Orbiting Carbon Observatory-2: Observing CO_2 from Space

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The Orbiting Carbon Observatory-2 Mission

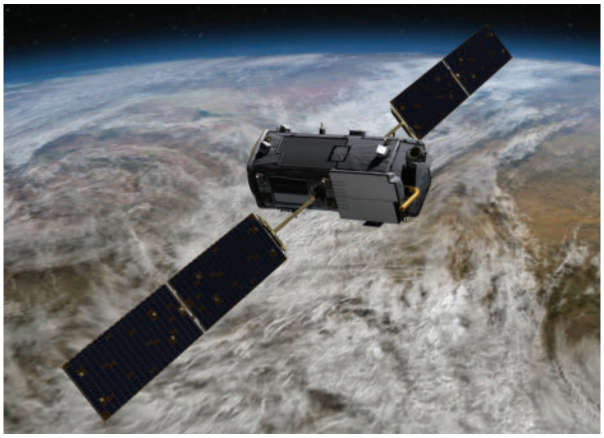
On July 2, 2014, NASA successfully launched the second Orbiting Carbon Observatory (OCO-2) spacecraft from Vandenberg Air Force Base in California. With this launch, NASA now has an important new tool for studying and understanding the fundamental processes that control the accumulation of carbon dioxide (CO_2) in the atmosphere, now and into the future. OCO-2 is not the first satellite designed to measure atmospheric CO_2, but it is the first to provide the precision, resolution, and coverage necessary to observe regional carbon sources and sinks.

Data from OCO-2 will provide scientists insight into the location of natural and anthropogenic processes involved in CO_2 absorption and emission. A better understanding of these processes will allow decision makers to more effectively manage our planet's natural resources and design and implement strategies that minimize human impact on the climbing atmospheric CO_2 rate.

To place the OCO-2 mission in context, we will first provide some background on CO_2 and its place in the Earth system. Then we will provide details of the mission, instrumentation, spacecraft, and planned data acquisition. Finally, we will discuss how the data may be used for the betterment of society.

Sources of Carbon Dioxide in the Earth System

Life as we know it would not exist without carbon. All living and once-living things (i.e., biomass) are based on carbon, the fourth most abundant element in our universe. Carbon, in many gaseous forms—e.g., CO_2, carbon monoxide (CO), and methane (CH_4)—can be released into the atmosphere or absorbed from the atmosphere by processes at the surface. The continual exchanges of carbon between the atmosphere, oceans, and terrestrial ecosystems define Earth's global carbon cycle. Carbon moves more quickly through some parts of the carbon cycle than others. For example, respiration (i.e., the conversion of carbon-containing molecules by biological systems into energy) is a rapid process compared to the longevity of trees, carbonate rocks, or fossil fuels.



Carbon dioxide is the most abundant carbon-bearing gas in Earth's atmosphere, and plays a special role in the carbon cycle. From an atmospheric perspective, sources emit or release carbon—primarily as CO_2—into the atmosphere, while sinks remove CO_2 from the atmosphere. Natural processes are affected by CO_2, such that—collectively—CO_2 emission and absorption are roughly balanced over time. Since the beginning of the industrial age, however, humans have disrupted this balance with increased use of carbon-containing compounds to provide energy for heat, light, and to meet our transportation needs and other industrial requirements.

For example, each time humans use coal or CH_4 (also known as *natural gas*) to generate electricity, or drive a petroleum-powered car, or cut down a forest, or intentionally ignite a forest fire to clear land for agriculture, CO_2 is released into the atmosphere. Unlike natural processes, these human activities absorb little or no CO_2 in return and produce rapid increases in atmospheric CO_2, currently adding approximately 36 billion tons of it each year. Fossil fuel combustion is the largest and most rapidly growing source of CO_2 emission into the atmosphere, with global growth rates of 2.2% per year.

Since the turn of the century, the largest increases have occurred in the developing world, which is now responsible for 57% of all CO_2 emissions. Changes in land use (e.g., clearing forests, which while growing act as repositories or *sinks* for carbon) are the second largest source—although this contribution is decreasing. In many instances, forests and other vegetated land areas previously harvested for wood or to grow crops will experience natural (or intentional) regrowth, called *reforestation*. This allows an area cleared for wood or crops multiple decades ago to act as a carbon sink again, removing CO_2 from the atmosphere. However, not all such carbon sinks are replenished, and large-scale fluctuations in these reservoirs affect the global carbon cycle, ultimately impacting Earth's climate system in ways that will be summarized later.

