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MEASURING CO₂ FROM SPACE: THE NASA ORBITING CARBON OBSERVATORY-2

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The Orbiting Carbon Observatory (OCO) was the first NASA satellite designed to measure atmospheric carbon dioxide (CO₂) from space with the precision, resolution, and coverage needed to detect CO₂ surface fluxes. OCO was designed to collect 0.5 to 1 million soundings each day. Typical measurements over land were expected to have precisions of 0.3% within surface footprints smaller than 3 square km. This project suffered a major setback in February 2009 when the OCO launch vehicle failed to achieve orbit and the satellite was lost. The U.S. Congress has since authorized a restart of the OCO project, and the President's 2010 budget proposal includes funding to develop and fly a replacement for OCO that could be ready for launch no later than February 2013. This mission has been designated OCO-2. While this mission will be a near "carbon copy" of OCO, some changes were needed to replace components that were no longer available. Here, we describe the capabilities, of the OCO-2 mission, highlighting its differences from OCO.

I. INTRODUCTION

Fossil fuel combustion and other human activities are emitting more than 30 billion tons of carbon dioxide (CO₂) into the atmosphere every year. Interestingly, atmospheric CO₂ measurements currently being collected by a global network of surface stations indicate that less than half of this CO₂ is accumulating in the atmosphere. The remainder is apparently being absorbed by CO₂ "sinks" in the ocean and the terrestrial biosphere, whose nature and location are poorly understood. The efficiency of these sinks can vary dramatically from year to year. Some years, they absorb almost all of the CO₂ emitted by human activity, while in other years, they absorb very little. The mechanisms controlling their efficiency are poorly understood. Uncertainties in the nature, location, and behavior of the sinks severely hinder efforts to predict understand how they might evolve as the climate changes, or whether they will continue to reduce the rate of buildup of atmospheric CO₂ in the future.

While the existing surface greenhouse gas monitoring network has expanded continuously over the past 50 years and now provides the accuracy and coverage needed to quantify the abundance of this gas on global scales, it still lacks the spatial and temporal resolution and coverage needed to identify and quantify CO₂ sources and sinks on regional scales or to quantify emissions from discrete point sources. One way to address this problem is to collect spatially-resolved, global measurements of the column-averaged CO₂ dry air mole fraction, X_{CO₂}, from space.^{1,2} Precise measurements are needed for this application because surface sources and sinks of CO₂ produce small spatial and temporal variations in X_{CO₂}.^{3,4} While the atmospheric CO₂ mixing ratios can vary by as much as 8% near the ground (>30 ppm), these perturbations

decay rapidly with height, such that X_{CO₂} variations rarely exceed 2% (8 ppm) on regional to global scales. Existing measurements show that X_{CO₂} variations are usually no larger than 0.3% (1 ppm) on spatial scales that range from 100 km over continents to 1,000 km over the ocean.

Systematic biases with amplitudes larger than 0.3% on spatial scales of 100 to 1000 km will introduce spurious X_{CO₂} gradients that would be indistinguishable from those produced by true CO₂ sources or sinks. Absolute X_{CO₂} accuracies better than 0.3% on these scales are therefore essential for retrieving CO₂ fluxes. Truly global biases are less of a concern because they will not introduce spurious X_{CO₂} gradients. However, such biases can compromise validations of the space based measurements against other standards, such as the World Meteorological Organization (WMO) standard for atmospheric CO₂ that is used by the surface network.

Space based measurements of X_{CO₂} are likely to make their most significant contributions to our understanding of the carbon cycle over the ocean and over tropical land masses, because these regions are poorly sampled by the existing ground-based network. X_{CO₂} estimates over the ocean are needed to quantify their large natural oceanic CO₂ sources and sinks and to facilitate the tracking CO₂ emissions transported over the ocean by the prevailing winds. X_{CO₂} measurements must also be collected over nearly the full range of latitudes on the sunlit hemisphere to avoid uncertainties introduced by the transport of air in and out of the field of regard.

