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Acta Astronautica 56 (2005) 193–197

ACTA ASTRONAUTICA

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The orbiting carbon observatory mission

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Abstract

The Orbiting Carbon Observatory (OCO) mission was selected by NASA's Office of Earth Science as the fifth mission in its Earth System Science Pathfinder (ESSP) Program. OCO will make the first global, space-based measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize sources and sinks of this important green-house gas. These measurements will improve our ability to forecast CO_2-induced climate change. OCO will fly in a 1:15 PM sun-synchronous orbit, sharing its ground track with the Earth Observing System (EOS) Aqua platform. It will carry high-resolution spectrometers to measure reflected sunlight in the molecular oxygen (O_2) A-band at 0.76 μm and the CO_2 bands at 1.61 and 2.06 μm to retrieve the column-averaged CO_2 dry air mole fraction, X_{CO_2}. A comprehensive validation and correlative measurement program has been incorporated into this mission to ensure that X_{CO_2} can be retrieved with precisions of 0.3% (1 ppm) on regional scales.

1. Introduction

Over the past 40 years, measurements from a global network of ground-based stations indicate that only about half of the CO_2 that has been released into the atmosphere by fossil fuel combustion, biomass burning, and other human activities has remained there (Fig. 1). The rest has apparently been absorbed by the oceans and by land-based ecosystems. Unfortunately, the existing CO_2 monitoring network does not provide the coverage or spatial resolution needed to identify and monitor these CO_2 sinks. In particular, while these measurements provide strong evidence for a northern hemisphere sink, they cannot discriminate the relative roles of the North American and Asian continents and the ocean basins. They also cannot fully explain why the annual buildup of atmospheric carbon varies from 1 to 7 Gtons per year in response to steadily rising fossil fuel emission rates.

These uncertainties complicate efforts to predict future atmospheric CO_2 concentrations or their effects on the climate, because they limit our ability to predict how the sinks might change as the climate evolves. They also complicate efforts to monitor compliance to proposed green-house gas emission treaties that give credit for CO_2 sinks.

To address these issues, NASA selected the Orbiting Carbon Observatory (OCO) as the fifth mission

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doi:10.1016/j.actaastro.2004.09.032

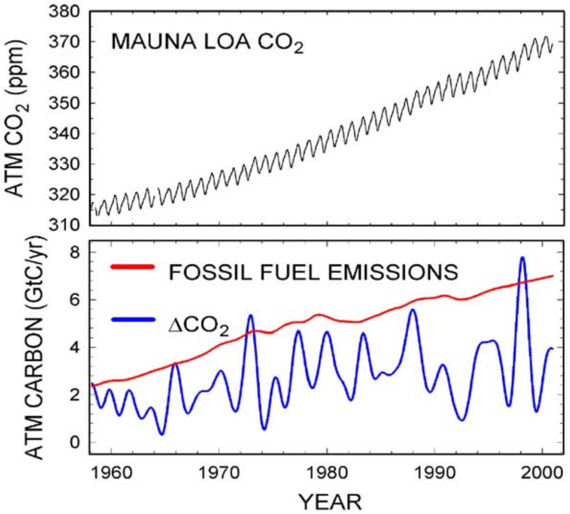

Fig. 1. Top: Atmospheric CO_2 concentrations measured at Mauna Loa Observatory since 1958 [2]. Bottom: Atmospheric carbon increases from fossil fuel combustion (red) are compared to the measured atmospheric carbon buildup (blue) [3].

in Earth System Science Pathfinder (ESSP) Program. OCO is designed to make global, space-based measurements of atmospheric CO_2 with the spatial resolution and accuracy needed to characterize surface sources and sinks. This paper summarizes the factors that influenced the design of the OCO mission, and provides a brief description of the implementation approach.

