The Orbiting Carbon Observatory: NASA's First Dedicated Carbon Dioxide Mission

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ABSTRACT

The Orbiting Carbon Observatory is scheduled for launch from Vandenberg Air Force Base in California in January 2009. This Earth System Science Pathfinder (ESSP) mission carries and points a single instrument that incorporates 3 high-resolution grating spectrometers designed to measure the absorption of reflected sunlight by near-infrared carbon dioxide (CO_2) and molecular oxygen bands. These spectra will be analyzed to retrieve estimates of the column-averaged CO_2 dry air mole fraction, X_{CO2}. Pre-flight qualification and calibration tests completed in early 2008 indicate that the instrument will provide high quality X_{CO2} data. The instrument was integrated into the spacecraft, and the completed Observatory was qualified and tested during the spring and summer of 2008, in preparation for delivery to the launch site in the fall of this year. The Observatory will initially be launched into a 635 km altitude, near-polar orbit. The on-board propulsion system will then raise the orbit to 705 km and insert OCO into the Earth Observing System Afternoon Constellation (A-Train). The first routine science observations are expected about 45 days after launch. Calibrated spectral radiances will be archived starting about 6 months later. An exploratory X_{CO2} product will be validated and then archived starting about 3 months after that.

Keywords: NASA, Earth System Science Pathfinder, Carbon Dioxide, Carbon Cycle, Climate

1. INTRODUCTION

Carbon dioxide (CO_2) is the primary human-produced greenhouse gas and an important driver for climate change [1]. Human activities iluding fossil fuel combustion, biomass burning, deforestation, and other land use practices are currently adding almost 30 x 10^9 tons of carbon dioxide (CO_2) to the atmosphere each year, and this rate of emission is increasing. Precise ground-based measurements of CO_2 indicate that only about 60% of the CO_2 that has been emitted into the atmosphere over the past half century has remained there. The rest has apparently been absorbed by the oceans or by land plants. Existing CO_2 measurements also show that the atmospheric CO_2 buildup varies dramatically from year to year in response to smoothly increasing emission rates. The existing CO_2 monitoring network does not have the spatial resolution, coverage, or sampling rates needed to identify the natural CO_2 "sinks" responsible for absorbing this CO_2 or the processes that control their efficiency over time [2]. A better understanding of the processes that are controlling the present-day atmospheric CO_2 is essential for predicting the rate of CO_2 increases in the future and its impact on the climate.

NASA selected the Orbiting Carbon Observatory (OCO) as the fifth mission in Earth System Science Pathfinder (ESSP) Program to address these issues [3,4]. During its nominal two-year operational lifetime, OCO will make space-based measurements of the CO_2 and molecular oxygen (O_2) column abundances over the sunlit hemisphere of the Earth. These data will be analyzed with remote sensing algorithms to retrieve estimates of the column-averaged CO_2 dry air mole fraction, X_{CO2} with the accuracy and sampling resolution needed to characterize surface sources and sinks of CO_2 on regional scales over the entire globe. This is a particularly challenging space-based measurement because the surface sources and sinks of CO_2 must be inferred from subtle spatial and temporal variations in X_{CO2}. Modeling studies predict that X_{CO2} variations will rarely exceed 2% on regional scales (8 parts per million by volume, or *ppm*, out of the ambient ~380 ppm background). Modeling studies indicate that X_{CO2} measurements with precisions near 0.3 to 0.5 % (1 to 2 ppm) on regional-to-continental scales are needed to identify surface CO_2 sources and sinks at these spatial resolutions and characterize their variability over the seasonal cycle [5, 6]. A comprehensive validation program is therefore an important component of this mission.

2. MEASURING CO_2 FROM SPACE: THE OCO INSTRUMENT

The OCO measurement objectives and instrument have been described earlier [3, 4], and are only summarized here. The Orbiting Carbon Observatory carries a single instrument that incorporates three, co-boresighted, long-slit, imaging grating spectrometers [7,8]. The spectrometers are optimized for the O_2 A-band centered near 0.765 μm and the CO_2 bands centered near 1.61 and 2.06 μm. The O_2 spectrometer has a resolving power of $\lambda/\Delta\lambda$~21,000, while the CO_2 spectrometers have resolving powers of ~24,000. All three spectrometers use similar optical designs and are integrated into a common structure to improve mechanical and thermal stability. A schematic of the spectrometer optical design is shown in Fig. 1a.