To resolve CO₂ fluxes on spatial scales ranging from <100 to ~1000 km, data must be collected at higher resolution to discriminate natural sinks from nearby sources. A small sampling footprint also helps to ensure that some cloud-free soundings can be obtained even in

partially cloudy regions, since the probability of measuring a cloud free scene is inversely proportional to footprint size. A small sounding footprint is also needed to quantify CO₂ emissions from discrete point sources, such as individual power plants or cities because the minimum detectable mass of CO₂ associated with a given concentration change (e.g. 1 ppm X_{CO2}) is inversely proportional to the area of the footprint.

II. THE ORBITING CARBON OBSERVATORY

The Orbiting Carbon Observatory (OCO) was the first NASA mission designed to measure atmospheric CO₂ with the sensitivity, spatial resolution, and coverage needed to characterize CO₂ sources and sinks on regional scales at monthly intervals.^{5,6,7} OCO was a Principal Investigator (PI) led mission selected through a competitive NASA Announcement of Opportunity that was released by the NASA Earth System Science Pathfinder (ESSP) program. The PI selected the Jet Propulsion Laboratory, California Institute of Technology (JPL) as the implementing center and JPL selected Orbital Sciences Corporation and Hamilton Sundstrand as the spacecraft bus and instrument partners, respectively. OCO was officially selected as the 5th ESSP mission in July 2002, approved to enter formulation phase in December 2003, and confirmed in May 2005. The completed observatory was shipped to Vandenberg Air Force Base in November, 2008 for integration with the Orbital Sciences Corporation Taurus XL 3110 launch vehicle.

The OCO project suffered a major setback on 24 February 2009 when the launch vehicle failed to reach orbit, and the observatory was lost.^{7,8} NASA convened a Mishap Investigation Board's to identify the cause of the launch failure. This board concluded that the protective fairing failed to deploy, but was unable to find the root cause.

In parallel with this investigation, NASA's Earth Science Directorate instructed the OCO science team to document the justification and requirements for an OCO reflight.⁷ This study concluded that "While there have been advances in space-based CO₂ measurement capabilities since 2002, including the recent launch of the Japanese Greenhouse gases Observing Satellite (GOSAT), no existing or confirmed satellite sensor can provide the measurements needed to quantify both CO₂ sources *and* sinks." These conclusions were subsequently reinforced by a comprehensive report from the National Academy of Sciences,⁹ which also recommended a rapid reflight of OCO.

NASA instructed the OCO team to conduct a series of design studies to determine the best way to replace the OCO capabilities.⁸ These studies included solar near-infrared, thermal infrared, and active (LIDAR) techniques for measuring CO₂. The team also explored several flight options including adding the OCO

instrument to other payloads, co-manifesting OCO with other satellites, and flying OCO in other orbits. While each of these approaches offered some advantages, a "carbon copy" of the original mission was found to offer the best way to minimize the implementation schedule, cost, and risk, while preserving the science return.

In December, 2009, the U.S. Congress provided the funding needed to initiate the development of a replacement mission. Support for the remainder of the mission was subsequently included in the U.S. President's 2011 budget request. If this budget request is approved by Congress, the OCO-2 mission could be ready for launch no later than February 2013.

To meet these objectives, the NASA Science Mission Directorate initiated the Orbiting Carbon Observatory-2 (OCO-2) project as a Directed mission and selected JPL/Caltech as the implementing center. OCO-2 will preserve as much of the heritage OCO design as possible, to minimize cost, schedule, and implementation risk. OCO-2 therefore uses a dedicated spacecraft based on the Orbital LEOSTar-2 bus.^{5,6,10} The bus carries a single instrument, which incorporates three high resolution imaging grating spectrometers, designed to record high resolution spectra of reflected sunlight in the CO₂ bands near 1.61 and 2.06 microns (μm) and in the molecular oxygen A-band near 0.765 μm. The observatory will be launched into a near-polar orbit on a dedicated Taurus 3110 launch vehicle, and will fly at the head of the Earth Observing System Afternoon Constellation (EOS A-Train).

While this approach minimizes changes, some modifications in the flight system and mission design were needed to replace components that were no longer available and to incorporate lessons learned from the OCO implementation. The OCO-2 measurement approach, instrument design, spacecraft bus, mission operations and data delivery plans are summarized in the following sections. Significant differences between OCO and OCO-2 are highlighted.

