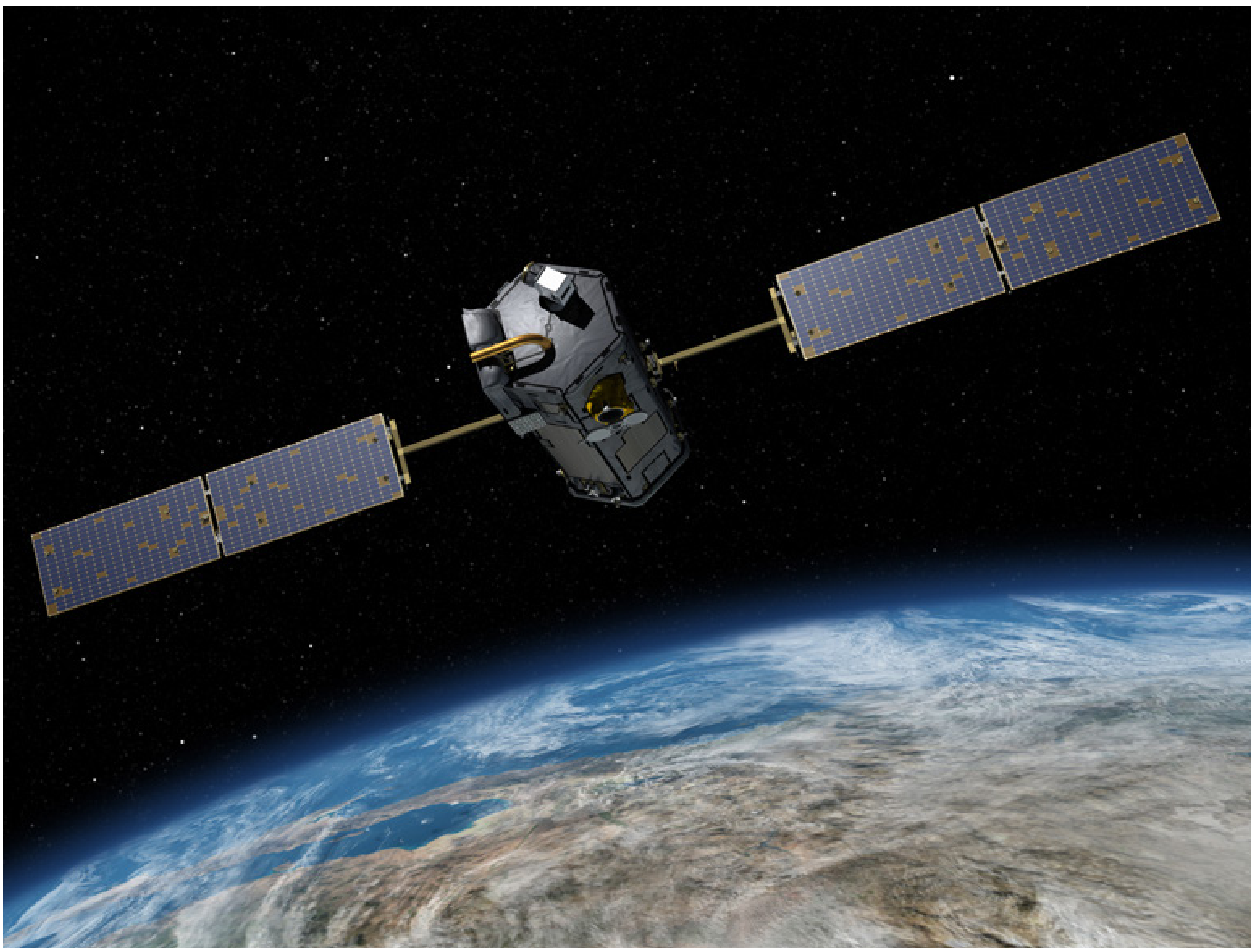
National Aeronautics and Space Administration

PRESS KIT/JULY 2014

Orbiting Carbon Observatory-2 Launch



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Contents

Media Services Information

NASA Television Transmission

NASA Television is available in continental North America, Alaska and Hawaii by C-band signal on AMC-18C, at 105 degrees west longitude, Transponder 3C, 3760 MHz, vertical polarization. A Digital Video Broadcast (DVB)-compliant Integrated Receiver Decoder is needed for reception. Transmission format is DVB-S, 4:2:0. Data rate is 38.80 Mbps; symbol rate 28.0681, modulation QPSK/DVB-S, FEC 3/4.

NASA TV Multichannel Broadcast includes: NTV-1 (formally the Public Channel) and NTV-3 (formally the Media Channel) in high definition, and NTV-2 (formally the Education Channel) in standard definition.

For digital downlink information for each NASA TV channel, access to all three channels online and a schedule of programming for Orbiting Carbon Observatory-2 mission activities, visit http://www.nasa.gov/ntv .

Audio

Audio of the launch minus two day pre-launch news conferences and launch coverage will be available on "V-circuits" that may be reached by dialing 321-867-1220, -1240, -1260 or -7135.

Briefings

A mission and science overview news conference is scheduled for NASA Headquarters at 2 p.m. EDT on June 12, 2014. The news conference will be broadcast live on NASA Television. Pre-launch readiness and mission science briefings will be held at 4 p.m. and 5 p.m. PDT (7 p.m. and 8 p.m. EDT), respectively, on launch minus two days in the NASA Resident Office, Building 840, Vandenberg Air Force Base, California. These briefings will also be carried live on NASA Television and on http://www.ustream.tv/nasajpl2 . Media advisories will be issued in advance, outlining details of these broadcasts.

Launch Media Credentials

News media interested in attending the launch should contact TSgt Vincent Mouzon in writing at U.S. Air Force 30th Space Wing Public Affairs Office, Vandenberg Air Force Base, California, 93437; by phone at 805-606-3595; by fax at 805-606-4571; or by email at Vincent.mouzon@us.af.mil . Please include full legal name, date of birth, nationality, passport number and media affiliation. A valid legal form of photo identification will be required upon arrival at Vandenberg to cover the launch.

News Center/Status Reports

The Orbiting Carbon Observatory-2 News Center at the NASA Vandenberg Resident Office will be staffed beginning on launch minus four days and may be reached at 805-605-3051. Recorded status reports will be available beginning on launch minus three days at 805-734-2693.

Internet Information

The Orbiting Carbon Observatory-2 News Center at the NASA Vandenberg Resident Office will be staffed beginning on launch minus four days and may be reached at 805-605-3051. Recorded status reports will be available beginning on launch minus three days at 805-734-2693.

Quick Facts

Spacecraft

Dimensions: 6.96 feet (2.12 meters) long by 3.08 feet (0.94 meters) wide (stowed)

Weight (spacecraft and science instrument): 999 pounds (454 kilograms)

Power: 815 watts

Primary Science Instrument: Three-channel grating spectrometer

Instrument Dimensions: 5.3 feet by 1.3 feet by 2 feet (1.6 meters by 0.4 meters by 0.6 meters)

Instrument Weight: 288 pounds (131 kilograms)

Mission

Launch: No earlier than July 1, 2014, at 2:56:44 a.m. PDT (5:56:44 a.m. EDT) from Launch Complex 2 West (SLC-2W), Vandenberg Air Force Base, California

Launch Vehicle: United Launch Alliance Delta II 7320-10

Launch Window: 30 seconds daily

Primary Mission: Two years

Orbit Path: Near-polar, sun-synchronous, 438 miles (705 kilometers), orbiting Earth once every 98.8 minutes and repeating the same ground track every 16 days

Orbital Inclination: 98.2 degrees

NASA Investment: $467.7 million (design, development, launch and operations)

Mission Overview

The Orbiting Carbon Observatory-2 is NASA's first spacecraft dedicated to making space-based observations of atmospheric carbon dioxide, the principal human-produced driver of climate change. This new Earth science mission, developed and managed by NASA's Jet Propulsion Laboratory (JPL), Pasadena, California, will have the accuracy, resolution and coverage needed to provide the first complete picture of the geographic distribution and seasonal variations of both human and natural sources of carbon dioxide emissions and the places where they are being absorbed (sinks), on regional scales at monthly intervals.