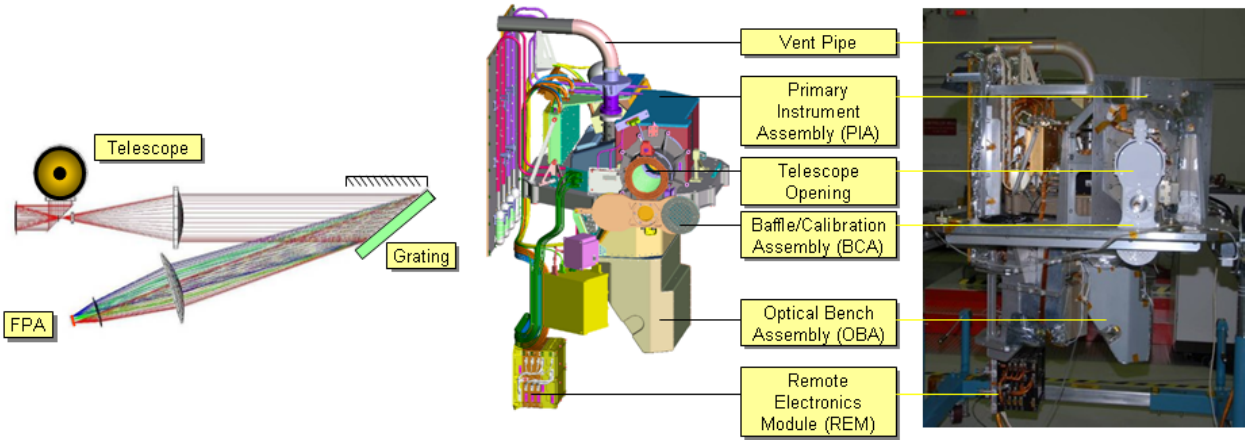

Fig. 1. (a) Optical schematic of the OCO foreoptics and one of the spectrometer channels, showing layout. (b) mechanical model of the assembled instrument, showing major components. (c) Picture of the assembled instrument in its handling fixture.

The instrument views the Earth through an f/1.8 Cassegrain telescope. The light captured by the telescope is focused on a field top, recollimated, and then distributed to the entrance slits of the three spectrometers by a set of relay optics (Fig. 1a). The relay optics for each spectrometer includes a beam splitter and narrow-band filter that act as a pre-disperser for the spectrometer, transmitting only the spectral range needed by that channel. A polarizer has been inserted in front of each spectrometer slit to reject light polarized in directions that would not be transmitted to the focal planes by the gratings [7]. Once light passes through each of the 3 spectrometer slits, it is collimated, dispersed by a planar holographic diffraction grating, and then refocused onto a 2-dimensional focal plane array (FPA) (Fig. 1a). A 2-dimensional image of the spectrum is displayed on a focal plane array (FPA) with wavelength variations in the direction perpendicular to the long axis of the slit and spatial variations in direction parallel to the long axis of the slit. The spectrum is recorded on a ~190 by 1024 pixel region near the middle of each 1024 by 1024 pixel FPA with 18 micron square pixels [4]. The FPA's are thermally isolated from the relatively warm (-5 °C) optical bench by cryogenic sub-system. The two CO_2 FPA's are cooled below −180 °C, while the O_2 FPA is cooled to below −120 °C. The FPA package includes a cold, narrow band filter just above the FPA to minimize the thermal emission from the spectrometer body and other sources of scattered light incident on the FPA.

The three spectrometers are each read out continuously at 3 Hz. To reduce the downlink data volume, a ~160-pixel wide segment of the ~190-pixel wide spatial dimension of each FPA is summed into ~20-pixel wide segments, producing up to 8 spatially-averaged spectra along the length of the slit [4]. The along-slit angular field of view of each of these spatially-averaged "super-pixels: is ~1.8 mrad. This corresponds to a ~1.3 km instantaneous field of view (IFOV) at nadir from a 705 km orbit. The angular width of the narrow dimension of the slit is only 0.14 mrad, but the telescope focus was purposely blurred to increase the effective full width at half maximum of each slit to ~0.6 mrad to simplify the co-alignment of the boresights of the 3 spectrometer slits. [7].