III. MEASUREMENT APPROACH

To meet its requirements, the OCO-2 instrument must measure the absorption of sunlight by CO₂ and O₂ with adequate precision to yield X_{CO2} estimates with precisions better than 0.3% on spatial scales smaller than 1000 km over more than 90% of range of latitudes on the on the sunlit hemisphere of the Earth. X_{CO2} is defined as the ratio of the column abundances of CO₂ and the column abundance of dry air.^{5,6}

$$X_{CO2} = \int_0^{\infty} N_{CO2}(z) dz / \int_0^{\infty} N_{air}(z) dz .$$

Here, $N_{CO2}(z)$ is the altitude (z) dependent number density of CO₂ (e.g. number of CO₂ molecules per cubic meter) and $N_{air}(z)$ is the altitude dependent number

density of dry air. Because O_2 constitutes $0.20955 N_{air}$, X_{CO_2} can also be expressed as:

$$X_{CO_2} = 0.20955 \int_0^\infty N_{CO_2}(z) dz / \int_0^\infty N_{O_2}(z) dz .$$

The number densities of CO_2 and O_2 can be inferred from precise, spectroscopic observations of reflected sunlight because the measured intensity of the sunlight at wavelengths where these gases absorb is inversely proportional to the total number of molecules along the optical path.

To make these measurements, the instrument must have a high sensitivity and a high signal-to-noise ratio (SNR) over a wide dynamic range.^{5,6,10} A high spectral resolving power ($\lambda/\delta\lambda > 20,000$) is needed to resolve the CO_2 and O_2 lines from the adjacent continuum to maximize the sensitivity to small ($<0.3\%$) variations in X_{CO_2} . Measurements across the entire O_2 or CO_2 band are needed at high SNR because a 0.3% variation in X_{CO_2} must be inferred from substantially smaller variations in O_2 and CO_2 absorption strength. The retrieval algorithm must then perform a least squares fit to dozens of lines within each band to yield X_{CO_2} retrievals with precisions near 0.3% . A wide dynamic range is needed because the contrast between line cores and the adjacent continuum can exceed $100:1$, and because the signal level depends on the intensity of the sunlight reflected from the surface, which decreases with increasing solar zenith angle (latitude) and decreasing surface reflectance.

IV. INSTRUMENT DESIGN

As for OCO, the OCO-2 instrument consists of three, co-bore-sited, long-slit, imaging grating spectrometers optimized for the O_2 A-band at $0.765 \mu m$ and the CO_2 bands at 1.61 and $2.06 \mu m$ (Fig. 1).^{5,6,10,11} The instrument mass is ~ 140 kg, and its average power consumption is ~ 100 Watts. The 3 spectrometers use similar optical designs and are integrated into a common structure to improve system rigidity and thermal stability. They share a common housing and a common F/1.8 Cassegrain telescope. The light path is illustrated in Fig. 1. Light entering the telescope is focused at a field stop and then re-collimated before entering a relay optics assembly. There, it is directed to one of the three spectrometers by a dichroic beam splitter, and then transmitted through a narrowband pre-disperser filter. The pre-disperser filter for each spectral range transmits light with wavelengths within $\sim \pm 1\%$ of the central wavelength of the CO_2 or O_2 band of interest and rejects the rest. The light is then refocused on the spectrometer slits by a reverse Newtonian telescope. Each spectrometer slit is about 3 mm long and about $25 \mu m$ wide. These long, narrow slits are aligned to produce co-bore-sited fields of view that are ~ 0.0001 radians

wide by ~ 0.0146 radians long. Because the diffraction gratings efficiently disperse only the light that is polarized in the direction parallel to the slit, a polarizer was included in front of the slit to reject the unwanted polarization before it enters the spectrometer, where it could contribute to the scattered light background.

Once the light traverses a spectrometer slit, it is collimated by a 2-element refractive collimator, dispersed by a gold-coated, reflective planar holographic diffraction grating, and then focused by a 2-element camera lens on a 2-dimensional focal plane array (FPA), after traversing a second, narrowband filter. The narrowband filter just above the FPA is cooled to $\sim 180K$ to reject thermal emission from the instrument.