2. Measurement approach

Modeling studies with source–sink inversion models [1] indicate that our understanding of CO_2 sources and sinks could be improved substantially if data from the existing ground-based CO_2 monitoring network were augmented by global, space-based measurements of the column-integrated CO_2 dry air mole fraction (X_{CO_2}) with accuracies of ~0.3% (1 ppm out of 370 ppm). The OCO mission incorporates space- and ground-based elements to address this need. The space-based observatory will collect high-resolution spectra of reflected sunlight in the 0.76 μm O_2 A-band, and the CO_2 bands at 1.58 and 2.06 μm (Fig. 2. These data will be analyzed with a simultaneous retrieval algorithm to estimate spatial and temporal gradients of X_{CO_2} along the ground track.

The space-based X_{CO_2} measurements will be complemented by in situ and remote sensing data from a ground-based validation and correlative measurement network to ensure that the space-based X_{CO_2} measurements have precisions of 0.3% (1-ppm CO_2) on regional scales at monthly intervals. Once validated, these measurements will be incorporated into sophisticated source–sink inversion models to characterize the geographic distribution of CO_2 sources and sinks over two annual cycles.

The requirements for the space-based measurements were derived from end-to-end observation system simulation experiments [4]. The weak CO_2 band near 1.61 μm was selected for CO_2 column measurements because this spectral region is relatively free of absorption by other gases (Fig. 2b). Measurements in this band are also ideal for studying near-surface CO_2 sources and sinks because high-resolution spectra of this band are most sensitive to the CO_2 concentration near the surface.

The absorption depth of these lines therefore increases almost linearly with the CO_2 number density and path length, such that high-resolution spectroscopic measurements yield their greatest information content near the surface.

Bore-sighted measurements in the 0.76 μm O_2 A-band provide direct constraints on the atmospheric pressure of the reflecting surface (Fig. 2a). This information must be combined with the CO_2 column estimates to derive the column-averaged CO_2 dry air mole fraction, X_{CO_2}. Aircraft studies show that A-band observations can provide surface pressure estimates with accuracies of ~1 mb (O'Brien and Mitchell, 1992). A-Band spectra also provide a sensitive indicator of clouds and optically thick aerosols, which preclude full column measurements of CO_2.

Finally, spectra of the strong 2.06 μm band will provide independent constraints on the aerosol optical properties at near-infrared wavelengths, dramatically improving the accuracy of X_{CO_2} retrievals in aerosol-laden conditions [4]. Bore-sighted measurements in this band also provide information about the atmospheric temperature and humidity along the optical path, minimizing systematic errors associated with uncertainties in these parameters. A single *sounding* consists of near-simultaneous, bore-sighted spectra in

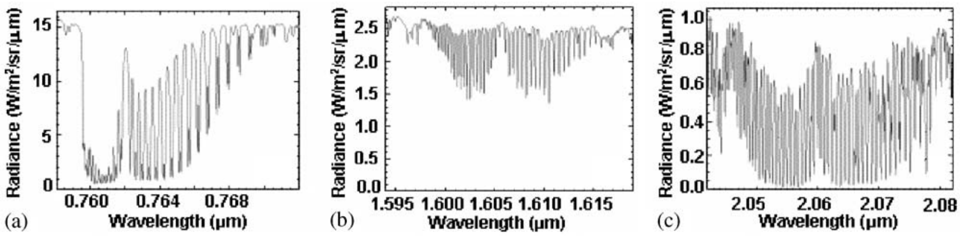

Fig. 2. The three spectral channels sampled by the OCO instrument. The O_2 A-Band at 0.76 yields constraints on clouds, aerosols, and surface pressures (a). The CO_2 column abundance is retrieved from the CO_2 bands near 1.61 μm (b) and 2.06 μm (c).

the 0.76 μm O_2 A-band and the CO_2 bands at 1.61 and 2.06 μm.