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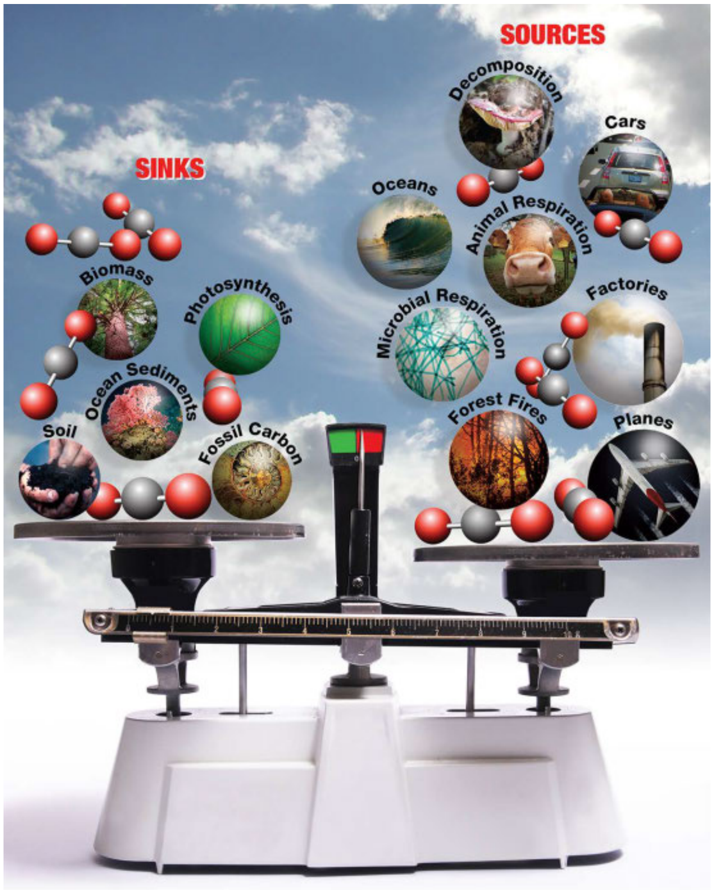
Because CO_2 reacts very slowly with other atmospheric gases and energy sources like solar ultraviolet radiation, most of the CO_2 emitted today will remain in the atmosphere for several hundred years. As this long-lived gas mixes in Earth's atmosphere and is transported around the globe and throughout the carbon cycle, it will continue to impact our planet. Scientists need to understand the processes that are controlling the buildup of CO_2 in Earth's atmosphere today so they can predict how fast CO_2 will accumulate in the future.

Where is the Carbon Dioxide Going?

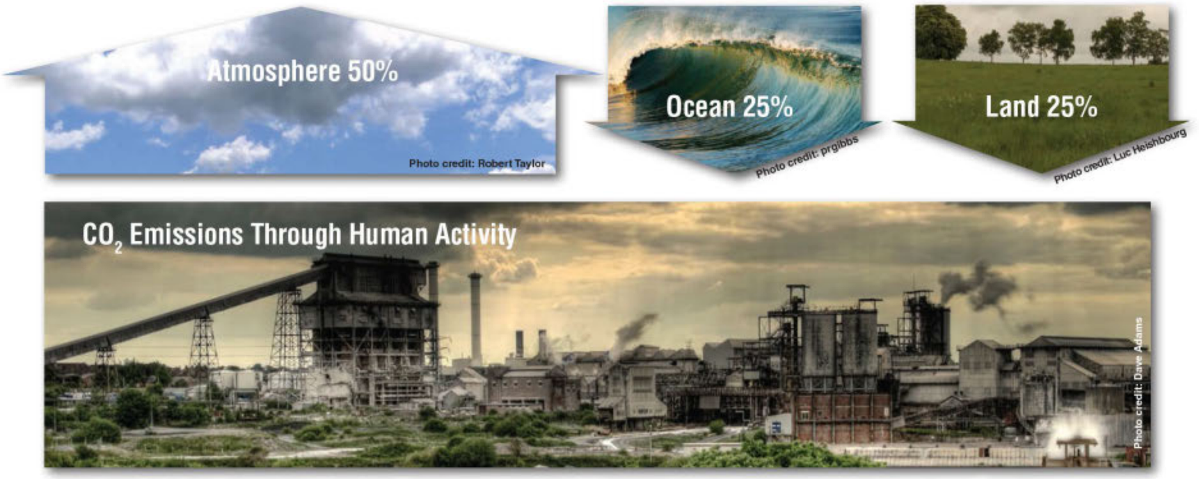
To monitor the impact of CO_2 emissions on the atmosphere, scientists rely on more than 150 ground-based stations around the world. These measurements show that CO_2 has increased by more than 40%, from approximately 280 parts per million (ppm) to about 400 ppm, since the beginning of the industrial age. In other words, 400 out of every one million air molecules is now a CO_2 molecule. Half of this growth has occurred since 1980, and a quarter has occurred since 2001. The current CO_2 abundance is now increasing by more than 2 parts per million (0.5%) each year.



