The Orbiting Carbon Observatory (OCO)
Instrument Optical Design

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ABSTRACT

The Orbiting Carbon Observatory (OCO) will measure the distribution of total column carbon dioxide in the Earth's atmosphere from an Earth-orbiting satellite. Three high-resolution grating spectrometers measure two CO_2 bands centered at 1.61 and 2.06 μm and the oxygen A-band centered at 0.76 μm in the near infrared region of the spectrum. This paper presents the optical design and highlights the critical optical requirements flowed down from the scientific requirements. These requirements necessitate a focal ratio of f/1.9, a spectral resolution of 20,000, and precedence-setting requirements for polarization stability and the instrument line shape function. The solution encompasses three grating spectrometers that are patterned after a simple refractive spectrometer approach consisting of an entrance slit, a two-element collimator, a planar reflection grating, and a two-element camera lens. Each spectrometer shares a common field of view through a single all-reflective telescope. The light is then re-collimated and passed through a relay system, separating the three bands before re-imaging the scene onto each of the spectrometer entrance slits using an all-reflective inverse Newtonian re-imager.

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

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 in order 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, while Orbital Sciences Corporation will provide the spacecraft and launch vehicle. The preliminary design review of the mission, which included the science, the instrument and the spacecraft, was completed in July of 2004. The mission is scheduled for launch aboard a Taurus rocket from launch facilities at Vandenburg, California in October of 2007.

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 ESE 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, 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 1 shows the typical spectral radiance profile of the spectra to be measured by the optical system.

1.3 Observing modes

Observations are cross-calibrated at monthly intervals between Nadir, Glint, and Target modes. In Nadir mode the instrument collects cloud-free scenes with a footprint area of less than 3 km^2. Glint mode observes the solar radiance reflected from the ocean's surface, improving the signal to noise ratio due to the low albedo of the water's surface in these measurements bands. Target mode points the instrument at specific well-known ground sites for in flight calibration of the instrument. The spatial sampling approach for Nadir mode is summarized in figure 2. A 10.3 km swath is measured from a nominal orbit height of 705 km. The swath is aggregated into 8 samples of 20 pixels per sample. Rolling readout results in the parallelogram-shaped ground footprints shown in the figure.

2. OPTICAL DESIGN

The optical design of the OCO instrument is driven by a set of critical requirements, summarized in table 1, flowed down from higher-level mission science requirements. Chief among these requirements is the relatively high spectral resolution specified, greater than 17,000 for the Oxygen A-band spectrometer and greater than 20,000 for both carbon dioxide spectrometers. These requirements are unusual for a dispersive spectrometer and are usually left to the domain of the Fourier Transform spectrometer. The high throughput and low focal ratio requirements are driven by the minimum signal to noise requirements needed for the mission science. The instrument acquires 8 cross-track samples with a minimum of 19 pixels each. The detector chosen for each of the CO_2 spectrometers is the HAWAII-1RG device produced by Rockwell Scientific Corporation, consisting of a 1024x1024 array of 18 μm-square pixels. The A-band spectrometer uses the similar HyViSI silicon version. The detector size, minimum spectral sampling requirement, and field of view establish the system focal length and spectrometer slit size. The selected solution for achieving these requirements is shown in the optical block diagram in figure 3.

2.1 Design approach

Referring to the figure 3 diagram, the three spectrometers are coupled to a shared telescope. The three spectral bands are separated by the spectral relay system, isolated by dichroic beam splitters and then re-imaged onto the entrance of each of the three spectrometers. A linear polarizer in the re-imaging optical path ahead of each spectrometer entrance slit passes only the polarization that is efficiently diffracted by the diffraction grating. Each spectrometer re-collimates the now-isolated band, disperses it using a diffracting element and re-images the now 2-dimensional, spectral-times-spatial scene onto the image plane using a camera lens.

2.2 Spectrometer heritage

Although the instrument covers a relatively broad wavelength range, 0.76 μm to 2.06 μm, each spectrometer has to perform over a relatively short spectral band, 25 to 40 nm, and this allows a very simple refractive-based spectrometer solution consisting of a slit, refractive collimator, a planar reflection diffraction grating, and a refractive camera to re-image the spectral-times-spatial image. An optical design originating from the California Institute of Technology Jet Propulsion Laboratory called Profiling A-Band Spectrometer/imager (PABSI) [1] chose such an approach but did not get beyond the preliminary design; however, this very narrow band refractive-based spectrometer approach offered the best solution for the Orbiting Carbon Observatory instrument. Figure 4, the OCO A-band breadboard spectrometer [2], is an example of the very high spectral resolution that can be achieved using this approach for a narrow band spectral retrieval. The inset in the figure is a photograph of the A-band breadboard at the Hamilton Sundstrand facility in Pomona California.