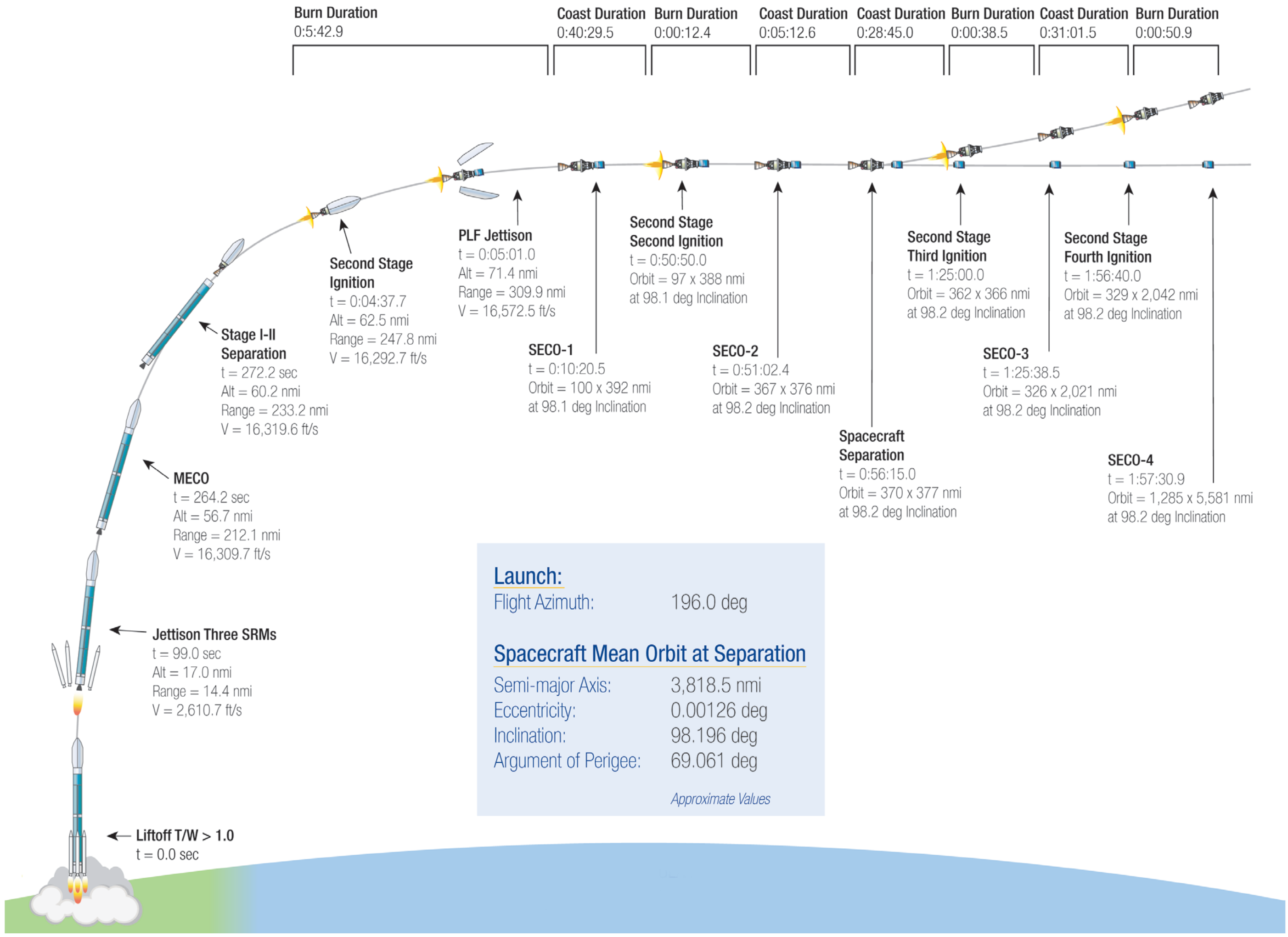
Currently, about 400 out of every million molecules in Earth's atmosphere are carbon dioxide. Modeling studies show that having the ability to estimate global concentrations of atmospheric carbon dioxide to an accuracy of one to two parts per million (0.3 to 0.5 percent), on regional scales at monthly intervals, would dramatically improve our understanding of the natural processes and human activities that regulate the abundance and distribution of this important greenhouse gas. The observatory will use unique implementations of mature technologies and advanced analytical techniques to do just that.

Scientists will use data from the mission to better understand what drives changes in atmospheric carbon dioxide concentrations, with the goal of making more reliable forecasts of future atmospheric carbon dioxide concentrations and how they may affect Earth's climate. This exploratory science mission is designed to last at least two years, long enough to validate a novel, space-based measurement approach and analysis concept that could be applied to future long-term, space-based carbon dioxide observing missions.

The observatory will fly at an altitude of 438 miles (705 kilometers), completing one near-polar Earth orbit every 98.8 minutes. The nearly north-south orbit track repeats every 16 days. It will fly in a formation with the other Earth-observing satellites of the 438-mile (705-kilometer) Afternoon Constellation, or "A-Train," each of which monitors various aspects of the same region of the atmosphere or Earth's surface within a few minutes of each other. Flying as part of the A-Train will complement the mission's science return and facilitate calibration and validation of the observatory. Its observations will be correlated with those of instruments aboard NASA's Aqua, CloudSat and Aura spacecraft, and the NASA/CNES Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and JAXA Global Change Observation Mission - Water 1 (GCOM-W1). Among these measurements are temperature, humidity and carbon dioxide data from the Atmospheric Infrared Sounder instrument on Aqua; the cloud, aerosol and ocean color observations, as well as carbon source and sink measurements from the Moderate Resolution Imaging Spectroradiometer instrument on Aqua; the cloud and aerosol observations by CloudSat and CALIPSO, respectively; methane and carbon monoxide retrievals from the Tropospheric Emission Spectrometer instrument on NASA's Aura satellite; and nitrogen dioxide from the Ozone Monitoring Instrument, also on Aura.

The Orbiting Carbon Observatory-2 is based on the original Orbiting Carbon Observatory mission, which was developed under NASA's Earth System Science Pathfinder (ESSP) Program. Overseen by NASA's Science Mission Directorate, the ESSP Program is a science-driven program designed to provide an innovative approach to Earth science research by providing periodic, competitively selected opportunities to accommodate new and emergent scientific priorities. ESSP projects comprise developmental, high-return Earth science missions, including advanced remote sensing instrument approaches to achieve these priorities. New opportunities within the ESSP Program are made available through NASA's Earth Venture Class solicitations, which are issued regularly. The ESSP Program Office, based at NASA's Langley Research Center in Hampton, Virginia, is responsible for managing, directing and implementing these science investigations.

The original Orbiting Carbon Observatory was launched from Vandenberg Air Force Base, California, on Feb. 24, 2009. During its ascent to orbit, the launch vehicle's payload fairing failed to separate from the observatory, preventing the observatory from reaching orbit and resulting in the loss of the mission. Work on the replacement mission, Orbiting Carbon Observatory-2, began in March 2010.



What the Orbiting Carbon Observatory-2 Will Do

The Orbiting Carbon Observatory-2 — the first NASA remote-sensing mission dedicated to studying carbon dioxide — is the latest mission in NASA's ongoing study of the global carbon cycle. The mission provides a key new measurement that can be combined with other ground and aircraft measurements and satellite data to answer important questions about the processes that regulate atmospheric carbon dioxide and carbon dioxide's role in the carbon cycle and climate. This information will help policymakers and business leaders make better decisions to ensure climate stability and, at the same time, retain our quality of life. The mission will also serve as a pathfinder for future long-term satellite missions to monitor carbon dioxide.

This experimental NASA Earth System Science Pathfinder Program mission will measure atmospheric carbon dioxide from space, densely sampling the globe once every 16 days for at least two years. It will have the precision, resolution and coverage needed to provide the first complete picture of the geographic distribution of both human and natural sources of carbon dioxide emissions, as well as the places where they are absorbed (sinks), at regional scales, everywhere on Earth, and will determine how these distributions vary from season to season.

Mission data will be used by the atmospheric and carbon cycle science communities to improve global carbon cycle models, reduce uncertainties in forecasts of how much carbon dioxide is in the atmosphere, and allow more accurate predictions of global climate change.

The Orbiting Carbon Observatory-2 will dramatically improve measurements of carbon dioxide over space and time, uniformly sampling Earth's land and ocean and collecting approximately 1 million measurements of atmospheric carbon dioxide concentration over Earth's entire sunlit hemisphere every day for at least two years.

Scientists will use these data to generate maps of carbon dioxide emission and uptake at Earth's surface on scales comparable to the size of the state of Colorado. These regional-scale global maps will provide new tools for locating and identifying carbon dioxide sources and sinks.

Locating the sources and sinks of carbon dioxide is a daunting assignment. Concentrations of atmospheric carbon dioxide rarely vary by more than two percent from one pole of Earth to the other (that's eight parts per million by volume out of a total concentration of about 400 parts per million). In addition, the global, rapid transport of carbon dioxide in Earth's atmosphere makes it difficult to spot sources and sinks. Scientific models have shown that we can reduce uncertainties in our understanding of the balance of carbon dioxide in our atmosphere by up to 80 percent if data from the existing ground-based carbon dioxide monitoring network can be augmented with high-resolution, global, space-based measurements of atmospheric carbon dioxide concentration accurate to 0.3 to 0.5 percent (about one to two parts per million) on regional to continental scales. The Orbiting Carbon Observatory-2 will have just such a level of precision.

The mission will use three high-resolution spectrometers to measure how carbon dioxide and molecular oxygen absorb sunlight reflected off Earth's surface when viewed in the near-infrared part of the electromagnetic spectrum. Each spectrometer focuses on a different, narrow range of colors to detect light with the specific colors absorbed by carbon dioxide and molecular oxygen. By analyzing these spectra, scientists can measure the relative concentrations of those chemicals in the sampled columns of Earth's atmosphere. The ratio of measured carbon dioxide to molecular oxygen is used to determine the atmospheric carbon dioxide concentration. Scientists will analyze observatory data using global atmospheric transport models similar to those used for weather prediction to quantify carbon dioxide sources and sinks.

The mission is designed to detect changes in the efficiency of sources and sinks from month to month over seasonal cycles and from year to year during its two-year planned lifetime. For example, forests are efficient carbon dioxide sinks in the spring and summer when they are growing rapidly and absorbing carbon dioxide to build leaves, branches and roots. Because trees need sunlight, water and other nutrients to grow, in addition to carbon dioxide, they are better sinks when these other factors are present. During the winter, when trees drop their leaves, they become sources of carbon dioxide. They also release carbon dioxide when they burn. Orbiting Carbon Observatory-2 measurements of carbon dioxide can therefore be combined with observations of rainfall, forest fires and other environmental data to help us understand why the amount of carbon dioxide absorbed by surface sinks varies dramatically from year to year, while carbon dioxide emissions from sources like fossil fuel burning increase at a steady rate.

Orbiting Carbon Observatory-2 measurements of atmospheric carbon dioxide will enable far better estimates of carbon exchanges between the atmosphere and other reservoirs within the active part of the global carbon cycle, principally the ocean and terrestrial ecosystems.