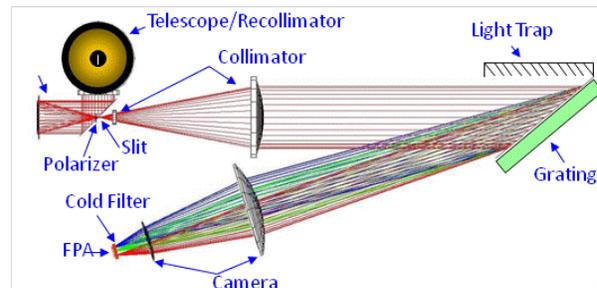


Fig. 1. The OCO-2 instrument showing the major optical components and optical path.

Following the OCO design, the spectral range and resolving power of each channel includes the complete molecular absorption band as well as some nearby continuum to provide constraints on the optical properties of the surface and aerosols as well as absorbing gases. To meet these requirements, the O_2 A-band channel covers 0.758 to $0.772 \mu m$ with a resolving power of $>17,000$, while the 1.61 and $2.06 \mu m$ CO_2 channel cover 1.594 to $1.619 \mu m$ and 2.042 to $2.082 \mu m$, respectively with a resolving power $> 20,000$.

The spectrometer optics project a 2-dimensional image of a spectrum on 1024 by 1024 pixel FPA with $18 \mu m$ pixels (Fig. 2). The grating disperses the 1024 -pixel wide spectrum in the direction perpendicular to the long axis of the slit. The full-width at half maximum (FWHM) of the slit image on the FPA is sampled by 2 to 3 pixels in the direction of dispersion. The length of the slit limits spatial field of view to only ~ 190 pixels in the dimension orthogonal to the direction of dispersion. Science measurements are restricted to the center ~ 160 of these 190 pixels.

For normal science operations, the FPAs are continuously read out at 3 Hz. To reduce the downlink data rate and increase the signal to noise ratio, ~ 20 adjacent pixels in the FPA dimension parallel to the slit (i.e. The ‘‘Spatial Direction’’ in Fig. 2) are summed on board to produce up to 8 spatially-averaged spectra

along the slit. The along-slit angular field of view of each of these spatially-averaged “super-pixels” is ~ 1.8 mrad (0.1° or ~ 1.3 km at nadir from a 705 km orbit). The angular width of the narrow dimension of the slit is only 0.14 mrad, but the focus of the entrance telescope was purposely blurred to increase the effective full width at half maximum of each slit to ~ 0.6 mrad to simplify the bore-sight alignment among the 3 spectrometer slits.

In addition to the 8 spatially-binned, 1024-element spectra, each spectrometer also returns 4 to 20 spectral samples without on-board spatial binning to provide the full along-slit spatial resolution. Each of these full-resolution “color stripes” covers a 220 pixel wide region of the FPA that includes the full length of the slit (190 pixels) as well as a few pixels beyond the ends of the slit (Fig. 2). These full-spatial-resolution color stripes are used to detect spatial variability within each of the spatially summed super pixels and to quantify the thermal emission and scattered light within the instrument.

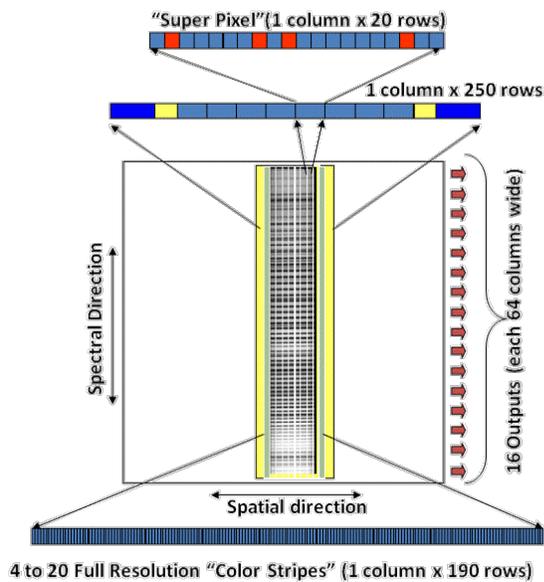


Fig. 2. The illumination and readout scheme used for the OCO-2 Focal Plane Arrays.