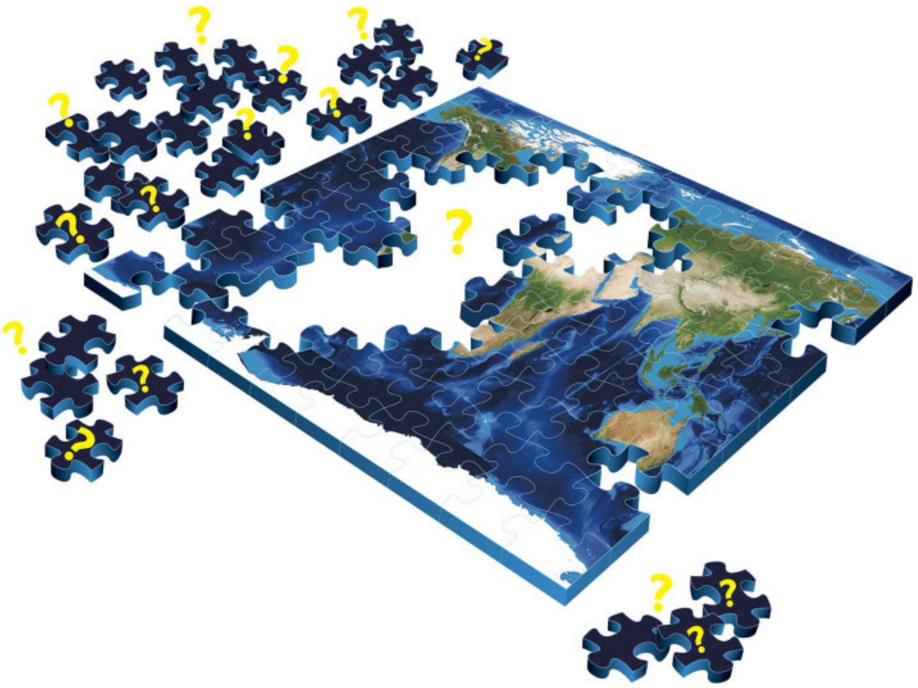
Although natural and anthropogenic (i.e., human-generated) sources and sinks can be found almost anywhere in the world, human activities are "tipping the scale," causing the sources of carbon to "outweigh" the sinks. Such activities are contributing to a rise in atmospheric CO_2, which impacts Earth's climate system. Note that this diagram is simply indicative, and does not include all known carbon sources and sinks. **Image credit:** NASA

Interestingly, however, this rapid buildup of CO_2 accounts for less than half of the 36 billion tons of CO_2 emitted into the atmosphere each year from fossil fuel use and other human activities. Processes at the surface are apparently absorbing the remainder. Measurements of the increasing acidity of seawater indicate that at least one quarter of the CO_2 emitted by human activities is being absorbed by the ocean. The remaining quarter is presumably being absorbed by the land biosphere, but the identity, location, and processes controlling this sink are currently unknown. Scientists refer to this mystery as the "missing-carbon sink."

Despite decades of research that have steadily increased our understanding of the global carbon cycle, scientists still face tremendous challenges as they try to understand the processes controlling the increased rate of CO_2 buildup in the atmosphere. For example, characterizing intense localized sources of CO_2 associated with fossil fuel combustion is much easier than distinguishing and quantifying natural sources and sinks such as CO_2 emitted from oceans, deforestation, and biomass burning. This is due in part to large gaps between ground-based instrument sites and thus limited availability of precise measurements over large portions of Earth's surface.