The mission will contribute to a number of additional scientific investigations related to the global carbon cycle. These include:

- The dynamics of how the ocean exchanges carbon with the atmosphere
- The seasonal dynamics of northern hemisphere terrestrial ecosystems in Eurasia and North America
- The exchange of carbon between the atmosphere and tropical ecosystems due to plant growth, respiration and fires
- The movement of fossil fuel plumes across North America, Europe and Asia
- The effect of weather fronts, storms and hurricanes on the exchange of carbon dioxide between different geographic and ecological regions
- The mixing of atmospheric gases across hemispheres

The observatory will fly in formation with the other missions of the 438-mile (705-kilometer) Afternoon Constellation (the “A-Train”). This formation will enable researchers to correlate observatory data with data acquired by instruments on other spacecraft in the constellation. In particular, scientists will compare observatory data with nearly simultaneous carbon dioxide measurements acquired by the Atmospheric Infrared Sounder instrument flying on NASA’s Aqua satellite.

The Orbiting Carbon Observatory-2’s mission is expected to overlap with Japan’s Greenhouse gases Observing SATellite, which launched successfully in January 2009 and has been returning data on atmospheric carbon dioxide since that time. While using different measurement approaches, particularly in their sampling strategies, both missions will make global measurements of atmospheric carbon dioxide with the precision and sampling needed to identify sources and sinks. Scientists will compare and combine data from the two missions to improve our understanding of natural processes and human activities that control atmospheric carbon dioxide and its variability. The two missions are exploring opportunities for cross-calibration, cross-validation and coordinated observations that may benefit the carbon cycle science community by increasing spatial coverage and increasing the frequency of observations by either satellite alone.

Launch Site and Vehicle

The Orbiting Carbon Observatory-2 will be launched from Space Launch Complex 2 West (SLC-2W) at Vandenberg Air Force Base, California, on a United Launch Alliance Delta II 7320-10 launch vehicle.

Manufactured by United Launch Alliance, the Delta II is part of the Delta rocket family and entered service in 1989. Delta II launch vehicles include the Delta 6000, 7000 and 7000H or “Heavy” varieties. The Delta II 7320 rocket offers a reliable means of launching satellites up to 13,440 pounds (6,100 kilograms) into low-Earth orbit. Since its debut flight, there have been 149 successful Delta II launches, carrying satellites for government and commercial customers. It has a 98 percent success rate.

The Delta II launch vehicle is an expendable launch vehicle, which means it can only be used once. The Delta II was originally designed to accommodate the Global Positioning System Block II series of navigation satellites in 1989. Since that time, however, the Delta II has successfully launched a number of NASA payloads/missions into space, including Mars Pathfinder, CloudSat and Jason-2.

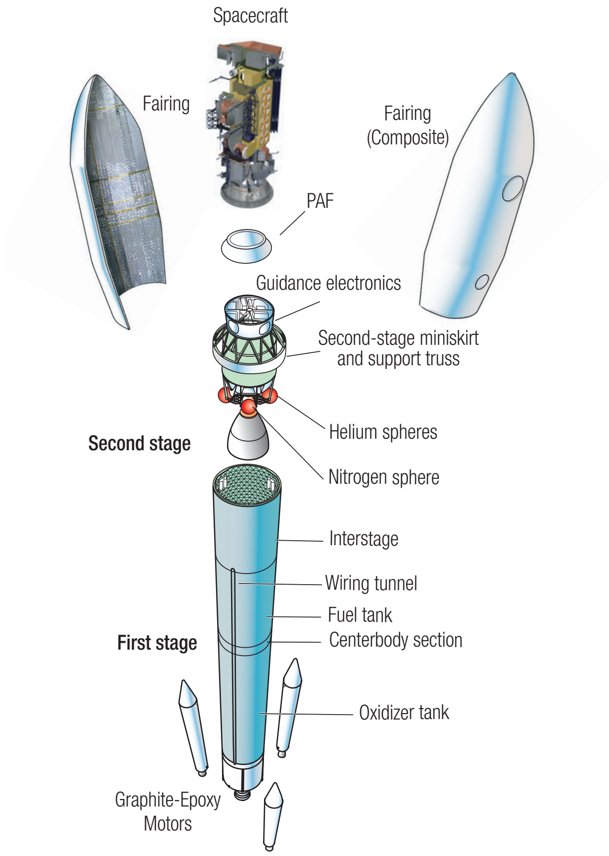
The Delta II family uses a four-digit reference designation system. The first digit is either 6 or 7, denoting the 6000 or 7000 series. The second digit indicates the number of boosters. The third digit is a 2, denoting a second stage. The last digit denotes the third stage. The number 0 indicates that there is no third stage. Sometimes, the four-digit number includes an extension indicating the payload fairing diameter in feet. Therefore, the Delta II 7320-10 launch vehicle for the OCO-2 mission is a 7000 series vehicle, with three boosters, a second stage, no third stage and a 10-foot- (3-meter-) diameter payload fairing.

The first stage of the Delta II uses an Aerojet Rocketdyne RS-27A main engine (12:1 expansion ration) burning RP-1 fuel, a thermally stable kerosene, and liquid oxygen. The total thrust is approximately a 237,000 pound force (1,054,000 newtons). The first stage will be augmented with three boosters, specifically, Alliant Graphite Epoxy Motors using hydroxyl-terminated polybutadiene solid propellant. The thrust of each solid rocket-fueled booster is approximately a 109,135 pound force (486,458 newtons).

The second stage of the Delta II uses a restartable Aerojet Rocketdyne AJ10-118K engine burning Aerozine 50, which is a mixture of hydrazine and dimethyl hydrazine, reacting with nitrogen tetroxide as an oxidizer. The total thrust is estimated at a 9,750 pound force (43,370 newtons).

The observatory will be contained inside the vehicle’s payload fairing, which has a diameter of 10 feet (3 meters). The Orbiting Carbon Observatory-2 mission will use a “payload stack” between the launch vehicle Direct Mate Adapter and the observatory that will include a Load Isolation System to reduce the loads transmitted to the relatively low-mass observatory.

At launch, the Delta II will stand approximately 126.6 feet (38.6 meters) tall and weigh approximately 165.5 tons (150,173 kilograms).



Launch Timing

The Orbiting Carbon Observatory-2 will be launched at a specific time and trajectory needed to join the A-Train constellation. Unlike spacecraft sent to other planets, comets or asteroids, the launches of Earth-orbiting satellites do not need to be timed based on the alignment of the planets. Earth-orbiting satellites do, however, need to be launched during particular windows within any given 24-hour day in order to get into the proper orbit around Earth. The Orbiting Carbon Observatory-2 will assume what is called a "sun-synchronous" orbit, flying within eight degrees of Earth's north and south poles with a Mean Local Time of the Ascending Node (MLTAN) of approximately 1:36 p.m. Because it needs to adjust to the even more precise orbit of the 438-mile (705-kilometer) Afternoon Constellation, or "A-Train" of Earth-observing satellites that it will join, the launch vehicle must be launched during a specific 30-second daily launch window that repeats daily.

The launch date is based on the readiness of the observatory, the Delta II 7320-10 launch vehicle, and the Western Range at Vandenberg Air Force Base. Launch is currently scheduled for no earlier than 2:56 a.m. PDT (5:56 a.m. EDT) July 1, 2014.

Launch Sequence

The Delta II will launch the Orbiting Carbon Observatory-2 from Space Launch Complex 2 West down an initial flight azimuth of 196 degrees from true north (south-southwest). The boost phase trajectory is designed to place the observatory into the proper intermediate orbit (115 by 451 miles, or 185 by 726 kilometers) by the time of the first cutoff of the Delta II Second Stage (SECO-1). Three graphite epoxy solid motors are ignited 0.2 seconds prior to liftoff once the first-stage engine reaches its required thrust level. The three solid rocket motors burn for approximately 64 seconds but are not jettisoned until 99 seconds into flight in order to satisfy range safety constraints. During the first 100 to 140 seconds of the boost phase, the vehicle steers the trajectory so that it achieves the required orbital inclination. Main Engine Cutoff (MECO) occurs approximately 264 seconds into flight, followed 8 seconds later by Stage I-II separation. After Stage I-II separation, the second stage ignites and burns until reaching the intermediate orbit. During this second stage burn, the payload fairing, or launch vehicle nose cone, will separate into two halves, like a clamshell, and fall away at approximately 301 seconds after liftoff when the free molecular heating rate has dropped to the required level. SECO-1 occurs nominally at 620.5 seconds after liftoff, after the intermediate orbit conditions are reached.

After SECO-1, the Orbiting Carbon Observatory-2 and the second stage will coast in the intermediate orbit before the 12.4-second restart burn, which begins at 3,050 seconds after liftoff and places the observatory into the desired orbit. The observatory's folded solar panels will be oriented toward the sun during sunlit portions of the coast phase so that some amount of battery recharging can occur prior to final separation. After final cutoff of the second stage at SECO-2, the second stage will orient for separation by pointing the observatory's +Z-axis at the sun. Separation occurs above a tracking station at Hartebeesthoek, South Africa (HBK) and will be monitored by a video camera attached to the second stage, with the video signal being sent down to HBK and transmitted back to NASA's Kennedy Space Center in Florida in near-real-time.

Separation of the Orbiting Carbon Observatory-2 satellite occurs approximately 56 minutes and 15 seconds after liftoff, with the vehicle in a 429-mile (690-kilometer) injection orbit, from which the spacecraft will subsequently maneuver over the course of several weeks and adjust its orbit until it reaches its final operational orbit of 438 miles (705 kilometers). The Delta II second stage separates from the spacecraft at a relative separation velocity of about 1.7 feet (0.52 meters) per second.

Approximately 330 seconds after separation, the Delta II upper stage will perform a series of collision and contamination avoidance maneuvers to ensure that there is no possibility of re-contact with the spacecraft, and to minimize the explosive potential of the stage and thereby minimize the amount of orbital debris that may be generated. At the end of these maneuvers, the second stage will be placed in a 1,478-by-6,422 mile (2,379-by-10,335 kilometer) storage orbit that is compliant with NASA policy for limiting orbital debris.