An on-board calibration assembly is integrated into the telescope baffle [7]. This assembly consists of a paddle that has an aperture cover (lens cap) on one end and a transmission diffuser on the other. Either end of this paddle can be rotated in front of the telescope aperture by an actuator (Fig. 2a). The cover is closed to protect the instrument during launch and orbit maintenance operations. It is also closed to acquire "darks" that are used to monitor the zero-level offset of the

FPAs. The surface of the aperture cover that faces the telescope objective has a gold-coated diffuser that can be illuminated by one of 3 tungsten lamps installed the baffle assembly (2b). These lamps are used to take "flat field" images that are used to monitor the relative gain of the pixels on each FPA.

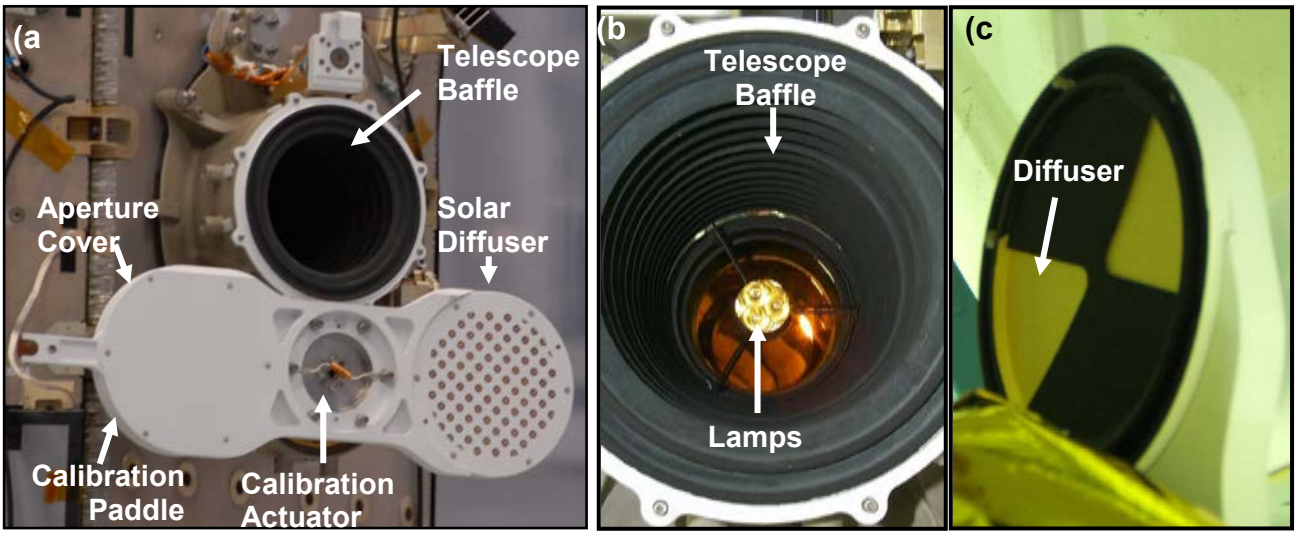

Fig. 2: (a) The calibration/baffle assembly is shown in "open" position used for normal science operations. (b) A view into the telescope baffle assembly, showing the location of the calibration lamps on the back of the Cassegrain secondary. (c) The calibration diffuser on the back of the aperture cover. The pattern on this diffuser optimizes the intensity of the lamps in all three channels.

The calibration paddle is rotated 180 degrees from the closed position to place the transmission diffuser in front of the telescope aperture to view the sun. Measurements of sunlight through the diffuser provide an absolute radiometric calibration for the instrument. The calibration paddle is rotated 90 degrees from either the closed or diffuser positions for normal science observations.