The spectral range for each channel includes the complete molecular absorption band as well as some nearby continuum. This minimizes biases due to uncertainties in atmospheric temperature and provides constraints on the optical properties of the surface albedo and aerosols. The spectral resolving power for each channel was selected to maximize the sensitivity to variations in the column abundances of CO_2 and O_2, and to minimize the impact of systematic measurement errors. A spectral resolving power, $\lambda/\Delta\lambda \sim$ 21,000 separates individual CO_2 lines in the 1.61 and 2.06 μm regions from weak H_2O and CH_4 lines and from the underlying continuum. For the O_2 A-band, a resolving power of 17,500 is needed to distinguish the O_2 doublets. With these resolving powers, the OCO retrieval algorithm can characterize the surface reflectance throughout the band and solve for the wavelength dependence of the aerosol scattering, minimizing X_{CO_2} retrieval errors contributed by uncertainties in the continuum level.

While many soundings must be collected on regional scales to adequately characterize regional variations in X_{CO_2} on monthly time scales, contiguous spatial sampling is not required because CO_2 diffuses over a large area as it is mixed through the column. However, the full atmospheric column must be sampled to provide constraints on surface CO_2 sources and sinks. Clouds and optically thick aerosols preclude measurements of the complete column. Studies by the OCO team indicate that probability of viewing a cloud-free scene increases as the size of the footprint decreases.

To obtain an adequate number of soundings on regional scales, even in the presence of patchy clouds, each OCO spectrometer will have a 10 km-wide cross-track field of view (FOV) at nadir. This FOV is divided into 10 (or more) cross-track elements. Soundings are collected at a rate of 45 soundings per second as the spacecraft moves along its ground track at 6.78 km/s. This yields ∼740 soundings per degree of latitude along the orbit track. At this sampling rate, thousands of samples are collected on regional scales during each 16-day ground repeat cycle.

The OCO instrument incorporates independent bore-sighted, long-slit, imaging, grating spectrometers for the 1.61 μm and 2.06 μm CO_2 bands and the 0.76 μm O_2 A-band. These three spectrometers are integrated into a common structure to improve rigidity and thermal stability. They use similar optical designs, consisting of an optimized 100 mm diameter, f/2 telescope that focuses light on a long, narrow slit that is aligned perpendicular to the orbit track. Behind the slit, the light is collimated, dispersed by a grating, and focused by a camera lens, forming an image of a spectrum on a focal plane array (FPA). The spectrum is dispersed across the FPA in the direction orthogonal to the slit, and (cross-track) spatial information is recorded along the slit.

The OCO instrument will be manufactured by Hamilton Sundstand Sensor Systems, in Pomona California. This is the same organization that supplied the last 4 total ozone mapping spectrometer (TOMS) instruments to NASA.

3. Spacecraft and mission design

OCO will use a 3-axis stabilized spacecraft based on the Orbital LEOStar-II bus. This bus was used previously for OrbView-4 (OV-4), Galaxy Explorer

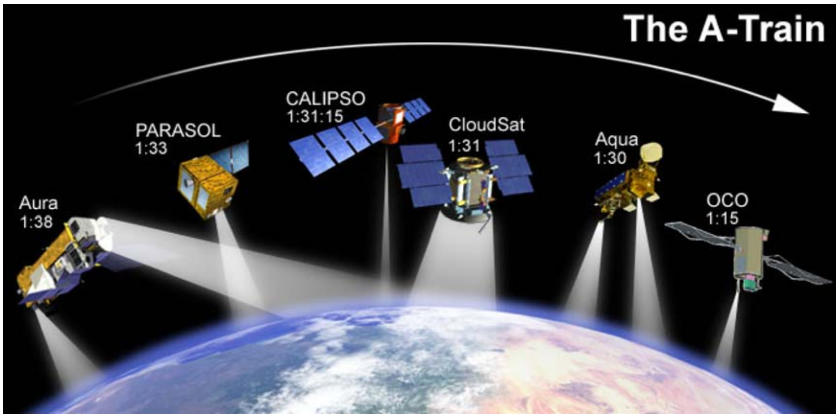

Fig. 3. The OCO satellite will fly in formation with the NASA Earth Observing Syster (EOS) Afternoon Constellation (A-Train), just ahead of the Aqua platform. The other satellites in the A-Train include the NASA ESSP CloudSat and CALIPSO missio the CNES PARASOL mission, and the EOS Aura mission [5].