Following separation, the observatory will eliminate any tumbling induced during its separation from the launch vehicle and will then point itself toward the sun and begin to activate its subsystems. Three minutes after separation, the observatory will begin deploying its twin solar arrays. This deployment should be complete within three minutes. The spacecraft should have compensated for any tumbling received during separation from the launch vehicle before entering its first eclipse. Throughout this time, the spacecraft will establish two-way communications via NASA's Tracking and Data Relay Satellite System, and approximately 20 minutes after separation will establish the first two-way communication with a ground station. Before the first contact with a ground station, the observatory should be receiving power through its solar arrays, in a stable attitude and with two-way Tracking and Data Relay Satellite System communication established. The observatory's science instrument will be powered on within the first 12 hours of the mission.

Checkout of the spacecraft will begin on launch day and conclude at launch plus 10 days. Eleven days after launch, the spacecraft will begin a series of maneuvers that will place it in its operational orbit in NASA's A-Train constellation, nominally by day 30. Checkout of the observatory's science instrument will begin 31 days into the mission and conclude at launch plus 37 days. A science data quality check will consume the remainder of the In-Orbit Checkout Phase, with routine science operations slated to nominally begin at launch plus 45 days.

Satellite Constellation Flying

Constellation flying is the coordinated operations of two or more spacecraft that are separated in time, by seconds to minutes, in this case the six satellites of the A-Train constellation. During each orbit, all six of the A-Train satellites will cross the equator within a few minutes of one another at around 1:30 p.m. in the time zone they are flying over; Orbiting Carbon Observatory-2 will cross the equator at 1:36 p.m. local time, an ideal time of day for making spectroscopic observations of carbon dioxide using reflected sunlight.

As the A-Train satellites circle Earth, about 15.5 minutes pass between the time the first satellite (the Orbiting Carbon Observatory-2) and the last (Aura) pass the equator. The Orbiting Carbon Observatory-2 precedes GCOM-W1 by 185 seconds, and precedes Aqua, the anchor satellite in the A-Train, by an average of 444.5 seconds. This nominal separation in satellite spacing between OCO-2 and GCOM-W1 is much greater than that between Aqua, CloudSat and CALIPSO, allowing for looser control and higher margins of safety while still supporting coordinated measurements. Maneuvers to maintain this circular orbit will be carried out approximately every 10 weeks, with annual inclination adjust maneuvers carried out in close coordination with the rest of the A-Train.

After launch, maneuvers within the first 30 days of the mission will bring the Orbiting Carbon Observatory-2 into formation with GCOM-W1, Aqua and the other satellites of the A-Train. Even though the observatory's orbit is closest to GCOM-W1, it is adjusted and monitored to hold at a fixed distance from Aqua, the A-Train's reference satellite. The satellite will be controlled so that its sensors, along with those of CloudSat and CALIPSO, view the same ground track whenever the observatory is observing straight down at the ground below.

Satellite Operations

The observatory's ground segment includes all facilities required to operate the satellite; acquire the data that it transmits to the ground; and process, distribute and archive science data products. The Orbital Sciences

Mission Operations Center in Dulles, Virginia, is responsible for all ground operations that track and control the spacecraft, under the leadership of JPL. Science data will be transmitted to NASA ground network stations in Alaska and Virginia.

Science Data Processing

Once received on the ground, the raw data from the observatory will be processed by the Science Data Operations System facility at JPL, which houses the hardware and software that convert science data telemetry to higher-level data products for distribution to the user community. Data products derived from Orbiting Carbon Observatory-2 measurements will be archived and distributed to the science community by the NASA Goddard Earth Science Data and Information Services Center (GES DISC).

Data Products

The primary product delivered by the Orbiting Carbon Observatory-2 consists of spatially resolved estimates of atmospheric columns of carbon dioxide. These estimates quantify the average concentration of carbon dioxide in a column of air extending from Earth's surface to the top of the atmosphere.

The Orbiting Carbon Observatory-2 mission will produce four primary data products for the user community that will provide comprehensive mission results and material for further research and investigation:

- Level 1B – spectrally-calibrated and geographically lo cated radiances. This product contains a unique record of every sounding the instrument collects while viewing Earth during a single spacecraft orbit — approximately 74,000 soundings. Each sounding consists of co-located (observing the same location) spectra from the three spectrometer channels.

- Level 2 — geographically located estimates of atmo spheric columns of carbon dioxide and several at mospheric and geophysical properties collected during each spacecraft orbit. This product typically includes more than 4,000 retrievals of the conce tration of atmospheric carbon dioxide in cloud-free scenes, as well as profiles of surface pressure, surface albedo (the fraction of solar energy reflected from Earth back into space), aerosol content, water vapor and temperature. Estimates of the solar-induced chlorophyll fluorescence are also provided.

- Level 3 – Gridded global maps of the atmospheri carbon dioxide concentration, generated monthly by members of the competed Orbiting Carbon Observatory-2 science team.

- Level 4 — maps of global carbon dioxide sources and sinks. This product will also be generated monthly by members of the competed Orbiting Carbon Observatory-2 science team by combining Orbiting Carbon Observatory-2 Level 2 data with numerical models of atmospheric transport and atmosphere/surface carbon dioxide exchange.

The NASA Goddard Earth Science Data and Information Services Center (GES DISC) will archive and distribute the mission's data products. Scientists expect to begin delivering calibrated spectral radiances about three months after the end of the spacecraft's in-orbit checkout. An exploratory atmospheric carbon dioxide concentration product is expected to be available within six months after completing in-orbit checkout.

Calibration

A robust calibration program ensures that the data received from the observatory instrument are converted into accurate, scientifically useful measurements. The observatory team will perform three types of calibration on the spectroscopic measurements collected by the observatory's instrument:

- Radiometric calibrations, which convert raw data numbers into spectral radiances

- Spectral calibrations, which identify the wavelength-of light that falls on each pixel

- Geometric calibrations, which provide the parameters required to accurately determine the location of each measurement on Earth's surface along with its illumination and observation geometry

Validation

The Orbiting Carbon Observatory-2 team will verify the estimates of atmospheric carbon dioxide retrieved from the spectroscopic measurements collected by the observatory's instrument. These estimates will be validated against directly measured data and remote sensing data from a ground-based network and airborne measurements calibrated to the same standard. This ensures that its measurements meet the mission's precision requirements of 0.3 percent (one part per million) out of the background (400 parts per million) on collections of more than 100 cloud-free soundings.

Science Team

An international competitively selected science team will address the mission's science objectives and goals. Among its responsibilities, the science team will advise the project on aspects of the mission that influence the scientific usefulness of the data. The team has formulated a mission science plan and will oversee mission operations activities. The science calibration theme group has worked closely with the instrument team to develop strategies for calibrating the instrument's measurements prior to launch and in flight. The science algorithm theme group has developed and validated the numerical methods used to retrieve estimates of carbon dioxide atmospheric columns and other geophysical properties from Orbiting Carbon Observatory-2 measurements. The science validation theme group will collect datasets acquired by in situ and remote-sensing instruments on the ground, mounted on tall towers and flown in aircraft, which can be used to validate estimates of carbon dioxide atmospheric columns and other geophysical quantities retrieved from Orbiting Carbon Observatory-2 measurements. These theme groups will work with the uncertainty quantification theme group to establish procedures to ensure the quality of Orbiting Carbon Observatory-2 data products. The science team will regularly review operations plans and propose modifications based on the content and quality of data to take advantage of special observing opportunities such as forest fires or volcanic eruptions. Once validated, they will assimilate Orbiting Carbon Observatory-2 data products into atmospheric flux inversion models to retrieve spatial maps of carbon dioxide sources and sinks.

NASA/Japan Collaboration

NASA's original Orbiting Carbon Observatory and the Japanese Greenhouse gases Observing SATellite (GOSAT) were the first two missions designed specifically to collect space-based observations of atmospheric carbon dioxide with the sensitivity, coverage and resolution needed to identify its sources and sinks on regional scales over the globe. The Orbiting Carbon Observatory and GOSAT teams formed a close collaboration during the development phases of these missions, and had an agreement to perform cross-calibration on data comparisons. After the loss of the Orbiting Carbon Observatory, the GOSAT project team invited the Orbiting Carbon Observatory team to use GOSAT in-flight data to validate and refine the algorithms developed by the Orbiting Carbon Observatory team before launch. NASA Headquarters saw the benefit and funded the effort, reformulating the Orbiting Carbon Observatory science team under a program called Atmospheric Carbon Dioxide Observations from Space (ACOS). ACOS has helped to reduce the technical risk of the OCO-2 science mission and is expected to substantially accelerate the delivery of high-quality science products from the Orbiting Carbon Observatory-2 mission.

Mission Phases

After mission development, the Orbiting Carbon Observatory-2 mission is divided into three primary phases:

- The launch/injection orbit phase covers the time period from observatory delivery to the Western Range at Vandenberg Air Force Base, California, until the instrument has been checked out in orbit and is ready to begin normal operations. It is divided into four sub phases: launch, spacecraft checkout, orbit ascent and instrument checkout.

- The launch sub phase began on April 29, 2014, with the arrival of the observatory at Vandenberg Air Force Base and will end when the observatory separates from the launch vehicle and is placed into its injection orbit. Activities during this phase focus on prelaunch preparations of the observatory, such as final checkout and test, fueling and mating to the launch vehicle. In addition, final tests and checkout of the mission operations software are performed to assure their readiness for on-orbit activities and maneuvers. The time from liftoff to spacecraft separation is approximately 56 minutes.

- The spacecraft checkout sub phase will immediately follow the launch sub phase, beginning when the observatory physically separates from the Delta

II second stage. It focuses on the transition of the observatory to communications with the ground, enabling command and control. This involves both the Tracking and Data Relay Satellite System and S-band links with the Near-Earth Network ground stations. Early in this phase, the solar arrays are deployed and the spacecraft's attitude is stabilized in an orientation with its arrays pointed at the sun. Once proper power levels are sustainable, the spacecraft communicates with Earth tracking stations to acquire new commands and verify the spacecraft's readiness for further actions. This includes the initial on-orbit checkout and calibration of spacecraft systems to ensure they are functional and that the spacecraft is able to properly orient itself and the instrument. The science instrument is not yet turned on. This sub phase is several days in duration. When it is completed, the spacecraft will be in a stable attitude with the instrument and antenna pointed straight down toward the ground. The craft will be routinely communicating with ground-tracking stations as it moves along the injection orbit and passes over ground telemetry stations.