For OCO, the entrance slits for the 3 spectrometers were carefully co-aligned during the optical bench assembly to ensure that all 3 spectrometers would share a common bore site. After the instrument vibration test, an optical component in the $1.61 \mu\text{m}$ CO_2 channel shifted, introducing a ~ 70 arc second shift in the bore site of that channel.¹² The root cause of the misalignment was traced to a specific step in the optical bench assembly process. While it was not possible to correct this misalignment for the OCO instrument, a second vibration test was performed to ensure that no further movement would occur, and the science algorithms were modified to accommodate the pointing

offset. For OCO-2, the optical bench assembly process has been modified to avoid this problem. This modification will be verified by performing a “seating vibration” followed by an alignment test prior to full optical bench integration.

The OCO instrument used Teledyne mercury cadmium telluride (HgCdTe) FPAs in the 1.61 and $2.06 \mu\text{m}$ CO_2 channels and a silicon, HyViSiTM FPA in the O_2 A-band channel.^{5,6,12} All 3 FPAs used Teledyne HAWAII-1RGTM read-out integrated circuits, so that a common design could be used for their control and readout electronics design.

New FPAs are needed for OCO-2 for two reasons. First, there were not enough high quality spare HgCdTe FPAs from OCO to provide flight and flight spare FPAs for the CO_2 channels in the OCO-2 instrument. Second, there was a strong desire to mitigate the residual image artifacts discovered in the HyViSiTM FPA during OCO pre-flight instrument testing.^{8,14} The substrate-removed HgCdTe HAWAII-1RGTM FPA’s from Teledyne, like those recently flight qualified for the Hubble Space Telescope Wide Field Camera-3 (WF3), could address both of these issues. These FPA’s use the same electrical, thermal, and mechanical interfaces as those on OCO, minimizing the design changes needed for their accommodation. They also have slightly lower read noise than those used for OCO. In addition, because these FPAs are sensitive to the wavelengths sampled by the A-band as well as those sampled by the CO_2 channels, it might be possible to use these FPA’s in all 3 channels. This both reduces risk and provides an approach for mitigating the HyViSiTM residual image issues, because the HgCdTe FPAs show no evidence of this problem.

Because of their higher dark currents, the HgCdTe FPAs in the two CO_2 channels on OCO were maintained below 120 K, while silicon FPA in the O_2 A-band channel was cooled to <180 K.^{6,13,15} For the OCO-2 instrument, the cryolinks to the FPA’s have been redesigned to maintain all three FPA’s at <120 K. This change preserves the option of using substrate-removed HgCdTe FPA’s in all three channels. It may also facilitate the use of an existing HyViSiTM FPA in the A-band channel. Recent laboratory tests show that operating the A-Band HyViSiTM FPA at 120 K, rather than 180 K reduces the amplitude of the residual image anomaly to almost undetectable levels.

To cool its FPAs, the OCO instrument, used a Northrup Grumman Space Technology (NGST, formerly TRW) pulse tube cryocooler that was thermally coupled to an external radiator through variable conductance heat pipes.¹² This cryocooler was the flight spare from the EOS Aura Tropospheric Emission Spectrometer (TES) project, and the last of its kind. A different cryocooler was therefore needed for OCO-2. A single-stage version of the NGST pulse tube

cryocooler used by the National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite – R (GOES-R) Advanced Baseline Imager (ABI) was adopted to minimize the changes to the instrument’s thermal and electrical interfaces.^{8,12} This cryocooler is slightly smaller and more efficient than the one used by OCO, but did require changes in the cryocooler electronics and the heat pipes.

Thermal emission within the body of the spectrometer is an important source of noise in the 2.06 micron channel. For OCO, this emission this emission was reduced by cooling the optical bench to -5 °C. To do this, the instrument’s thermal radiative shroud was coupled to an external passive radiator by variable conductance heat pipes. The same approach will be used for OCO-2.



Fig. 3. The OCO-2 spacecraft bus will be a build-to-print of the original OCO LEOSTar-2 bus.