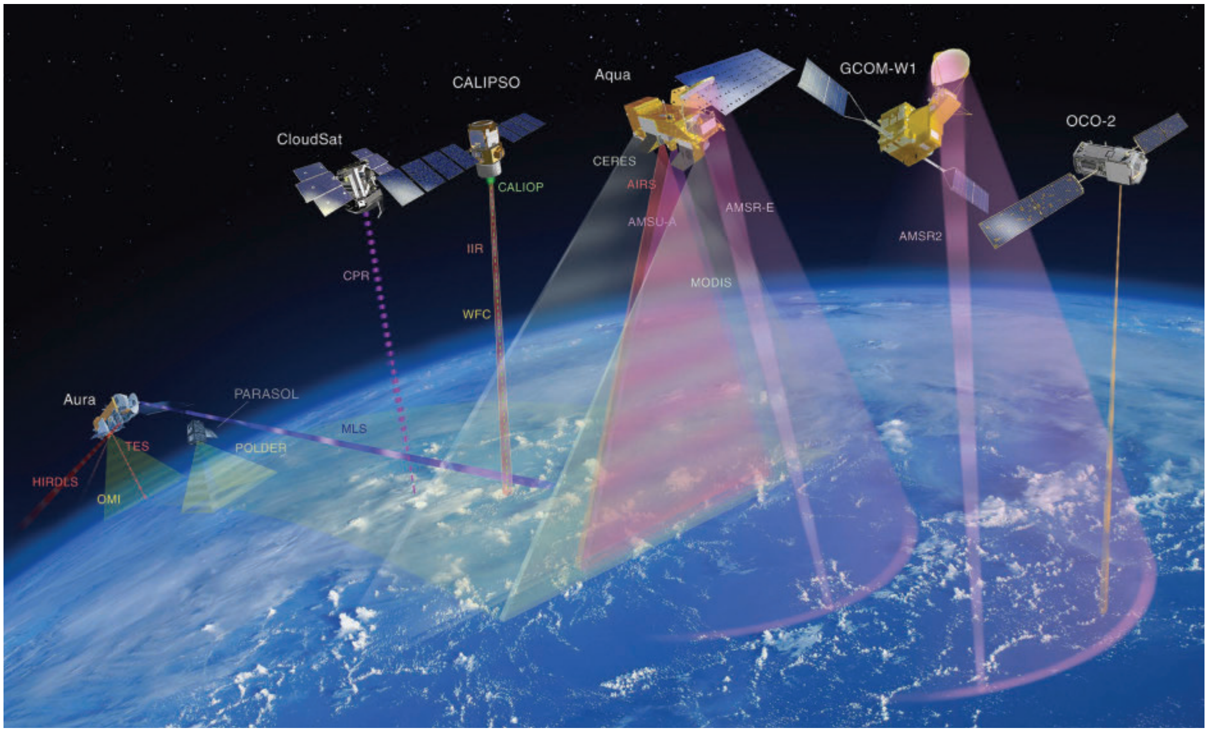
Approximately half of the CO_2 emissions from human activities stay in the atmosphere, while oceans and land sinks absorb the rest. Data from OCO-2 will help scientists better understand these sinks and their locations. Note that while there is substantial year-to-year variability, these percentages reflect the long-term averages. **Image credit:** NASA



Carbon sinks found on land absorb approximately 25% of CO_2 emissions from human activities. However, scientists do not know the location of most of the land sinks. If we imagine the carbon cycle is a 100-piece jigsaw puzzle, scientists know that the 25 puzzle pieces that represent the location of land sinks exist, but they do not understand where they fit into the puzzle. Data from OCO-2 will help scientists better understand this so-called "missing-carbon sink," allowing them to piece together the puzzle. **Image credit:** NASA

ellite observations can provide the continuous, high spatial resolution, global observations of CO_2 that are needed to help answer the question of where the carbon is going.