- The ascent sub phase incorporates a series of propulsive maneuvers to correct for errors in the launch trajectory and boost the observatory into its operational orbit in the A-Train constellation. This sub phase is complete when the observatory is thoroughly checked out, is operating normally and is properly inserted in the A-Train.

- The instrument checkout sub phase — Once in its operational orbit, the observatory will turn on, cool down, and begin calibrating and checking out its instrument. Once the instrument has been cooled to its operational temperatures and is stable, the calibration team will assess its performance and identify any biases relative to its expected performance. The observatory is then ready to begin its routine science operations.

- The operations phase begins at the end of in-orbit checkout and continues through the nominal two-year mission. Throughout this phase, the mission will continuously collect science data and transmit it to ground stations.
- The observatory will collect atmospheric carbon dioxide observations in nadir, glint and target modes, and conduct regularly scheduled instrument calibrations.

- Data from these observations will be transmitted to a ground station twice each day using the Ground Network, also known as the Near-Earth Network. The Ground Network's primary site is located near Fairbanks, Alaska, with the 36-foot (11-meter) antennas AS1 and AS3 at the Alaska Satellite Facility. The 36-foot (11-meter) antenna at the Wallops Ground Station in Virginia will serve as the back-up ground station.

- The raw telemetry will be sent to the Earth Observing System (EOS) Data and Operations System (EDOS) at NASA's Goddard Space Flight Center in Greenbelt, Maryland, for preliminary processing, and then to the Orbiting Carbon Observatory-2 Science Data Operations System (SDOS) at JPL to generate science data products.

- Once the calibrated, geographically-located spectral radiances and estimates of carbon dioxide atmospheric columns and other geophysical quantities are validated, they will be sent to the Orbiting Carbon Observatory-2 science team for further analysis and to the Goddard Earth Sciences Data and Information Services Center (GES DISC) for archiving and distribution to the global science community.

- Higher-level products including maps of the global carbon dioxide distribution and the locations of carbon dioxide sources and sinks will be generated by members of the science team and sent to the GES DISC for archiving and distribution.

- At the end of the mission's useful lifetime, it will begin its decommissioning phase, which is designed to minimize the potential creation of orbital debris and any possible collision with other satellites in the A-Train. In this phase, the observatory will be commanded to maneuver, will use its remaining fuel to inject into a lower disposal orbit and will be shut down. Earth's atmosphere will gradually pull the satellite downward until it reenters the atmosphere. This phase can last up to 25 years.

Why Study Carbon Dioxide?

Carbon. Without it, life as we know it would not exist. The fourth most abundant element in the universe, carbon is the building block for all life, anchoring all organic substances. Not only is carbon the chemical foundation of all living things, it is present in the atmosphere, in the layers of limestone sediment on the ocean floor and in fossil fuels like coal.

What is Carbon Dioxide?

When carbon bonds with oxygen, it primarily forms carbon dioxide, a colorless, odorless gas composed of two atoms of oxygen and one atom of carbon. Carbon dioxide is produced both naturally — by volcanoes, the respiration of plants and animals and the decay of their remains — and through human activities, such as the burning of fossil fuels for use in transportation, power generation, manufacturing, and heating and cooling buildings; making cement; and deforestation and other land use changes.

Carbon dioxide is the most significant human-produced greenhouse gas. (Greenhouse gases contribute to warming Earth's atmosphere by absorbing radiation emitted from Earth's surface.) It is also the principal human-produced driver of changes to Earth's climate.

Carbon dioxide is a long-lived gas in Earth's atmosphere. While more than half of the carbon dioxide emitted is removed from the atmosphere within a century, about 20 percent remains in the atmosphere for thousands of years.

Though generated at Earth's surface, carbon dioxide rises into the free troposphere, which begins at roughly 1.2 miles (2 kilometers) above the surface. There, winds (weather systems and jet streams) transport it around the globe, across oceans and continents.

The Carbon Cycle

The exchange of carbon between its various storage reservoirs (the ocean, atmosphere, terrestrial biosphere and geologic fossil fuel reserves) is known as the carbon cycle.

The global carbon cycle can be defined by two categories, based on their time scales: the geological carbon cycle, which operates over large time scales (millions of years); and the biological/physical carbon cycle, which operates at shorter time scales (days to thousands of years).

Geological Carbon Cycle

In the geological carbon cycle, carbon moves between rocks and minerals, seawater and the atmosphere. Carbon dioxide in the atmosphere can be dissolved in rain or seawater to form carbonic acid. This solution reacts with calcium, magnesium and other elements in Earth's crust through a process called "weathering" to form a wide range of carbonate minerals, such as calcium carbonate (limestone). These minerals can precipitate out of rivers, lakes, the ocean or hydrothermal systems to form layers of carbonate rock. As Earth's plates move, through the process of plate tectonics, these sediments can be subducted underneath the continents. (Subduction is a geological process where one edge of an Earth crustal plate is forced sideways and downward into Earth's mantle below another plate.) Under the great heat and pressure far below Earth's surface, the carbonate rocks melt and react with other minerals, releasing carbon dioxide. The carbon dioxide is then re-emitted into the atmosphere through volcanic vents, fumaroles (vents in Earth's surface from which hot smoke and gases escape) and hydrothermal systems.

The balance among weathering, subduction and volcanism controls atmospheric carbon dioxide concentrations over time periods of hundreds of millions of years. The oldest geologic sediments suggest that, before life evolved, the concentration of atmospheric carbon dioxide may have been 100 times what it is now, providing a substantial greenhouse effect during a time of low solar output, billions of years ago. On the other hand, ice core samples taken in Antarctica and Greenland have led scientists to hypothesize that carbon dioxide concentrations during the last ice age (20,000 years ago) were only half of what they are today.

Biological/Physical Carbon Cycle: Photosynthesis and Respiration

Biology also plays an important role in the movement of carbon in and out of the land and ocean through the processes of photosynthesis and respiration. Through photosynthesis, green plants absorb solar energy and remove carbon dioxide from the atmosphere to produce carbohydrates (sugars). Plants and animals effectively "burn" these carbohydrates (and other products derived from them) through the process of respiration, the reverse of photosynthesis. Respiration releases the energy contained in sugars for use in metabolism and renders the carbohydrate "fuel" back to carbon dioxide. Together, respiration and decomposition (respiration that consumes organic matter mostly by bacteria and fungi) return the biologically fixed carbon back to the atmosphere. The amount of carbon taken up by photosynthesis and released back to the atmosphere by respiration each year is 1,000 times greater than the amount of carbon that moves through the geological cycle on an annual basis.

Photosynthesis and respiration also play an important role in the long-term geological cycling of carbon. The presence of land vegetation enhances the weathering of soil, leading to the long-term — but slow — uptake of carbon dioxide from the atmosphere. In the ocean, some of the carbon is taken up by phytoplankton (microscopic marine plants that form the basis of the marine food chain) to make shells of calcium carbonate that settle to the bottom after they die to form sediments. During times when photosynthesis exceeded respiration, organic matter slowly built up over millions of years to form coal and oil deposits. All of these biologically mediated processes represent a removal of carbon dioxide from the atmosphere and storage of carbon in geologic sediments.

During the daytime in the growing season, leaves absorb sunlight and take up carbon dioxide from the atmosphere. In parallel, plants, animals and soil microbes consume the carbon in organic matter and return carbon dioxide to the atmosphere. When conditions are too cold or too dry, photosynthesis and respiration cease along with the movement of carbon between the atmosphere and the land surface. The amounts of carbon that move from the atmosphere through photosynthesis and respiration and back to the atmosphere are large and produce oscillations in atmospheric carbon dioxide concentrations that vary by season and location and from one year to the next. Over the course of a year, these biological fluxes of carbon are more than 10 times greater than the amount of carbon introduced to the atmosphere by fossil fuel burning.

Fire also plays an important role in the transfer of carbon dioxide from the land to the atmosphere. Fires consume biomass and organic matter to produce carbon dioxide (along with methane, carbon monoxide and smoke), and the vegetation that is killed but not consumed by the fire decomposes over time, adding further carbon dioxide to the atmosphere.

Over periods of years to decades, significant amounts of carbon can be stored on land or released from land to the atmosphere. For example, when forests are cleared for agriculture, the carbon contained in the living material and soil is released, causing atmospheric carbon dioxide concentrations to increase. When agricultural land is abandoned and forests are allowed to regrow, carbon is stored in the accumulating living biomass and soils, causing atmospheric carbon dioxide concentrations to decrease.

In the ocean, carbon dioxide exchange is largely controlled by sea surface temperatures, winds (and associated wave mixing), circulating currents, and photosynthesis and respiration. Carbon dioxide can dissolve easily into the ocean and the amount of carbon dioxide that the ocean can hold depends on ocean temperature and the amount of carbon dioxide already present. Cold ocean temperatures favor the uptake of carbon dioxide from the atmosphere, whereas warm temperatures can cause the ocean surface to release carbon dioxide. Cold, downward-moving currents, such as those that occur in the North Atlantic, absorb carbon dioxide and transfer it to the deep ocean. Upward moving currents, such as those in the tropics, bring carbon dioxide up from deep waters and release it to the atmosphere.

Life in the ocean consumes and releases significant quantities of carbon dioxide. But in contrast to land, carbon cycles between photosynthesis and respiration vary rapidly; that is, there is virtually no storage of carbon in ocean plants as there is on land (e.g., tree trunks and soil). Photosynthetic microscopic phytoplankton are consumed by respiring zooplankton (microscopic marine animals) within a matter of days to weeks. Only small amounts of residual carbon from these plankton settle out to the ocean bottom on a daily basis, but over long periods of time these small amounts add up to a significant removal of carbon from the atmosphere.