V. SPACECRAFT BUS

The OCO-2 spacecraft bus is based on a build-to-print of the Orbital Sciences LEOSTar-2 bus developed for OCO.^{5,6,13} The bus houses and points the instrument, provides power, receives and processes commands from the ground, records, and downlinks the data collected by the instrument, and maintains its position with the EOS A-Train. The primary structure consists of a 2.12 m long hexagonal column that is 0.94 m wide (Fig. 3). The central electronics unit uses a BAE RAD6000 flight computer to manage the attitude control, power, propulsion, and telecom systems, and the 128 Gigabit Seaker solid-state recorder that stores the science data collected by the instrument. The RAD6000 had to be modified to replace the static read-only memory (SRAM) part, which was based on an obsolete, 16-chip multi-chip module (MCM) with a newer SRAM part.⁸

The spacecraft attitude control system (ASC) points the instrument for science and calibration observations and the body-mounted X-band antenna at the ground station for data downlink. Pitch, roll, and yaw are controlled by 4 reaction wheels. Three magnetic torque

rods are used to de-spin the reaction wheels. OCO-2 uses the same types of Goodrich/Ithaco reaction wheels and torque rods that were used for OCO. The reaction wheels have been modified to address lifetime issues identified over the past decade.

The spacecraft’s position along its orbit is determined by a General Dynamics Viceroy GPS receiver. Pointing information is provided by a Sodern star tracker, a Honeywell miniature inertial measurement unit (MIMU), and a Goodrich magnetometer. The Sodern star tracker model used by OCO is no longer available. OCO-2 uses a new model that meets the same performance and interface requirements. Changes to the other ACS sensors are limited to replacements of individual parts due to obsolescence or evolution of the product line.

Both science and housekeeping data are usually returned to the ground at 150 megabits/second using an L3Communications X-band transmitter and a body-mounted X-band patch antenna. Spacecraft and instrument housekeeping data can also be returned by an S-band transmitter to a ground station or through a NASA Tracking and Data Relay Satellite (TDRS). Commands are received through an S-band receiver and a pair of omni-directional antennas. The S-band transmitter and receiver used by OCO are obsolete and are no longer available. OCO-2 will use S-band hardware from Thales Alenia that meets the same performance requirements, but is based on a new, all-digital design.

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). Once in orbit, it is used to adjust the orbit altitude and inclination as necessary to maintain the spacecraft’s position in the EOS-A-Train. Finally, it is used to de-orbit the Observatory at the end of the mission.

Two deployable solar panels supply ~900 Watts when illuminated at near normal incidence (Fig. 3). Their position is determined by encoders and course sun sensors. OCO used coarse sun sensors based on silicon solar cells, which are obsolete and no longer available. OCO-2 will use a sensor based on GaAs solar cells. The solar panels charge an Eagle Picher 35 Amp-hr nickel-hydrogen battery that provides power during eclipse. OCO-2 uses the same battery model used by OCO.

VI. MISSION DESIGN AND OPERATIONS

OCO-2 will initially be launched into a 635 km altitude, near-polar orbit on a Taurus XL 3110 launch vehicle. 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”). Like OCO, OCO-2 will fly at the head of the A-Train, but there are two significant

differences between the OCO and OCO-2 plans. First, after the loss of OCO, its location in front of the EOS Aqua spacecraft was allocated for the JAXA GCOM-W1 satellite. OCO-2 will fly in front of GCOM-W1. This change necessitated a reduction in size of the along-track orbit “control box” from 107 to 86 seconds. This change will require more frequent drag make-up maneuvers, but should not require more fuel.

This 705 km altitude, sun synchronous orbit follows the World Reference System-2 (WRS-2) ground track, yielding 233 orbits over its 16-day ground track repeat cycle. The orbit’s 1:30 PM mean local time is well suited for acquiring observations of the absorption of reflected sunlight by CO₂ and O₂ because the sun is high, maximizing the available signal. It also facilitates coordinated calibration and validation campaigns with other A-Train instruments, and synergistic use of OCO data with that from other A-Train platforms.

For normal science operations, the spacecraft bus orients the instrument to collect science data in Nadir, Glint, and Target modes.^{5,6} For Nadir observations, the bus points the instrument aperture to the local nadir, so that data can be collected along the ground track just beneath the spacecraft. For Glint observations, the ACS is programmed to point the instrument aperture toward the bright “glint” spot, where sunlight is specularly reflected from the surface. For Target observations, the ACS points the instrument’s aperture at specific stationary surface targets as the satellite flies overhead. To ensure that the target is not missed, and to characterize the X_{CO2} distribution near the target, the ACS superimposes a small amplitude sinusoidal oscillation ($\pm 0.23^\circ$ about the spacecraft y axis) in the direction perpendicular to the long dimension of the spectrometer slit. This scans the slits over a region centered on the nominal target. This “Target scan”, combined with the instruments 0.8° wide field of view, allows the instrument to collect thousands of observations over a 0.46° by 0.8° viewing box around the target. This approach could be very useful for characterizing CO₂ emissions from point sources.