2.3 Design implementation

The OCO instrument optical design is shown in figure 5. Light enters via a single telescope relay system providing a common field of view for the three spectrometers. Since the telescope and re-collimator must work over the much broader spectral range, 0.76 to 2.06 um, an all-reflective implementation is chosen to avoid complexities associated with refractive designs. A Cassegrain telescope and re-collimator are chosen for the front-end optics. Dichroic beam splitters separate the two CO_2 bands from the oxygen A-band. Each channel is re-imaged onto the entrance slit of a spectrometer. A plan view of this OCO implementation is at the top left inset of figure 5.

2.3 Spectrometer design

The optomechanical packaging, Figure 6, alludes to the approach taken to the design of the three spectrometers. It looks like a V six engine block. Each cylinder, a separate spectrometer, is geometrically the same. Constraints imposed during optimization included a common inter element spacing of the lens elements in both the collimator and camera lens assemblies. Common glasses were chosen to avoid risk of availability. Aspheric elements were allowed but only simple conics and then only one surface per element. The simple conic surface reduces both test and alignment efforts. Finally, the design was optimized for a shorter focal ratio to provide margin. In this end each spectrometer was designed for working at a focal ratio of F/1.8 versus the requirement of F/1.9. The benefited of maintaining this margin is to provide signal to noise margin.

2.4 Preliminary design performance

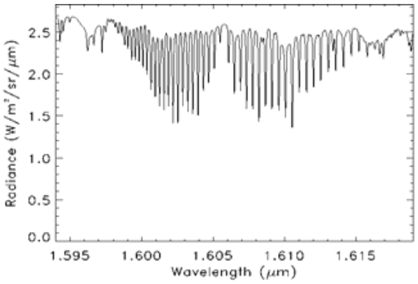
The spot diagrams shown in figure 7 represent the preliminary design performance of the typical optimized spectrometer. The merit function for the optimization weights the RMS spots size in the dispersion direction a factor of ten higher than the spatial direction. This produces long, narrow spots with an aspect ratio consistent with the detector pixel sampling in both spatial and spectral directions; i.e. approximately 20 pixels per spatial sample by 2 pixels in the spectral direction, the minimum requirement per sample. A Y-enclosed energy plot of the 2.06 µm spectrometer optimized design, figure 8, shows 100% of the energy in the dispersion direction is contained within a distance of less than 4.5 µm from image centroid. At a wavelength of 2.06 µm, this is less than diffraction limit. Each spectrometer, the A-band, and the two CO_2 bands, was optimized using the same technique, resulting in preliminary designs with the projected resolution and sampling characteristics graphed in figure 9. The minimum and maximum wavelengths for each plot are tabulated at the bottom of the figure. The predicted resolution of the A-band spectrometer is in reality more like the CO_2 channels, except that the spectrometer slit has been widened to improve the throughput at the expense of resolution, which is only required to be 17,000 verses 20,000.

2.6 Instrument line shape

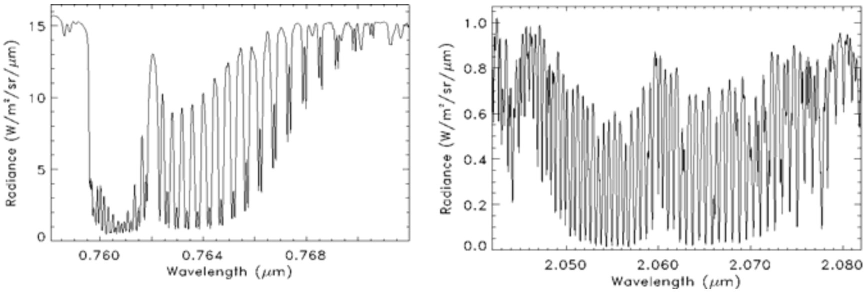
The requirements for instrument line shape are based the W(x) function. The integral function used to numerically calculate this parameter for each spectrometer is shown in the left corner of figure 10. In this expression, the integration limits of the instrument normalized line shape function, ILS, are enumerated for x= 0.5, 1.0, and 6.0 where x is the number of multiples of the Full Width at Half Maximum (FWHM) response, $\Delta\lambda$. For example, for x=6.0 the requirement is that greater than 0.99 of the total integrated energy in the dispersion direction be enclosed within 6 FWHM from the line peak. The plot on the lower left of the figure was generated from one of the typical numerical results. Symmetric instrument line shapes are predicted for the OCO spectrometers. The analysis does not yet include the effects of stray/scattered light reaching the image plane; however, preliminary design predictions, tabulated at the far right column at the bottom of figure 10 indicate requirements are exceed and provide margin for stray/scattered light contributions.