It is to further refine our understanding of where CO_2 in the Earth system is going that NASA decided to fly a second OCO mission—see *The First Orbiting Carbon Observatory and a Long-Standing Partnership* on page 8 for the fate of the first mission. The recently launched satellite will collect a million measurements over the sunlit hemisphere each day. While fewer than 20% of these measurements are expected to be sufficiently cloud-free to yield precise estimates of CO_2, OCO-2 will still yield over a million useful measurements each week. These data will help scientists understand where CO_2 is being emitted and removed from the atmosphere and how much of it is from natural processes and human activities, subsequently allowing them to make realistic projections of how Earth's climate might respond to these changes.



OCO-2 will fly at the front of the A-Train configuration. **NOTE:** A detailed description of this drawing can be found at *atrain.gsfc.nasa.gov*. **Image credit:** NASA

As of this writing, OCO-2 is scheduled to join the Afternoon Constellation of Earth-observing satellites, or A-Train[1], in early August. The A-Train is a group of satellites operated by NASA and its international partners that closely follow one after another along the same orbital "track." The satellites are in a polar orbit, crossing the equator northbound at about 1:30 PM local time, within seconds-to-minutes of each other. This allows near-simultaneous observations of a wide variety of parameters to aid the scientific community in advancing our knowledge of Earth-system science and applying this knowledge for the benefit of society.

Measurements from OCO-2 will also be used in conjunction with measurements from ground-based stations, aircraft, and other satellites operated by NASA and its partners—see *Observing the Global Carbon Cycle and Earth's Changing Climate* on page 11. For example, OCO-2 data will be combined with measurements of water vapor and CH_4—other strong greenhouse gases—from NASA's Aqua and Aura satellites and the Japanese Greenhouse Gases Observation Satellite (GOSAT, nicknamed, "Ibuki," Japanese for *breath* or *vitality*) mission, to more fully understand the contribution of greenhouse gases to climate change. OCO-2 data will be supplemented with measurements of other atmospheric gases—such as tropospheric ozone and nitrogen dioxide—from NASA's Aura mission to study the relationship between CO_2 and other gases associated with air pollution. By combining Earth-observation data from multiple sources, scientists can view the Earth as one interconnected system, better understand how humans are contributing to climate change, and improve computer predictions of how climate will change in the future.

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The OCO-2 Instrument: Searching for Carbon Dioxide's "Fingerprints"

When CO_2 is emitted into the atmosphere from a source or absorbed from the atmosphere by a sink, the resulting CO_2-rich or CO_2-poor air is rapidly mixed and transported by winds. This rapid mixing can dilute the CO_2 signature quickly, partially obscuring the sources and sinks. To account for this, the OCO-2 instrument has been optimized to rapidly collect high-precision measurements of the average CO_2 concentration between the sensor and Earth's surface. Furthermore, the instrument

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[1] Five satellites currently fly in the A-Train: GCOM-W1, Aqua, CALIPSO, CloudSat, and Aura. PARASOL ceased operation on December 18, 2013. For more information, visit *atrain.gsfc.nasa.gov.*

has been designed to be most sensitive to the CO_2 concentration in the lower troposphere—the atmospheric layer closest to Earth's surface, where we live and breathe, and where variations in CO_2 are greatest. Data from OCO-2 will provide scientists with unprecedented amounts of new information about CO_2 emissions on regional scales.

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The largest known sources and sinks of CO_2 produce differences no larger than a few percent on spatial scales of 1000 km (~621 mi), and typical variations are no larger than 0.25%—1 part per million (ppm) out of the ambient 400 ppm background. To measure such small quantities accurately, the OCO-2 spacecraft deploys a single instrument that consists of three, high-resolution spectrometers.

OCO-2's spectrometers have been designed to detect the spectral fingerprints of CO_2 as well as molecular oxygen (O_2) in the near-infrared part of the electromagnetic spectrum. Specifically, each spectrometer is tuned to measure the absorption in three specific ranges of wavelengths where CO_2 weakly absorbs sunlight (1.61 µm), another region where it strongly absorbs sunlight (2.06 µm), and within the so-called molecular oxygen (O_2) "A-band" near 0.765 µm—see **Figure 1**. Each of these ranges includes dozens of dark absorption lines produced by either CO_2 or O_2. The amount of light absorbed to generate each spectral line increases with the number of molecules along the optical path. OCO-2's spectrometers simultaneously measure the fraction of the light absorbed to generate each of these lines with very high precision.