For OCO, the nominal plan was to switch from Nadir to Glint observations on alternate 16-day global ground-track repeat cycles so that the entire Earth is mapped in each mode every 32 days.^{6,10} A similar approach has been adopted for OCO-2. Comparisons between Nadir and Glint observations will provide opportunities to identify and correct for biases introduced by the viewing geometry. Target observation will be acquired over an OCO-2 validation site roughly once each day.

The same data sampling rate is used for Nadir, Glint, and Target observations. In each mode, the instrument can collect up to 8 soundings over its 0.8-degree wide swath every 0.333 seconds. For nadir observations from a 705 km orbit, traveling at ~7 km/second, the 0.333

second frame rate yields surface footprints with down-track dimensions < 2.25 km. The cross-track dimension of the swath depends on the orientation of the slit with respect to the orbit path, which changes as the spacecraft travels from south to north along its orbit track.^{6,10} Near the polar terminators, when the spectrometer slit is oriented perpendicular to the orbit track, the cross-track swath for nadir observations is ~10.5 km wide. At the sub-solar latitude, where the spectrometer slit is almost perpendicular to the orbit track, the cross-track dimension of the swath is limited to the projected width of the slit, which is only about 0.1 km wide at nadir.

The high spatial resolution facilitates the discrimination of natural sinks from nearby sources and enhances the coverage by increasing the probability of collecting some cloud free soundings even in partially cloudy conditions. While the rapid down-track sampling yields high spatial resolution along the orbit tracks, the east-west resolution is largely determined by the distance between orbit tracks. The 98.8 minute orbit period, yields ~14.56 orbits each day that are separated by ~24.7° of longitude. The orbit track spacing decreases to ~13° after 2 days, and to 1.5° after a full 16-day repeat cycle.

The OCO instrument and data system were designed to collect up to 8 cross-track soundings every 0.333 seconds, yielding more than a million soundings over the sunlit hemisphere each day. Even with this high sampling rate, the narrow swath limits the spatial sampling to only about 7% of the Earth’s surface area over the 16 day ground repeat cycle. This was not considered to be a significant limitation for OCO, because the instrument is sensitive to the column-averaged CO₂ mole fraction, and CO₂ is distributed over a large area as it is distributed throughout the atmospheric column.

For OCO, the nominal plan was to reduce the swath to only 4 cross-track soundings per frame, so that the data volume for an entire day can be returned during a single overpass of a ground station. A similar plan has been adopted for OCO-2 as a cost saving measure. Even at this reduced data rate, OCO-2 will return over 500,000 soundings over the sunlit hemisphere each day and sample ~3.5% of the Earth’s surface area over each 16-day ground track repeat cycle.

VII. VALIDATION OF X_{CO2} RETRIEVALS

To ensure their accuracy, the space based X_{CO2} estimates are validated through comparisons with near-simultaneous measurements of X_{CO2} acquired by ground-based Fourier Transform Spectrometers in the Total Carbon Column Observing Network (TCCON).^{16,17} This network currently includes over a dozen stations, distributed over a range of latitudes spanning Lauder New Zealand and Ny Alesund,

Norway, and is continuing to grow. To relate TCCON measurements to the WMO CO₂ standard, aircraft observations have been collected over several stations, using the same in situ CO₂ measurement approaches used to define that standard. OCO-2 will target a TCCON site as often as once each day, acquiring thousands of measurements as it flies overhead. These measurements will be analyzed to reduce biases below 0.1% (0.3 ppm) at these sites. The space-based X_{CO_2} estimates will be further validated through comparisons with CO₂ and surface pressure measurements from ground based sites with the aid of data assimilation models to provide a more complete global assessment of measurement accuracy.