2.5 Distortion

Distortion is characterized by keystone and smile. Ideally, spectra imaged at the focal plane would form a vertical column so that a given column would represent the spectrum for a given spatial footprint, and deviations from ideal are called 'keystone'. Likewise, any given wavelength within the band should occupy a unique horizontal row position at the image plane, and deviations from this ideal are called 'smile'. Figure 11 shows the how keystone and smile are defined for the OCO instrument optical system. The table at the right of the figure lists the smile and keystone requirements for each spectral band and the predictions for the preliminary designs of each. Requirements are met for all spectrometers except keystone for the Oxygen A-band spectrometer at 0.76 µm. During the detail design phase this value will be reduced to the levels predicted for the CO_2 channels.



Measures Column CO_2



Measures O_2,
Surface Pressure

Measures
Clouds/Aerosols,
H_2O, Temperature

Figure 1 The OCO spectral bands

- Requirements:
  - $\geq$ 10 km swath
  - $\geq$ 5 cross-track samples
  - $\geq$ 24 samples/second
  - $\leq$ 3 km^2/sample
- Implementation
  - Swath: 10.3 ± 0.3 km
  - X-track samples: 8
  - Samples/second: 24
  - Sample area 2.92 km^2
- Comments
  - Swath was set at 10.3 ± 0.3 km
    - 10.0 km is minimum
    - 10.6 km hits the 3 km^2 limit