A number of factors can change the amount of CO_2 along the atmospheric path between the sun, Earth's surface, and the instrument, and only a few of these are associated with sources and sinks. For example, there are typically more CO_2 molecules above a deep valley than over an adjacent mountain range because there is a longer path and a larger atmospheric mass over the valley. Clouds and optically thick aerosols can also introduce uncertainties in the atmospheric path, as will instrument pointing errors. All these factors have to be removed to get to the actual signature of carbon sources and sinks.

The First Orbiting Carbon Observatory and a Long-Standing Partnership

Launched in February 2009, NASA's original Orbiting Carbon Observatory (OCO) spacecraft was designed to provide the most accurate atmospheric measurements of CO_2 ever made from space. Data from OCO were expected to show the location of carbon sources and sinks, and help improve scientists understanding of the global carbon cycle. Sadly, the mission was lost in a launch failure when the protective payload fairing of the Taurus launch vehicle failed to separate during ascent.

Prior to launch, however, the original OCO and GOSAT science teams formed a close partnership to cross calibrate instruments and validate CO_2 retrievals. GOSAT was successfully launched on January 23, 2009, and has been returning routine measurements of CO_2 and CH_4 since mid-2009. After the OCO launch failure, the GOSAT science team reached out to NASA and invited the OCO science team to participate in GOSAT data analysis, allowing them to use data from GOSAT to test the algorithms developed for OCO data. In 2010 NASA decided to support the second OCO mission, now known as OCO-2. Collaboration between the two science teams has continued for many years and is expected to enhance data retrievals from OCO-2 and GOSAT-2.

NASA's OCO-2 satellite joins GOSAT to obtain the important scientific measurements "lost" as a result of the OCO failure. **Image credit:** NASA

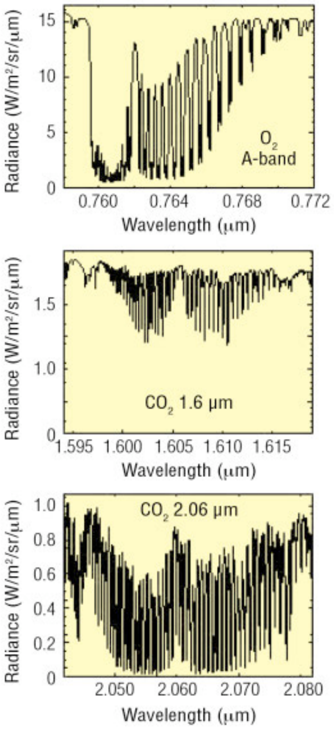
One way to minimize the impact of these sources of uncertainty is to directly measure the abundance of CO_2 and that of the background atmosphere, and use these measurements to estimate the CO_2 concentration along the path. If one such measurement shows a relatively high CO_2 concentration and another shows a relatively low CO_2 concentration, it is safe to assume that some process has enriched the first sample, indicating a source, while some process has depleted the other, indicating a sink. To estimate the CO_2 concentration along the optical path, the OCO-2 spectrometers will collect coincident measurements of CO_2 and O_2. These data will be combined to estimate the column-averaged CO_2 dry air mole fraction, X_{CO_2}. O_2 is an ideal gas for estimating the total atmospheric dry air mass along the optical path because its concentration is constant, well known, and uniform throughout the atmosphere. Scientists then analyze this information to determine the number of molecules along the path between the top of the atmosphere and the surface.

Measurement Details

The instrument records an image of the spectrum produced by each spectrometer three times every second as the satellite flies over the surface at more than four miles per second. Each image is divided into eight discrete "footprints" along a ~10-km (6-mi) wide field-of-view, and recorded for later transmission to the ground, yielding 24 "soundings" per second. At this rate, the instrument gathers between 67,000 and 71,000 individual measurements over a narrow ground track each orbit. The surface footprint of each measurement is just under 3 km² (~1 mi²).

The satellite orbits the Earth about 14.5 times each day in a 705-km (~438-mi), sun-synchronous, 98.2° orbit with a 98.8-minute period and a 1:30 PM equator crossing time. Every 16 days, after 233 orbits, the spacecraft returns to the same ground track. Over each 233-orbit ground track repeat cycle, it collects about 16,000,000 measurements, with orbit tracks separated by just over 1.5° longitude (170 km or 105 mi) at the equator—see **Figure 2**. With measurement footprints of this size and density, the instrument can make an adequate number of high-quality soundings, even in regions with clouds, aerosols, and variations in topography.