3. PRE-LAUNCH TESTING OF THE OCO INSTRUMENT

The integration of the OCO instrument optical bench assembly was completed in the late summer of 2007. It was then installed in a thermo-vacuum (TV) chamber to focus the spectrometers on the FPA's. This operation had to be performed in vacuum because the optical bench and focal planes had to be at their operating temperatures and because the refractive optics in the spectrometers are designed to focus only in vacuum [8]. Once the spectrometers were focused, the instrument was removed from the chamber, the FPA focus mechanisms were replaced with hard shims, and the instrument was returned to the TV chamber to verify the focus. The instrument was then removed from the TV chamber to complete the integration process, and then to perform the remaining flight qualification tests (e.g. shake tests, electrical compatibility, etc.).

The instrument was returned to the TV chamber to perform the final characterization and calibration tests in January and February of 2008. These tests employed a board range of sources designed to verify the radiometric, geometric, and spectroscopic performance of the instrument. All of these sources were located external to the TV chamber, on a deck located above the chamber, and illuminated the instrument through a window on the top of the chamber (Fig. 3).

The primary tool for radiometric calibration was a 0.9 m diameter, barium sulphate coated integrating sphere. This integrating sphere was illuminated by 3 internal tungsten light bulbs (35, 75, and 75 Watts), and one external 1000 Watt bulb with a variable shutter. During each radiometric calibration test, the sphere was purged with dry nitrogen to minimize absorption by CO_2 and O_2 in the air. The illumination level in this sphere was monitored by diodes with spectral passbands for the 0.765, 1.61 and 2.06 micron channels defined by flight spare spectral filters. These diodes

were calibrated against a standard lamp, traceable is to standards from the U.S. National Institute of Standards and Technology (NIST). The flight instrument collected measurements at more than 30 illumination levels to determine the instrument gain, gain linearity, and signal to noise ratio (SNR) over the full range of illumination levels expected on orbit. Preliminary analyses of these data indicated that all three channels deviate from linearity by less than 1% of their maximum signal level over their dynamic range. The two CO_2 channels exceed their SNR requirements with significant margins. A stop that was inserted into the O_2 A-band channel to prevent saturation reduced the throughput slightly more than intended, such that the SNR in this channel fell slightly (~14%) below its nominal specifications. However, the SNR in this channel is still comparable to that in the two CO_2 channels.

A collimator illuminated by continuum sources, atomic lamps, and tunable diode lasers was used to characterize the geometric, polarimetric, and spectroscopic performance of the instrument. All light sources with the exception of the atomic lamps, were introduced through a small integrating sphere designed to illuminate the full field of view of the flight instrument. Slits, knife-edge targets, and pinholes at the focus of the collimator were used to assess the focus and geometric performance of the spectrometers and their foreoptics. These measurements indicate that the OCO instrument meets it imaging requirements with one noteworthy exception. While the optical alignment of the slits for the O_2 A-band and 2.06 μm band are aligned within their specifications (±26 arc-seconds), the 1.61 μm slit is pointed ~70 arc-seconds away from the other two. This offset corresponds to an offset of ~300 m at nadir. We plan to correct this slit mis-alignment error in post-acquisition data processing.

Variable polarizers installed at the focus of the collimator were used to assess the degree and angle of polarization for each channel. The peak response of all 3 channels is within ±2.5° of nominal (defined by the polarization passed by the grating), well within the specification (±4°). The relative attenuation of the unwanted polarization was several thousand to 1, dramatically exceeding their nominal requirements.

The atomic lamps provided an absolute wavelength standard in each spectral channel and provided constraints on the instrument line shape function. Argon, neon, krypton, and xenon pen-ray lamps and a hollow-cathode thorium-argon lamp were used in both the integrating sphere and in the collimator, but these sources produced a more useful range of illuminations in the collimator, where several atomic lines could be seen in each channel.

Three external cavity tunable diode lasers (TDL's) provided the most effective approach for characterizing the core of the ILS, because these sources produced spectral lines much narrower (typically a few hundred kHz) than the full-width-at-half-maximum (FWHM) of the instrument line shape (ILS). The wavelengths of each laser was tuned in small steps (typically < 1/10 of a pixel) across selected regions of each FPA to map out the ILS on selected pixels. There functions were then interpolated to other parts of the wavelength range.