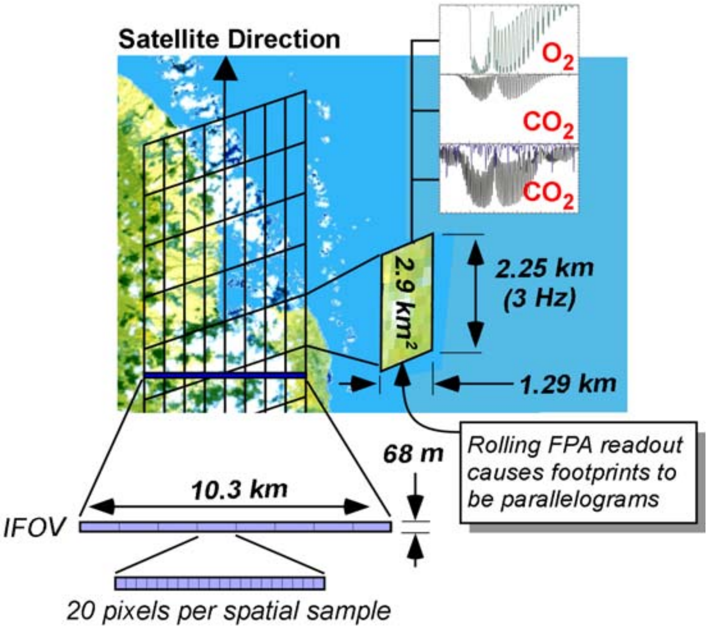


Figure 2 Spatial sampling

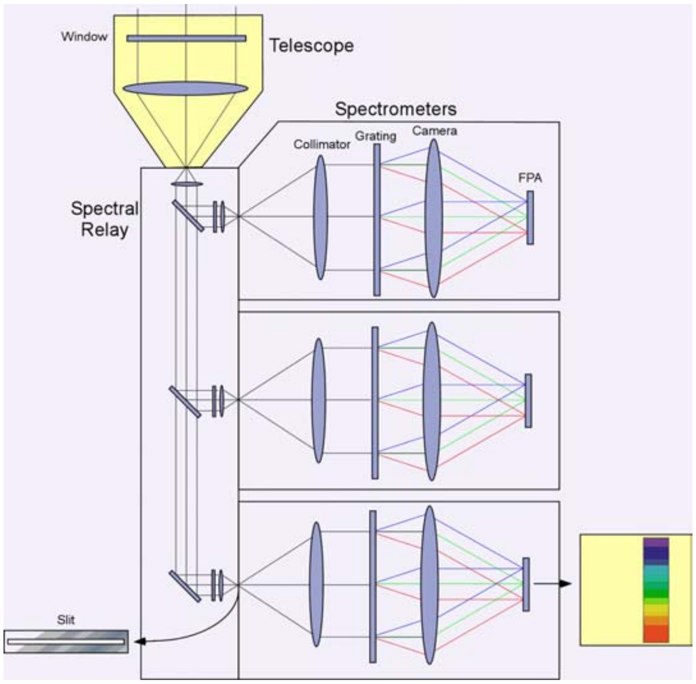


Figure 3 Optical block diagram

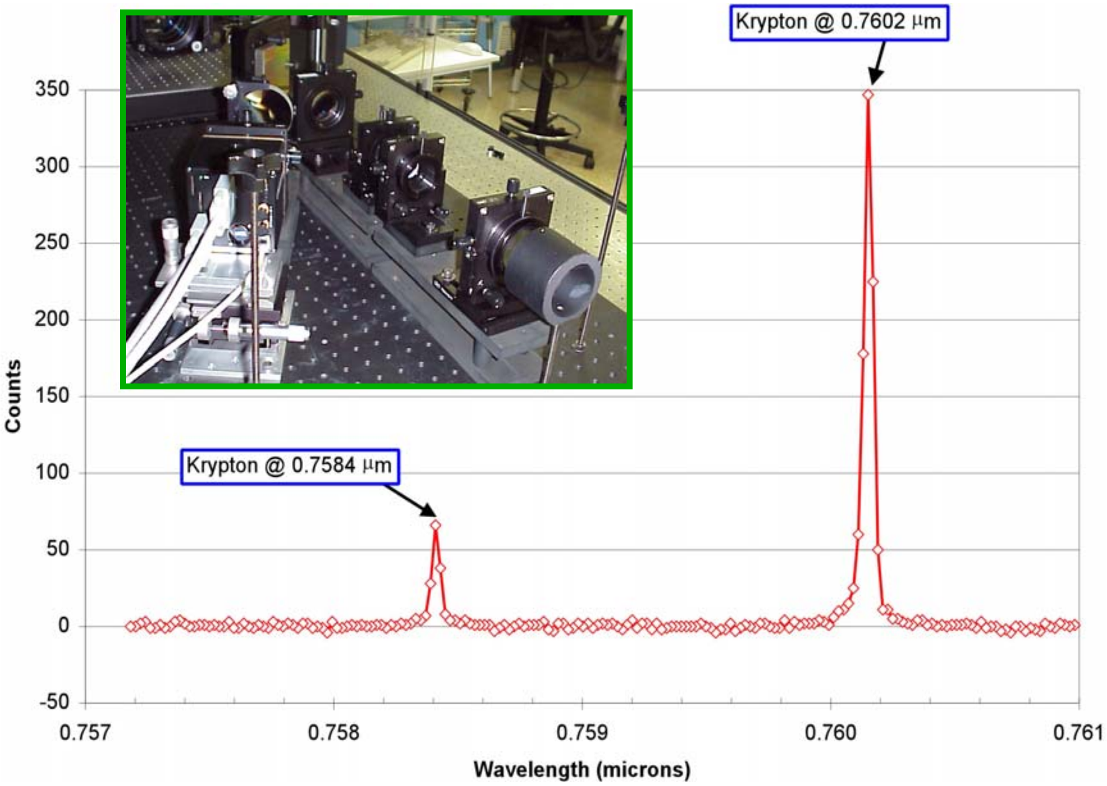