VIII. EXPERIENCE WITH GOSAT DATA

The OCO and GOSAT science teams formed a close collaboration during the implementation phases of these two missions. The primary focus of this collaboration was to cross calibrate the OCO and GOSAT instruments¹⁸ and cross validate their X_{CO_2} retrievals against common standard,¹⁷ to facilitate the combination of these two new space based data sets. Immediately after the loss of the OCO spacecraft, the GOSAT team invited the OCO science team to join their efforts to analyze the GOSAT data. NASA responded by reformulating the OCO science team as the Atmospheric Carbon Observations from Space (ACOS) team to (i) meet the NASA's obligations to its GOSAT partners, (ii) recover some of the science knowledge expected from OCO, and (iii) validate the OCO retrieval algorithms in a realistic environment.

Over the past 2 years, the ACOS team has participated in a series of GOSAT vicarious calibration campaigns in Railroad Valley, NV, retrieved global estimates of X_{CO_2} from GOSAT soundings, and validated these X_{CO_2} retrievals against ground-based remote sensing observations from TCCON. The GOSAT data are also being used to assess the impact of clouds, optically thick aerosols, and other environmental conditions on the accuracy, coverage, and total yield of X_{CO_2} soundings.

The vicarious calibration experiments have helped to verify and correct drifts in the pre-launch GOSAT radiometric calibration parameters. Comparisons of ACOS GOSAT X_{CO_2} retrievals with TCCON measurements have revealed global, -2% bias in the estimated X_{CO_2} . Comparisons of GOSAT O₂ A-band retrievals of surface pressure with surface pressure estimates from the European Centre for Medium-Range Weather Forecasts (ECMWF) show that about half of this X_{CO_2} bias can be attributed to a +10 hPa bias in the retrieved surface pressure. The ACOS team is working closely with the GOSAT team to identify and correct biases, and to improve the yield of GOSAT retrievals.

IX. DATA PRODUCTS DELIVERY

Science and housekeeping data are transmitted to a NASA Near Earth Network station in Alaska once each day. While the OCO mission planned to use the Poker Flats station, OCO-2 will use the Alaska Satellite facility. The raw telemetry are transferred to the Earth Science Mission Operations (ESMO) center at the NASA Goddard Space Flight Center (GSFC) where it is converted to time-ordered raw radiance spectra (Level 0 Products). This product is delivered to the OCO-2 Science Data Operations System (SDOS) at the NASA Jet Propulsion Laboratory, where full orbits are first processed to yield radiometrically calibrated, geolocated spectral radiances within the O₂ and CO₂ bands (Level 1 Products). The bore-sighted spectra for each coincident CO₂ / O₂ sounding are then processed to estimate the column averaged CO₂ dry air mole fraction, X_{CO_2} (Level 2 Products). Other Level 2 data products to be retrieved from each sounding include the surface pressure, surface-weighted estimates of the column-averaged water vapor and atmospheric temperature, the vertical distribution and optical depth of optically-thin clouds and aerosols, the CO₂ column averaging kernels, and a number of diagnostic products.

For the OCO mission, the project was required to begin delivering Level 1 data products to a NASA archive within 6 months of the start of routine science operations. The project was required to start delivering Level 2 product to the archive within three months after that. These relatively long latency times were needed to verify the calibration and validate the retrievals against TCCON measurements to the extent needed meet the stringent accuracy requirements.

Experience gained from GOSAT data processing has substantially accelerated the OCO-2 retrieval algorithm development effort, and has provided valuable practice with the calibration of spectral radiances and the validation of the X_{CO_2} retrievals. Given this experience, the OCO-2 project plans to begin delivering Level 1 data products to the NASA archive within 3 months of the start of routine science operations. Level 2 products will start being delivered no more than three months after that. The project will then strive to reduce these latencies to less than 3 weeks for Level 1 and 6 weeks for Level 2 products.

X. CONCLUSIONS

While the loss of OCO dealt a serious setback to NASA's plans for monitoring CO₂ from space, the rapid rebuild of OCO-2 provides opportunities to recover from this the original objectives within 3 years of the original schedule. The OCO-2 project has successfully passed its Critical Design Review (CDR) and is entering its implementation phase. Within a year, the instrument and spacecraft bus are expected to begin their pre-flight testing programs. If all goes as planned, the completed

observatory will be delivered to Vandenberg Air Force Base in late 2012 for integration with the launch vehicle, in preparation for launch in February 2013. The orbit raising and in-orbit checkout will require about 45 days. Routine science observations will then begin.

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