aeronautics and Space Administration*.

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