Figure 4 A-band breadboard spectrometer

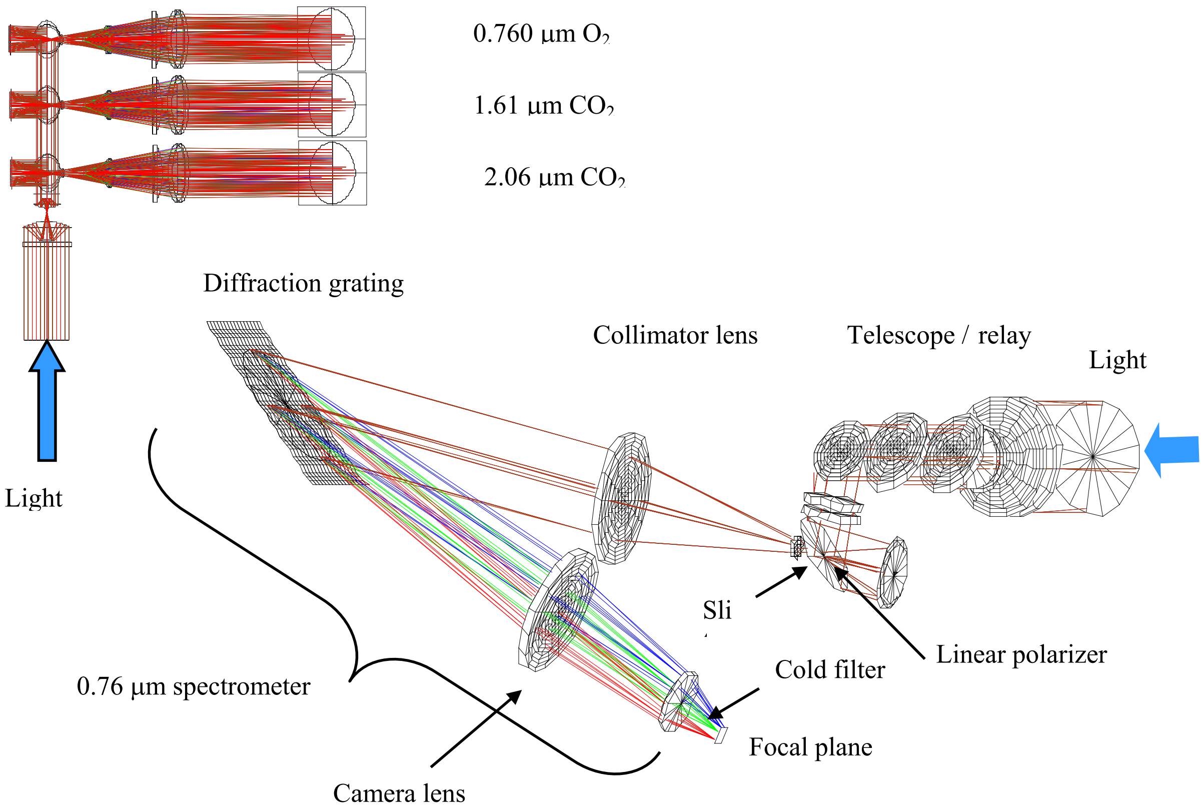


Figure 5 OCO optical design

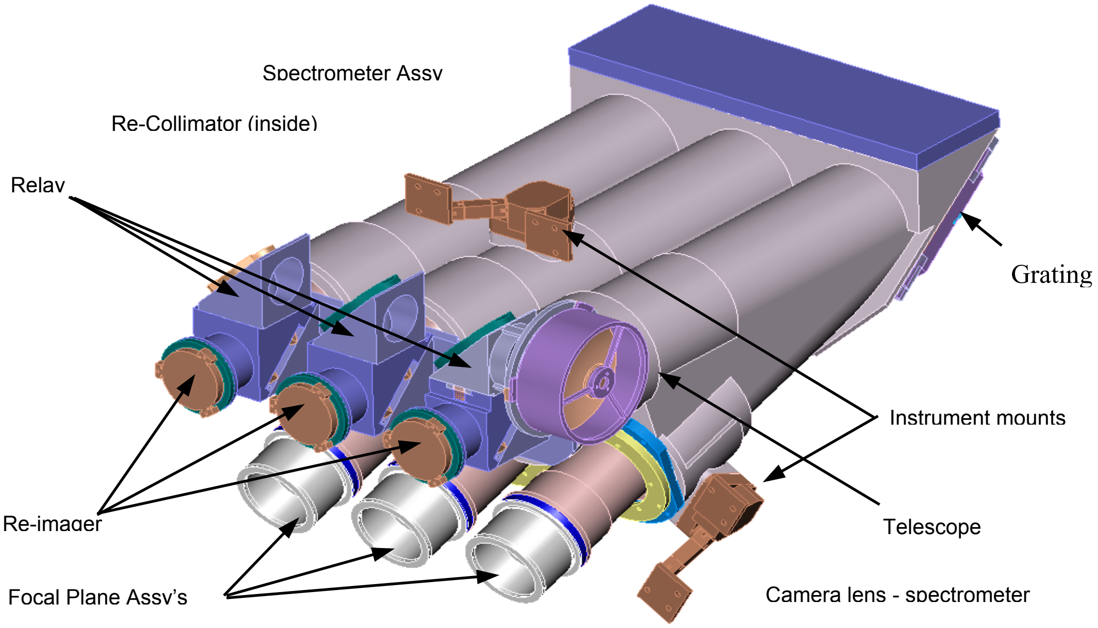
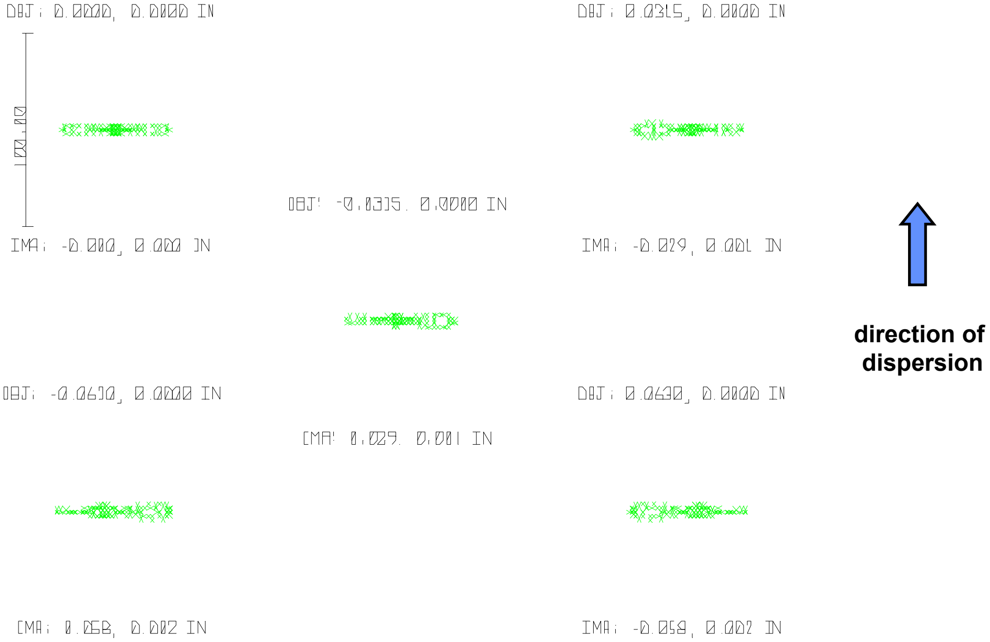