The Human Role

In addition to the natural fluxes of carbon through the Earth system, human activities, particularly fossil fuel burning and deforestation, are also affecting carbon dioxide levels in the atmosphere.

With the arrival of the Industrial Revolution in 1750, humans needed new sources of energy to power their activities. The answer was hydrocarbon fuels such as oil, coal and natural gas. While effective, they also came with a cost: when the bond between hydrogen and carbon is broken during combustion, the carbon, hydrogen, and oxygen recombine to form carbon dioxide, water vapor and other greenhouse gases that are emitted into our atmosphere.

These activities move carbon more rapidly into the atmosphere than it is removed naturally through the sedimentation of carbon, causing atmospheric carbon dioxide steady-state concentrations to increase. Also, by clearing forests to support agriculture, we transfer carbon from living biomass into the atmosphere. (Dry wood is about 50 percent carbon.) The result is that humans are adding ever-increasing amounts of extra carbon dioxide into the atmosphere.

The concentration of carbon dioxide in Earth's atmosphere has increased from about 280 parts per million before the Industrial Revolution to more than 400 parts per million today. The recent rate of change is both dramatic and unprecedented. As reported by the Intergovernmental Panel on Climate Change, carbon dioxide levels have risen by 40 parts per million in just the last 20 years. Previous increases of that size took 1,000 years or longer. Analyses of ice core samples from Greenland and Antarctica reveal that atmospheric carbon dioxide concentrations are significantly higher today than at any time in that record, which spans 800,000 years.

The burning of fossil fuels by humans, with contributions from the manufacture of cement, is currently adding nearly 40 billion tons of carbon dioxide to the atmosphere every year, and this rate of emission is increasing. Each 4 billion tons of fossil carbon burned raises the atmospheric carbon dioxide concentration by about one part per million. Every one billion tons of carbon emitted into the atmosphere corresponds to 3.67 billion tons of carbon dioxide.

In addition, up to 3 billion tons of additional carbon dioxide are released each year by biomass burning, forest fires and land-use practices such as "slash-and-burn" agriculture. Combined, these activities have increased atmospheric carbon dioxide levels by almost 20 percent during the past 50 years.

Scientists know the increases in atmospheric carbon dioxide concentration are caused primarily by human activities, because fossil fuel carbon has a different ratio of isotopic heavy-to-light carbon atoms. A relative decline in the amount of heavy carbon-13 isotopes in the atmosphere points to fossil fuel sources. Also, the burning of fossil fuels depletes oxygen and lowers the ratio of oxygen to nitrogen in the atmosphere.

The Greenhouse Effect

Earth's climate is powered by our sun, which sends radiant energy with short wavelengths (primarily in the shortwave-infrared, near-infrared, visible and ultraviolet parts of the spectrum) to our planet. About 30 percent of this energy gets reflected directly back to space by Earth and its atmosphere; the rest is absorbed by Earth's surface and atmosphere. Earth balances the incoming energy it absorbs by radiating a nearly equivalent amount of energy back to space. But since Earth's surface is cool compared to the sun, the energy it radiates is in the infrared part of the spectrum, at much longer wavelengths. While the atmosphere, with the exception of clouds, is relatively transparent to the short-wavelength solar radiation, greenhouse gases, such as carbon dioxide, water vapor and ozone, and clouds absorb much of the thermal radiation that Earth's surface emits and re-radiate some of this energy back to the surface. This trapped radiant energy warms Earth's surface, much as the glass walls of a greenhouse trap the sun's energy and increase its interior air temperature. This atmospheric "greenhouse effect" benefits life on Earth by warming Earth's surface, allowing light from the sun to reach Earth but keeping much of that radiant heat from re-radiating back into space. Without it, Earth's average surface temperature would be below freezing.

But as the old saying goes, too much of a good thing can be bad for you, and too much of a greenhouse effect is definitely bad for our planet.

Ninety-nine percent of Earth's dry atmosphere (atmosphere excluding water vapor) is composed of nitrogen and oxygen, neither of which has any significant greenhouse effect. Within that other one percent, however, are numerous more complex trace gases, including water vapor, carbon dioxide, methane, nitrous oxide and ozone. These trace gases absorb infrared light in Earth's atmosphere and prevent it from escaping back to space. While molecules of carbon dioxide amount to only a few hundred parts per million in the atmosphere, they are an efficient greenhouse gas because they absorb thermal radiation in precisely the middle of the wavelength range where Earth's surface emits most of its heat. When their concentration in our atmosphere increases, they intensify the greenhouse effect and warm our planet. How much it warms depends on a complex set of interconnected Earth system processes.

Atmospheric concentrations of greenhouse gases like carbon dioxide are affected by numerous components of Earth's climate system, including the ocean and living organisms. Human activities, especially the burning of fossil fuels and deforestation, have significantly increased the concentration of greenhouse gases like carbon dioxide in our atmosphere. As a result, they have intensified the natural greenhouse effect and have caused our planet to warm.

The Carbon Dioxide/Climate Connection

Since the beginning of the industrial era, the buildup of atmospheric carbon dioxide from burning fossil fuels and other human activities has been the primary cause of the observed increases in Earth's surface temperature. Therefore, to accurately estimate the rate of global warming, we have to understand the rate of buildup of carbon dioxide in the atmosphere.

Studies have calculated that a doubling of the concentration of atmospheric carbon dioxide results in an increase of about 5 degrees Fahrenheit (3 degrees Celsius) in average global temperatures. Temperature increases are even greater at Earth's poles.

During the 20th century, temperatures around the world increased on average by about 1 degree Fahrenheit (0.6 degree Celsius). Scientists attribute the increase primarily to increased emissions of carbon dioxide and other greenhouse gases by humans. In just the 10 years from 1995 to 2005, the amount of climate warming due to carbon dioxide concentrations increased by 20 percent, the largest change for any decade in at least the last 200 years, or since the Industrial Revolution.

The effects of global warming are numerous and varied. They include the retreat of glaciers and changes in weather patterns, Arctic sea ice, sea level rise and ocean circulation, to name just a few.

The long time scales required to remove carbon dioxide from our atmosphere mean that past and future carbon dioxide emissions produced by humans will continue to warm our planet and raise sea level for more than 1,000 years to come, even if carbon emissions are substantially reduced from today's levels.

Continuing increases in atmospheric carbon dioxide may impact ocean currents, the jet stream and rain patterns. Some parts of Earth might actually cool while the average global temperature increases.

On land, increased concentrations of atmospheric carbon dioxide can affect climate by changing the way plants grow so as to warm the air near Earth's surface. Increased carbon dioxide levels can also stimulate photosynthesis, which increases vegetation cover and leaf area. However, the higher temperatures associated with greenhouse-gas-induced warming will increase respiration as well as photosynthesis, and can lead to more moisture stress and larger carbon dioxide emissions. The net effect of increased carbon dioxide on plant growth is therefore not well understood and is likely to vary from place to place.

Scientists know that climate extremes such as droughts have a major effect on exchange rates between the atmosphere and biosphere because plants need water as well as carbon dioxide to grow. A severe drought in the United States in 2002 added 360 million tons of carbon to the atmosphere by reducing the growth of plants that would have otherwise absorbed it. That's equivalent to the yearly emissions from 200 million cars. The Amazon droughts of 2005 and 2010 produced much larger emissions.

Drought caused by a warming climate also increases the frequency and intensity of wildfires. University of

Colorado researchers reported in 2008 that the mega-wildfires in Southern California in the fall of 2007 released 7.9 million metric tons of carbon dioxide into the atmosphere in a single week, an amount equivalent to the emissions from all cars, trucks, factories and power plants in the state during that period.

Increased carbon dioxide concentrations are also harming Earth's ocean, causing it to become more acidic. The acidity of ocean water is usually expressed in terms of its hydrogen ion concentration, or pH. A pH of 7 is neutral, while lower values indicate more acidic conditions and higher values indicate more alkaline conditions. When carbon dioxide dissolves in seawater, it forms carbonic acid. The surface waters of the ocean are slightly alkaline, but their pH has fallen from about 8.21 to about 8.1 since the beginning of the industrial age as they have absorbed more carbon dioxide. The average pH of the ocean is projected to decrease between 0.14 and 0.35 units in this century. Acidic water is much less hospitable for many types of marine life.

Climate change can also reduce the ocean's ability to absorb carbon dioxide by reducing the solubility of carbon dioxide, suppressing the vertical mixing of ocean waters and decreasing ocean surface salinity. Large-scale ocean circulation changes can also result over long time scales.

As our climate warms, Earth system processes that couple the climate and the carbon cycle are expected to increase atmospheric carbon dioxide, but scientists do not yet know the magnitude of this effect. This makes it much more difficult to estimate the level of carbon dioxide emissions needed to reach a particular goal for stabilizing the growth of carbon dioxide emissions.

Measuring and Monitoring Carbon Dioxide

Before the late 1950s, scientists relied on indirect measurements of carbon dioxide. High-accuracy measurements of atmospheric carbon dioxide concentration began with the work of Charles David Keeling of the Scripps Institution of Oceanography, La Jolla, California, in 1958. From high atop the Mauna Loa volcano on Hawaii's Big Island, Keeling used a high-precision infrared gas analyzer instrument to measure the chemical composition of the global atmosphere. These measurements, which continue today, are considered the master time series documenting the changing composition of Earth's atmosphere. Climate scientists use these data as evidence of how human activities are affecting the chemical composition of the global atmosphere.

The Mauna Loa measurements were followed by continuous direct measurements at multiple other sites in the Northern and Southern Hemispheres. The sites selected were located far from known local sources and sinks of carbon dioxide to provide average measurements.