A more comprehensive description of the ILS across each spectral channel was obtained by adopting methods originally pioneered by the Atmospheric Infrared Sounder (AIRS) team [9]. In this approach, the output of a high-resolution step-scan Fourier transform spectrometer (FTS) was used to illuminate the OCO instrument aperture. Each of the 1024 spectral samples in each of the 8 measurement footprints records an interferogram at each FTIR mirror position. These data were then analyzed to define the far wings of the ILS, where the TDL's produced very little signal. Preliminary results from this experiment led to the discovery of scattered light near the edges of both the 1.61 and 2.06 μm CO_2 channels. This light originates from outside the passbands of these channels, and is thought to be scattered onto the FPA by some part of the FPA package. This source of scattered light appears to be stable and can be removed as part of the routine calibration process.

The last, and in some ways most valuable piece of pre-launch calibration equipment was a heliostat that was installed on the roof of the building above the TV chamber, allowing us to illuminate the flight instrument with sunlight that had traversed the atmosphere (Fig. 3). Direct sunlight from the heliostat was diffused with a Spectrlon® plate just above the window on the TV chamber, or directed into the chamber by a mirror to be diffused by the solar diffuser incorporated into the on-board calibrator. The heliostat was used to collect measurements of atmospheric O_2 and CO_2 absorption spectra with the flight instrument. The reference for these measurements consisted of spectra collected by a well-calibrated Brueker HR125 FTS located about 200 m away from the TV facility. This FTS is a part of the Total Column Carbon Observing Network, which is a major component of the OCO ground-based validation system. The FTS and flight instrument simultaneously collected spectra of sunlight that had traversed essentially the same atmospheric optical

path. Comparisons between the FTS and flight instrument spectra are providing an end-to-end test of the flight instrument's dispersion, ILS, and other aspects of instrument performance.