Figure 6 Optomechanical packaging



direction of dispersion

Figure 7 Typical spot diagram (2.06 um spectrometer)

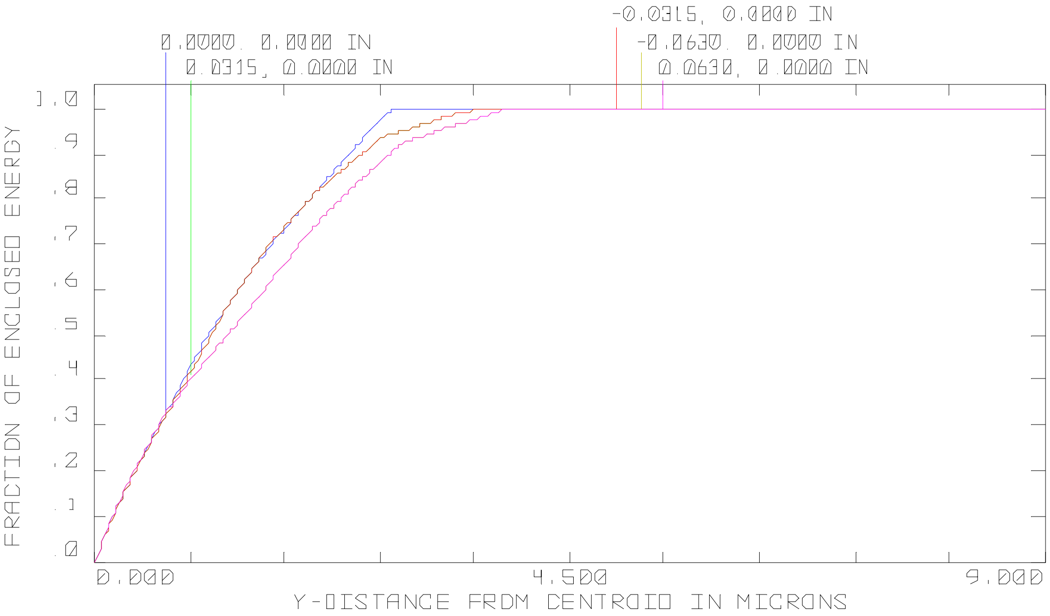


Figure 8 Spectral enclosed energy (2.06 um)

			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%

Table 1 Critical optical requirements

A-band	0.7584 µm - 0.7719 µm
Weak CO_2	1.5923 µm - 1.6207 µm
Strong CO_2	2.0439 µm - 2.0804 µm