Precise measurements of carbon dioxide made by the ground-based network since the late 1950s indicate that atmospheric carbon dioxide concentration has increased from 310 parts per million to more than 400 parts per million today.

In the 1980s and 1990s, scientists recognized that they needed greater coverage of carbon dioxide measurements over continents so that they could estimate sources and sinks of atmospheric carbon dioxide over land as well as ocean. Carbon dioxide analyzer instruments were supplemented by air samples collected in glass and metal containers at numerous sites. The samples are analyzed by multiple laboratories, with the most extensive network of air sampling sites operated by the National Oceanic and Atmospheric Administration's Global Monitoring Division. Worldwide databases of measurements are maintained by the Carbon Dioxide Information Analysis Center of the U.S. Department of Energy and the World Data Centre for Greenhouse Gases in the World Meteorological Organization Global Atmosphere Watch program.

The Carbon Dioxide Information Analysis Center tracks and monitors carbon dioxide emissions from a global network of ground-based sites. This network provides a tremendous amount of insight into the global abundance of carbon dioxide and its variability over seasons.

The current ground-based carbon dioxide monitoring network of about 160 sites does not have the spatial coverage, resolution or sampling rates necessary to sufficiently identify natural sinks responsible for absorbing carbon dioxide, or to characterize the processes that control how the efficiency of those sinks changes from one year to the next. Large parts of the world, especially in India, Africa, Siberia and South America, have few, if any, monitoring stations.

To put the increases measured since the late 1950s into perspective and compare them with previous natural cycles, scientists turned to ice core samples from Greenland and Antarctica. Periods of low carbon dioxide concentration in the samples correspond to ice ages, while higher carbon dioxide concentrations are linked to warmer periods. By analyzing the composition of air bubbles in these cores, they were able to show that carbon dioxide levels were much lower during the last ice age than over the last 10,000 years of the current Holocene epoch. From 10,000 years ago through the start of the industrial era, carbon dioxide levels remained within a range of 260 to 300 parts per million.

Carbon Sinks

The concentration of carbon dioxide in our atmosphere is determined by the balance between its sources (emissions due to human activities and natural processes) and its sinks (processes that pull carbon dioxide out of the atmosphere and store it). Natural processes, including photosynthesis, respiration, decay and the exchange of gases between the ocean and the atmosphere result in huge exchanges.

The current state of knowledge of these sources and sinks is summarized annually by the Global Carbon Project. The 2013 assessment indicates that between 2003 and 2012, plant growth on land absorbed between 122 and 124 billion metric tons of carbon each year, while respiration and decay returned about 120 billion metric tons of carbon back to the atmosphere each year. Meanwhile, the ocean absorbed about 92 billion metric tons of carbon from the atmosphere and released about 90 billion metric tons of carbon back into the atmosphere each year. These exchanges are much larger than the carbon emissions from human activities (about 10 billion metric tons of carbon each year), but the natural sources are roughly balanced by the natural sinks. Human activities constitute a net source of carbon to the atmosphere.

When scientists try to account for sources and sinks of carbon dioxide in the atmosphere, they uncover a major mystery. Between 1750 and 2012, fossil fuel combustion has added 385, plus or minus 20 billion tons, of carbon (1,400, plus or minus 73 billion tons, of carbon dioxide) to Earth's atmosphere. Land use practices (deforestation, slash-and-burn agriculture, etc.) have added another 205, plus or minus 70 billion tons, of carbon (1,080, plus or minus 256 billion tons, of carbon dioxide).

Meanwhile, only about 240 to 250 billion tons of the carbon emitted into the atmosphere by human activities over this period has remained in the atmosphere. The remaining 60 percent of the carbon (270 to 445 billion tons) was apparently absorbed (at least temporarily) by the ocean and land biosphere. Recent inventories of the ocean can account for about 145 to 185 billion tons, or about half of the missing carbon. The remaining 105 to 255 billion tons must have been absorbed somewhere on land, but scientists don't know where most of the land sinks are located or what controls their efficiency over time.

The large uncertainties in the numbers listed above are not simply artifacts of poor measurement collection in the past. Similar uncertainties are seen in recent carbon inventories. For example, during the 1990s, the average annual carbon emissions due to fossil fuel use and cement manufacturing were about 6.4 billion tons. That number increased to an average of 8.6 billion tons per year between 2003 and 2012 and to about 9.7 billion tons by 2012. Land use and land use change, primarily deforestation and harvest of wood products, has fallen somewhat, contributing an additional 0.8 billion tons of carbon in 2012. Of the 10.5 billion tons of carbon currently being released each year by human activities, approximately 5.2 billion tons remains in the atmosphere, increasing the atmospheric carbon dioxide concentration by about 3.3 parts per million per year. In addition, approximately 2.9 billion tons diffused into the world's ocean, thus leaving about 2.5 billion tons unaccounted for.

What happened to the leftover 2.5 billion tons? Scientists don't know for sure, but evidence points to the land surface. For example, regrowth of forests since the massive deforestation in the Northern Hemisphere over the last century could account for some of the missing carbon. Extended growing seasons in the boreal and arctic regions may contribute to more absorption. Another possibility is that the changing climate has contributed to greater uptake of carbon than release of carbon. However, the underlying mechanisms are so poorly understood that scientists refer to the mystery as the "missing" carbon sink.

Natural sinks are difficult to quantify because they tend to vary highly from one season to the next and one year to the next. In some years, most fossil fuel emissions are absorbed by the sinks, while in others virtually none is absorbed and the atmospheric carbon dioxide increases at the same rate as fossil fuel emissions.

The ocean absorbs carbon dioxide from the atmosphere in some places and emits it in others. Cooler waters can absorb more carbon dioxide. Cold, carbon dioxide-rich waters from high latitudes can sink and be transported great distances, before they are brought back to the surface, where they can release the carbon dioxide back to the atmosphere.

An improved understanding of the carbon sinks is essential for accurate predictions of how carbon dioxide affects Earth's climate. The natural carbon dioxide sinks are currently absorbing about 60 percent of all human-produced carbon emissions, slowing down climate change considerably compared to that expected if it all remained in the atmosphere. If carbon dioxide sinks were to lessen suddenly, it could be equivalent to adding more than 10 billion tons of carbon to the atmosphere every year instead of 5.2 billion, with a corresponding spike in atmospheric carbon dioxide concentrations. This is equivalent to a 40 percent increase in effective carbon emissions into the atmosphere. In a world trying to manage carbon in order to mitigate carbon dioxide increase and climate change, uncertainty about the missing carbon sink is a major concern. Today's carbon dioxide levels of about 400 parts per million would be about 100 parts per million higher were it not for these natural sinks.

It is critically important that we better understand the processes that control these sources and sinks so that we can predict their behavior in the future. Will these sinks continue to help soak up the carbon dioxide that we are producing? Or will they stop or even reverse and aggravate the atmospheric increases?

Characterizing and better quantifying these sinks, especially their geographical distribution, is crucial to predicting future carbon dioxide increases and to helping policymakers develop and evaluate carbon management strategies. Better understanding of the geographical distribution of the terrestrial sinks, in particular, will provide significant insight into the underlying mechanisms and inform studies of the processes involved.

Current carbon cycle models predict that an increasing fraction of total human-produced carbon dioxide emissions will remain in the atmosphere during this century. Most also predict that both the ocean and land areas will become less efficient sinks. This means that it will require even larger carbon emissions cuts than before to begin to have any substantive effect on stabilizing atmospheric carbon dioxide.

Other Carbon Questions

Scientists have a number of other unanswered questions about this key greenhouse gas. Among them:

- What natural processes dominate the absorption of carbon dioxide from human emissions?
- Will those processes continue to limit increases in atmospheric carbon dioxide in the future, as they do now? Or will they stop or even reverse and accelerate the atmospheric increases?
- Is the "missing" carbon dioxide being absorbed primarily by land or by the ocean and in what proportions?
- Which terrestrial ecosystems absorb more than others?
- Why does the increase in atmospheric carbon dioxide vary from one year to the next even though the emission rates increase uniformly?
- How will carbon dioxide sinks respond to changes in Earth's climate or land use?
- What are the processes controlling the rate at which carbon dioxide is building up in Earth's atmosphere? That rate is currently estimated at two to three parts per million by volume per year, or as much as a half percent per year.
- Where are the sources of carbon dioxide?
- What is the geographic distribution and quantity of carbon dioxide emitted through both fossil fuel combustion and less well understood sources, such as ocean outgassing, deforestation, fires and biomass burning? How does this distribution change over time?

Carbon Dioxide: Selected Statistics

- Carbon dioxide level during the last ice age: 180 parts per million; after the glaciers retreated: 280 parts per million; today: more than 400 parts per million.

- According to the NOAA Earth System Research Laboratory Global Monitoring Division, the annual growth rate of atmospheric carbon dioxide levels rose 1.3 parts per million per year during the 1970s; 1.6 parts per million during the 1980s; 1.5 parts per million during the 1990s; 2 parts per million from 2000 to 2007; and 2.62 parts per million in 2013 alone.

- While home to just five percent of Earth's people, the United States produces about 14 percent of all carbon dioxide emissions. Carbon dioxide emissions from China are now double that figure. In fact, the rapidly developing world (primarily China and India) is now responsible for more than 57 percent of all fossil fuel emissions.

- Carbon dioxide emissions due to global annual fossil fuel burning and cement manufacture together have increased by 70 percent over the last 30 years.

- Carbon dioxide levels rose less than one percent in the 10,000 years before the Industrial Revolution; since 1751, they've risen 42 percent.

- The first increase of 50-parts-per-million above pre-industrial levels was reached in the 1970s; the second increase of 50-parts-per-million took just 30 years.

- A typical 500-megawatt coal-fired power plant releases about three million tons of carbon dioxide each year.

- The average automobile produces 19 pounds of carbon dioxide for every gallon of gasoline or diesel burned.

- The annual carbon "footprint" of the average American (the amount of carbon dioxide created through all of his or her activities) is 16.8 tons.