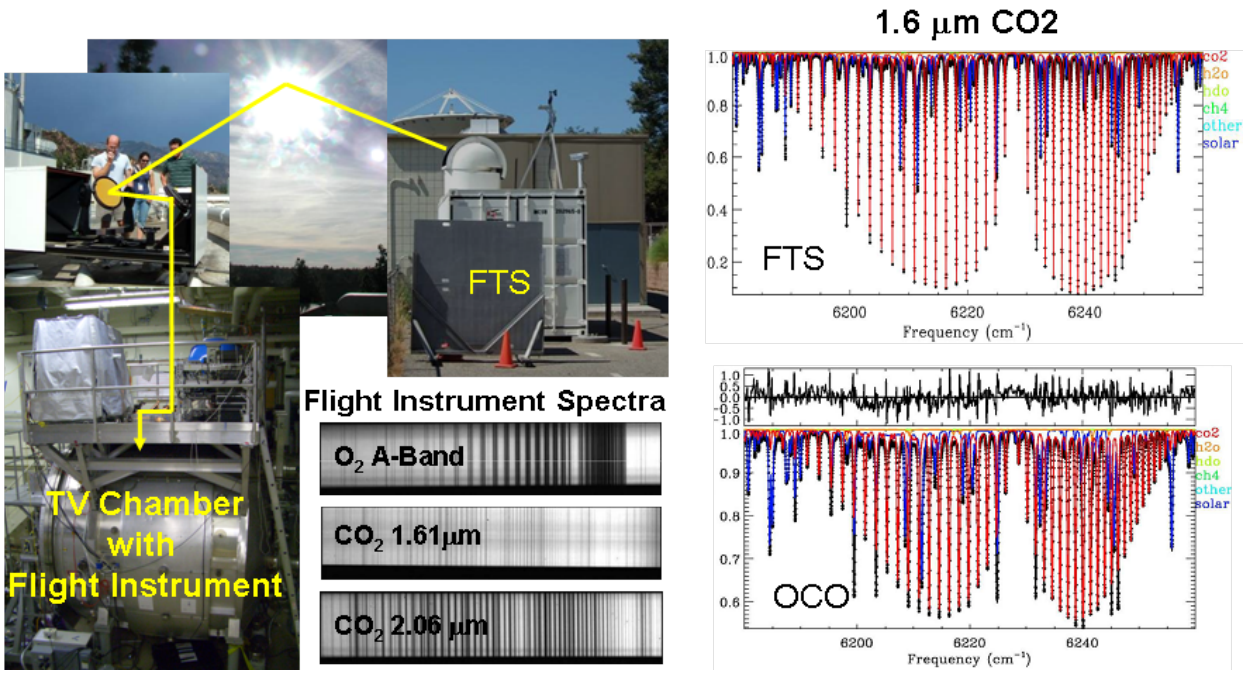

Fig. 3. This Montage shows the thermo-vacuum (TV) chamber with the flight instrument (bottom left), and the deck above it with the calibration equipment. The collimator is on the left side of the deck covered by its purged cover, and the integrating sphere (blue) is shown on the right hand side of the deck. The heliostat on the roof of the TV building is shown in the upper left. Raw spectra recorded by the flight instrument are shown at the bottom center. The shipping container with the dome houses the TCCON FTIR spectrometer used as a reference. Spectral from the FTIR (FTS) and flight instrument (OCO) are shown at right.

4. THE OCO SPACECRAFT

The OCO spacecraft bus is based on a single-string version of Orbital Sciences LEOStar-2 architecture [4]. This 3-axis stabilized bus consists of a 2.12 m long hexagonal column that is 0.94 m wide (face to face). It provides power, receives and processes commands from the ground, records, stores, and downlinks the data collected by the instrument. The bus also houses the instrument, which is enclosed within the upper half of the structure for thermal stability. Two deployable solar panels provide around 900 Watts when illuminated at near normal incidence. These panels rotate around the pitch (y) axis of the spacecraft bus to track the sun. They charge a 35 Amp-hr nickel-hydrogen battery that provides power during eclipse. The command and data handling system manages the attitude control, power, propulsion, and telecom systems, and the 128 Gigabit solid-state recorder that stores the science data. Both science and housekeeping data are usually returned to the ground station at 150 megabits/second using an X-band transmitter and a body-mounted X-band patch antenna. Spacecraft and instrument housekeeping data can also be returned using an S-band link to a ground station or through a NASA Tracking and Data Relay Satellite (TDRS). Commands are received through redundant S-band receivers, linked to a pair of helical omni-directional antennas. The spacecraft attitude control system points the instrument for science and calibration observations. It also points the body-mounted X-band antenna at the ground station for data downlink. A GPS receiver provides positional information along the orbit. A star tracker, inertial measurement unit, and a magnetometer provide pointing information. Pitch, roll, and yaw are controlled by 4 reaction wheels. Three magnetic torque rods are used to de-spin the reaction wheels. The propulsion system carries 45 kg of hydrazine to raise the orbit from the nominal injection altitude (~635 km) to the operational orbit (705 km), adjust the

orbit inclination as necessary, maintain the orbit during its 2-year nominal lifetime, and then de-orbit the Observatory at the end of the mission.

5. OBSERVATORY INTEGRATION AND TEST

The spacecraft bus integration and test activities were completed in early March 2008, just before the instrument was delivered for integration. The instrument integration went more smoothly than expected, and was completed ahead of schedule. The completed Observatory then went through a battery of flight qualification tests, including electrical compatibility, vibration, shock, acoustics, thermal-vacuum test, and then a comprehensive performance test. All tests were passed. At the time of writing, the Observatory is on track for an on-schedule delivery to Vandenberg Air Force Base for integration with the launch vehicle in late October 2008.

6. LAUNCH AND EARLY OPERATIONS

The Observatory is currently scheduled for launch from Vandeberg Air Force Base no earlier than January 15, 2009. The nominal launch time is 2:58 AM. The Observatory will initially be launched into a 635 km altitude, near-polar orbit. The on-board propulsion system will then raise the orbit to 705 km and insert OCO into the Earth Observing System (EOS) Afternoon Constellation (also known as the "A-Train"). OCO will fly approximately 3 minutes ahead of the EOS Aqua platform, with an ascending nodal crossing time of 1:27 PM. The orbit raising and in-orbit checkout (IOC) activities are expected to last about 45 days. The first routine science observations are expected in early March 2009. Calibrated spectral radiances will be archived in a NASA Distributed Active Archive Center (DAAC) starting 6 months after the end of IOC. An exploratory X_{CO2} product will first be validated using a global ground-based validation network [3,4] and then delivered to the OCO Active Archive Center within nine months of the IOC completion.

7. ACKNOWLEDGMENTS

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