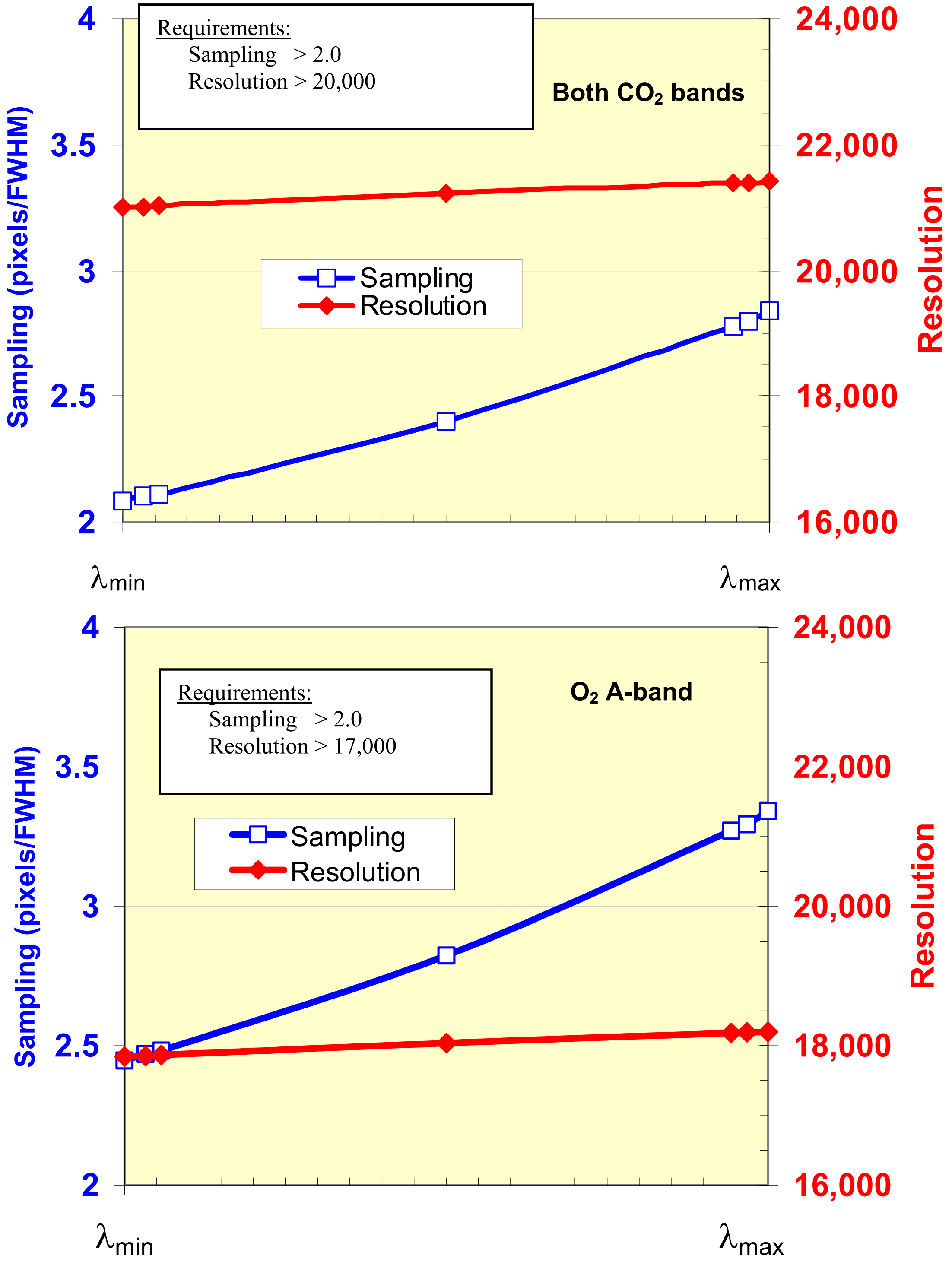
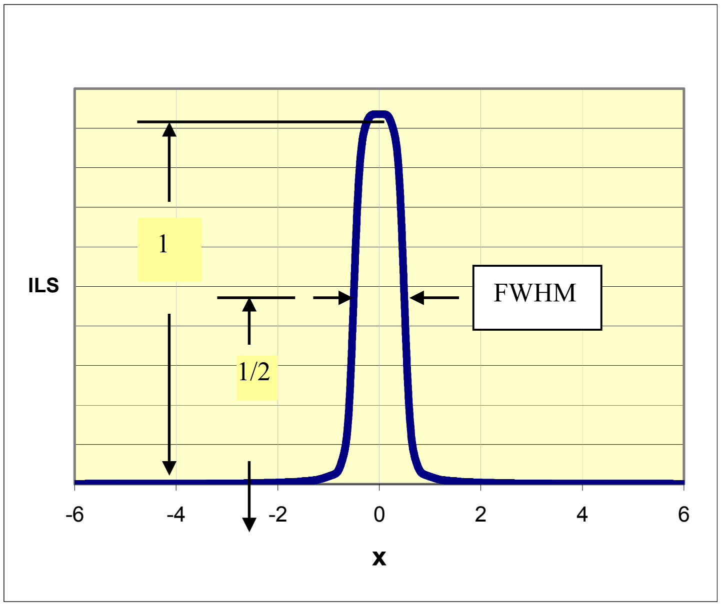