(GALEX), and Solar Radiation and Climate Explorer (SORCE).

As currently planned, OCO will be launched in late 2007 from the Western Test Range on a Taurus launch vehicle. It will fly in a near-polar orbit, just ahead of Earth Observing System (EOS) afternoon constellation (A-Train), with a 1:15 PM equator crossing time (Fig. 3). This orbit has a repeat time of 16 days and facilitates direct comparisons of OCO observations with complementary data taken by Aqua (e.g. AIRS temperature, humidity, and CO_2 retrievals; MODIS clouds, aerosols, and ocean color), Aura (TES CH_4 and CO), and other A-Train missions [5]. This orbit's 16-day repeat cycle also facilitates monitoring X_{CO_2} variations on semi-monthly intervals.

Once it is flying in formation with the A-Train, OCO will orbit the Earth 14.65 times each day. On two of these orbits, the spacecraft bus will point the body-mounted X-band antenna at the ground station. The bus will also be used to point the OCO instrument for science data collection and instrument calibration operations. The estimated pointing accuracy is ∼900 arcsec, and pointing knowledge is ∼200 arcsec.

OCO will use three different science observation modes (Fig. 4). In Nadir mode, the satellite will point the instrument to the local nadir, so that data can be collected along the ground track just below the spacecraft. This mode provides the highest spatial resolution on the surface, but may not provide adequate signal to noise over dark ocean surfaces. The Glint mode

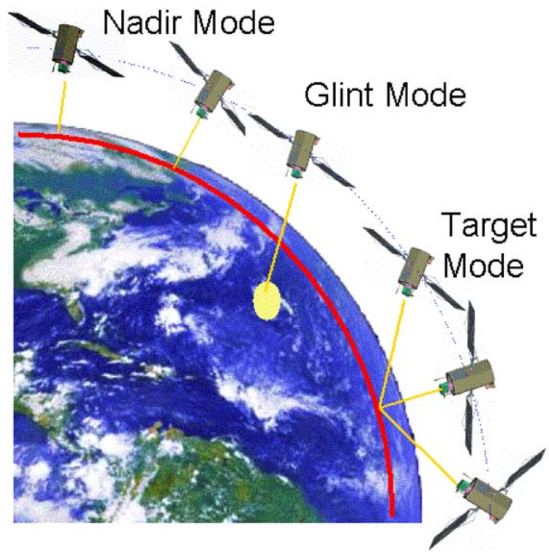

Fig. 4. OCO will collect measurements while over the sunlit hemisphere in Nadir Glint, and Target modes.

was designed to address this concern. In this mode, the spacecraft points the instrument toward the bright "glint" spot, where solar radiation is specularly reflected from the surface. Glint measurements should provide much higher signal-to-noise ratios over the ocean. OCO will switch from Nadir to Glint modes on alternate 16-day global ground track repeat cycles such that the entire Earth is mapped in each mode on roughly monthly time scales. Finally, a Target mode will be used to track specific surface targets as the satellite flies overhead. This mode will provide up to 27,000 samples over sites that include ground-based OCO calibration assets at monthly intervals.

4. Conclusions

The OCO mission was selected as one of two primary missions submitted in response to the third ESSP Announcement of Opportunity. The other primary mission was Aquarius. The Hydros mission was selected as the alternate. These three missions are currently completing a risk reduction phase. OCO is preparing to enter Formulation Phase before October 2003, in preparation for a launch in late 2007 and a 2-year operational lifetime as the 5th ESSP mission.

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