Figure 1. OCO-2's spectrometers are tuned to measure the O_2 A-band [*top*], weak CO_2 band [*middle*], and strong CO_2 band [*bottom*]. **Image credit:** NASA



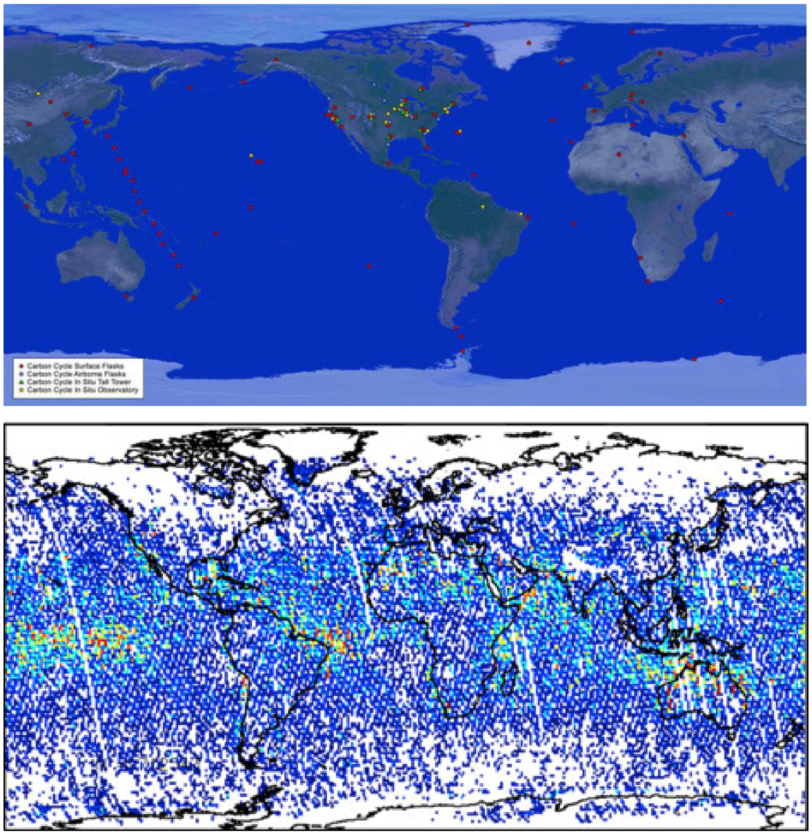


Figure 2. The top map shows the locations of ground-based instrument sites [*dots*]. The bottom map shows the expected sampling for a single 16-day ground track repeat cycle, where OCO-2 is collecting glint observations. Scientists will use aircraft and ground-based measurements of CO_2 to validate OCO-2's data. For more details and to see the maps in color, please refer to the online version at *eospso.gsfc.nasa.gov/earth-observer-archive*. **Image credit:** NASA

Scientists will infer the location of carbon sources and sinks by analyzing OCO-2's data using computer models. The results from the models will allow them to piece together the missing-carbon puzzle and better understand the global carbon cycle.

Launch Vehicle and Spacecraft

On July 16, 2012, NASA selected the United Launch Alliance (ULA) Delta II *7320-10C* launch vehicle to carry OCO-2 into space. The Delta II is part of a launch vehicle family that first entered service in 1989 and has recorded well over 140 successful launches to date[2]. The satellite is based on the LEOStar-2 multimission spacecraft bus—built by Orbital Sciences Corporation—which provides the on-orbit service platform for OCO-2's three-channel grating spectrometer. The spacecraft bus is made primarily of aluminum honeycomb panels that are both lightweight and strong, assembled to form a hexagonal structure approximately 1 m (3.3 ft) in diameter and 2 m (6.6 ft) in height. The structure contains most of the spacecraft bus support components and much of the instrument itself. Powering the spacecraft and measuring approximately 3 m (10 ft) in length, solar array wings are attached to both sides of the spacecraft by movable motors. The solar array panels provide electrical power when the observatory is operating in sunlight and a rechargeable battery provides power when the observatory is operating in the *umbra*—i.e., the shadow of the Earth. The mass of the entire observatory, including the spacecraft bus and instrument, is approximately 450 kg (990 lbs).