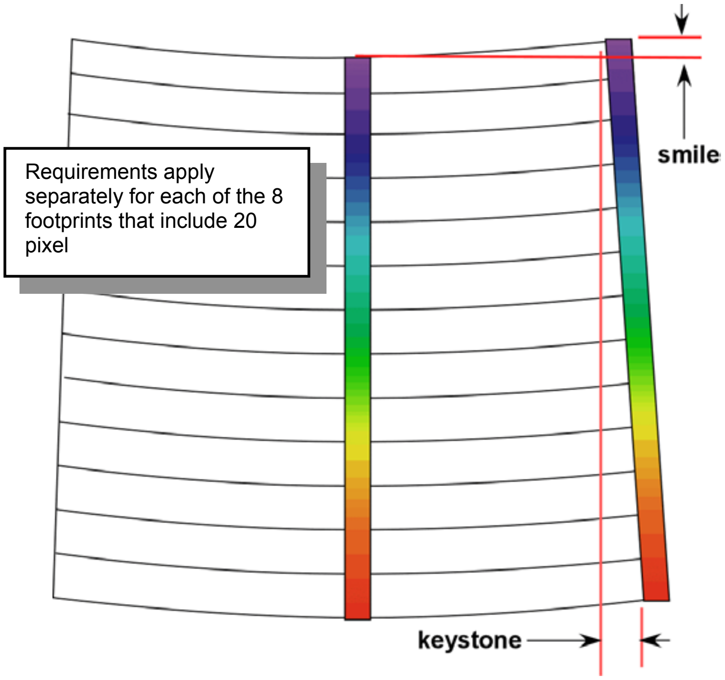
Figure 9 Spectral resolution and sampling

$$W(x)=\frac{\displaystyle\int_{\lambda=\lambda_0-x\cdot\Delta\lambda}^{\lambda_0+x\cdot\Delta\lambda} ILS(\lambda)\cdot d\lambda}{\displaystyle\int_{\lambda=0}^{\lambda=\infty} ILS(\lambda)\cdot d\lambda}$$



	Band	Requirement	Prediction*
	[μm]	[pixels/ sample]	[pixels/ sample]
W(0.5)	0.76	> 0.7	.90 to .94
	1.60		.87 to .89
	2.06		.85 to .88
W(1.0)	0.76	> 0.9	.98 to .99
	1.60		.97 to .98
	2.06		.97 to .98
W(6.0)	0.76	> 0.99	.992 to .997
	1.60		.996 to .999
	2.06		.997 to .999

Figure 10 Instrument line shape function



Requirements apply separately for each of the 8 footprints that include 20 pixel

	Band	Requirement	Prediction
	[µm]	[pixels/ sample]	[pixels/ sample]
Smile	0.76	0.25	0.083
	1.60	0.25	0.071
	2.06	0.25	0.085
Keystone	0.76	0.50	0.56*
	1.60	0.50	0.23
	2.06	0.50	0.37

Figure 11 Keystone and smile distortion

3. SUMMARY

The optical design of the Orbiting Carbon Observatory instrument is based on three substantially similar refractive spectrometer designs coupled to an all-reflective single telescope/re-collimator entrance optic via a simple dichroic relay system. The use of aspheric lens elements allows for a minimum of optical elements, while providing the necessary degrees of freedom to accomplish the demanding spectral resolution requirements needed for the science retrieval. A single, all-reflective telescope allows the three spectrometers to observe the same scene simultaneously. A dichroic relay system allows the bands to be separated, isolated, and re-imaged onto the individual spectrometer entrance slits. Finally, linear polarizers are introduced ahead of each spectrometer entrance slit to pass only the polarization that is efficiently diffracted by the spectrometer grating. Critical requirements for this optical system are presented along with predicted performance. With the exception of a minor adjustment in the A-band spectrometer prescription, critical requirements for spectral resolution, sampling, instrument line shape, and distortion are shown to meet or exceed requirements in the preliminary optical design.

REFERENCES

1. Crisp,D. V. Duval, P. Mouroulis, R. Pollock, D. Vane, "The Cloudsat Profiling A-band Spectrometer/Imager, PABSI", IGARSS 2000, FR01.0900,2000
2. R. Haring, R. Pollock, R. Cross, D Crisp, " Oxygen A-band spectrometer breadboard for the Orbiting Carbon Observatory, *Infrared Spaceborne Remote Sensing X*, Marji Strojnik, Bjom Anderseen,, Vol. 4818, 201-208, SPIE, Seattle, 2002