With new information comes new possibilities. OCO-2's measurements will improve scientists' ability to track changes in fossil fuel emissions in both hemispheres, and compare how CO_2 interacts with the land and ocean at different latitudes.

A star tracker, inertial measurement unit, and global positioning system (GPS) provide attitude determination (i.e., to assist the observatory in determining its orientation with respect to inertial space) and a set of momentum wheels allows the instrument telescope to be pointed in the proper direction. For example, the momentum wheels allow the telescope to look "directly downwards" in *Nadir Mode* and near the sun's reflection on the ocean in *Glint Mode*.

An onboard computer, which was designed to operate in the harsh space radiation environment, controls both the spacecraft bus and the instrument. Special flight software running on the computer allows the spacecraft to respond to commands stored in memory as well as those issued by ground controllers. The onboard telecommunications system provides a link to the ground through a set of electronics and antennas that operate in the *S-band*—a set of frequencies that include those typically used for wireless connections in our homes and businesses. Science data are transmitted from the observatory to the ground via the X-band antenna. The higher frequency X-band region allows the spacecraft to accommodate the quantity of data the instrument is expected to acquire.

Serving Society and Making a Difference

In May 2013 anthropogenic emissions pushed the monthly average CO_2 concentrations above 400 ppm—a level that has not been reached during the past 800,000 years. After several months of reduced values, in March 2014 CO_2 concentrations again reached 400 ppm, and remained there as the monthly average for April. These ever-increasing levels are raising concerns about greenhouse-gas-induced climate change. Data from OCO-2 will help scientists better identify how human activities, as well as the natural processes on Earth are influencing rising concentrations of atmospheric CO_2 and the global carbon cycle.

With new information comes new possibilities. OCO-2's measurements will improve scientists' ability to track changes in fossil fuel emissions in both hemispheres, and compare how CO_2 interacts with the land and ocean at different latitudes. Scientists also will discover new ways to study how plant and crop growth, deforestation, and wildfires influence the exchange of CO_2 between the atmosphere and tropical

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[2] The Delta II has also been selected to place several other Earth-orbiting satellites into orbit, including the Soil Moisture Active Passive (SMAP) mission and second Ice, Clouds, and land Elevation Satellite (ICESat-2) mission, scheduled for launch in late 2014 and 2017, respectively.

Observing the Global Carbon Cycle and Earth's Changing Climate

Since the 1970s NASA has played a continuous and critical role in studying the global carbon cycle and Earth's climate. Over the years, NASA has paved the way for global Earth observation through the use of satellite remote sensing technology, building a fleet of Earth-observing satellites that have helped the agency and the world meet specific scientific objectives for studying Earth's land, oceans, and atmosphere, and interactions between them.

Currently, there are 17 operating NASA Earth science satellite missions, including OCO-2. Each satellite has provided new perspectives and data that have helped us better understand our home planet as a complex system. The Landsat series (1972-present), the oldest U.S. land surface observation system, allowed the world to see seasonal and interannual land surface changes. The ocean's role in the global carbon cycle and ocean primary productivity (rate of carbon fixation from the atmosphere) was studied using data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) from 1997 to 2010, which also helped to estimate the rate of oceanic carbon uptake. Ocean color and photosynthetic activity are measured by the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments onboard the Terra and Aqua satellites (launched in 1999 and 2002, respectively), and more recently by the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite, launched in 2011. NASA studies the atmosphere and weather with the Atmospheric Infrared Sounder (AIRS) on Aqua, which is tracking the most abundant greenhouse gas—water vapor—as well as mid-tropospheric CO_2. The launch of OCO-2 continues these essential measurements, needed to further our scientific understanding of such phenomena.

OCO-2 joined 16 other Earth-observing satellite missions already in orbit. Measurements of multiple variables, across multiple scales provide the "big-picture view" scientists need to understand our planet's ever-changing environment. **Image credit:** NASA

ecosystems. These types of data will support decision and policy makers to make better-informed decisions that will provide societal benefits for years to come.

Data from OCO-2 will provide significant clues in the quest to find those elusive "missing pieces" of the carbon puzzle and where they fit in the larger picture. Piece by piece, scientists will continue reaching their goal of better understanding Earth's complex carbon cycle and the impact humans are having on Earth's environment.

OCO-2 Websites

www.nasa.gov/oco2

oco.jpl.nasa.gov