- In the past decade, humans removed 50,193 square miles (13,000,000 hectares) of tropical forests each year, primarily in the tropical Americas, tropical Asia and tropical Africa. That deforestation emitted 1.5 billion tons of carbon each year during that time frame, or 16 percent of all emissions.

- According to the Global Carbon Project, an international consortium of scientists that tracks carbon emissions, in 2012 alone, carbon released from burning fossil fuels and cement production increased nearly three percent over that released in 2006, to 9.7 billion tons. That level of continued emission increase could result in a global temperature rise of more than 11 degrees Fahrenheit (6 degrees Celsius) by the end of this century.

- According to the U.S. Department of Energy, humans have added about 590 billion tons of carbon to the atmosphere since the start of the Industrial Revolution through the use of fossil fuels, land use changes and cement production.

Looking Beyond Carbon Dioxide

When plants photosynthesize, they use energy from sunlight to turn carbon dioxide from the air into sugars used to live and grow. In doing so, they give off a fluorescent light — a glow that cannot be seen with the naked eye, but that can be seen with the right instruments. Since this fluorescence happens as a result of sunlight and plant activity, it is referred to as solar induced fluorescence. More photosynthesis translates into more fluorescence, also meaning that the plants are very productive in taking up carbon dioxide. In fact, while healthy plants and stressed plants may both look green, the healthy plants will have a lot of solar-induced fluorescence, while the stressed plants will have less or even no solar-induced fluorescence. The amount of carbon dioxide taken up by plants is called "gross primary productivity," and is the largest part of the global carbon cycle.

Now, satellite instruments have given climate researchers at NASA and other research institutions an unexpected global view from space of solar-induced fluorescence that sheds new light on the productivity of vegetation on land. Previously, global views of this glow were only possible over Earth's ocean using NASA's Moderate Resolution Imaging Spectroradiometer

(MODIS) instruments on NASA's Terra and Aqua spacecraft.

When the Japanese Greenhouse gases Observing SATellite (GOSAT), known as "IBUKI" in Japan, launched into orbit in 2009, its primary mission was to measure levels of carbon dioxide and methane, two major heat-trapping greenhouse gases in Earth's atmosphere. However, NASA researchers, in collaboration with Japanese and other international colleagues, found another treasure hidden in the data: fluorescence from chlorophyll contained within plants. Although scientists have measured fluorescence in laboratory settings and ground-based field experiments for decades, these new satellite data now provide the ability to monitor solar-induced chlorophyll fluorescence on a global scale, opening up a world of potential new applications for studying vegetation on land. The Orbiting Carbon Observatory-2 will also be looking in the same spectral region and therefore be able to contribute solar-induced fluorescence measurements. The instrument aboard the Orbiting Carbon Observatory-2 will make precise measurements of carbon dioxide in the atmosphere, recording 24 observations a second versus GOSAT's single observation every four seconds, resulting in almost 100 times more fluorescence observations than GOSAT.

The Orbiting Carbon Observatory-2 and Carbon Management

Carbon management is a key resource management and policy issue of the 21st century. Continued increases in atmospheric carbon dioxide concentrations will alter our climate and result in accompanying changes in Earth's energy and water cycles that will profoundly impact society and Earth's ecosystems. It's been estimated that at the current carbon emission rate, in less than 90 years, carbon emission levels would have to be completely eliminated just to cap carbon dioxide levels at twice their pre-industrial era level (560 parts per million). This implies that controls on emissions alone will not be sufficient — we will need to remove carbon dioxide from the atmosphere.

Carbon sequestration is one strategy to reduce emissions of greenhouse gases like carbon dioxide. Examples include strategically planting trees or crops to remove carbon from the atmosphere and mechanically removing carbon dioxide when it is created and then storing it in underground reservoirs or in the deep ocean basins. Several pilot projects to sequester carbon are currently under way around the world, primarily by energy companies.

NASA's carbon management observational assets focus on carbon emissions and sequestration in land, ocean and geologic systems. These assets include the NASA space missions Landsat, Terra, Aqua, Aura, SeaWiFS and the Orbiting Carbon Observatory-2 to measure and monitor carbon sequestration in terrestrial, freshwater and ocean environments, and the flow of carbon among them and the atmosphere.

The Orbiting Carbon Observatory-2 will make measurements at the regional scales that will be relevant to decision makers. It will give them direct insight into the impact land use changes have on carbon dioxide absorption and emission. By knowing where important natural sinks are, policymakers can make more informed land use decisions that take into consideration the impact they would have on atmospheric carbon dioxide levels.

Orbiting Carbon Observatory-2 data may also make it easier for governments and decision makers to monitor compliance with future carbon dioxide emissions treaties that offer credits for reducing carbon dioxide emissions and removing these emissions from the atmosphere.

In addition, a better understanding of the processes that are controlling the rate of carbon dioxide buildup in the atmosphere today will help to predict how fast this greenhouse gas will build up in the future, and how much time we will have to adapt to the resulting climate change.

Science Goals and Objectives

The primary objective of the Orbiting Carbon Observatory-2 is to substantially increase our understanding of how carbon dioxide sources and sinks are geographically distributed on regional scales and to study how this distribution changes over time. The mission will satisfy this objective by providing globally distributed, space-based measurements of the concentration of carbon dioxide present in Earth's atmosphere with the accuracy and resolution necessary to characterize this distribution. The atmospheric science community, including the Orbiting Carbon Observatory-2 science investigators, will use the data from these measurements to improve global carbon cycle models, reduce uncertainties in forecasts of how much carbon dioxide is in the atmosphere and make more accurate predictions of global climate change.

The mission goals are to:

- Collect the space-based measurements needed to retrieve estimates of the atmospheric concentration of carbon dioxide with random errors and systematic biases no larger than 0.3 percent (one part per million) on regional scales (approximately 621-mile, or 1,000-kilometer, scales) over both continents and oceans on the sunlit hemisphere of Earth at semi-monthly intervals for at least two years;

- Record, calibrate, validate, publish and archive science data records and calibrated geophysical data products in a NASA Distributed Active Archive Center for use by the scientific community; and

- Validate a space-based measurement approach and analysis concept that could be used for future systematic carbon dioxide monitoring missions.

Spacecraft

Built in Dulles, Virginia, by Orbital Sciences Corp., the Orbiting Carbon Observatory-2 is one of several scientific spacecraft that Orbital has built, or is in the process of building, for NASA based on the company's evolving line of LEOStar satellite platforms. The observatory is based on Orbital's LEOStar-2 configuration, on which several other NASA science satellite projects were produced, including the highly successful Galaxy Evolution Explorer, Solar Radiation and Climate Experiment and Aeronomy of Ice in the Mesosphere low-Earth orbit missions, as well as the Dawn deep space mission to the dwarf planet Ceres and asteroid Vesta.

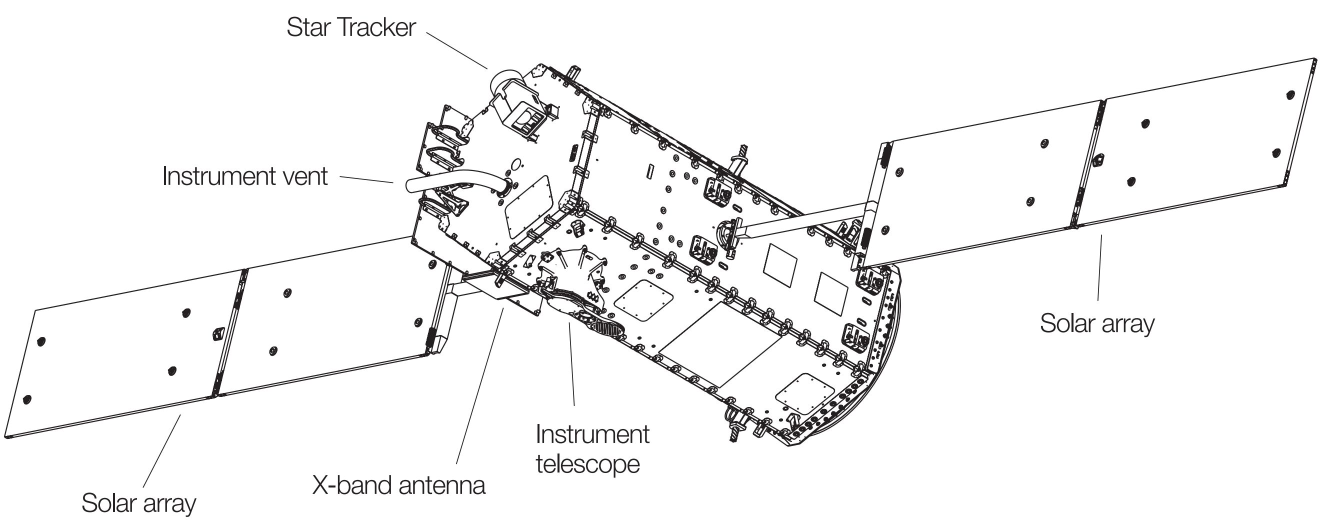
The majority of the spacecraft components have been flight proven or flight qualified. For the Orbiting Carbon Observatory-2, the spacecraft has been elongated to accommodate the instrument and the instrument has been embedded into the structure of the spacecraft.

The Orbiting Carbon Observatory-2 is about the size of a phone booth. Its main structure, or "bus," is made of aluminum honeycomb panels in a hexagon-shaped structure that measures about 6.96 feet (2.12 meters) long by 3.08 feet (0.94 meters) wide. The three-axis stabilized bus houses the instrument and provides power; receives and processes commands from the ground; and receives, stores and downlinks the science data collected by the instrument. The observatory, including the spacecraft, science instrument and onboard propellant, weighs 999 pounds (454 kilograms). A metal forward separation ring, mounted to the bottom of the structure, attaches the observatory to the launch vehicle and separates the two after launch.

While the observatory is designed to last for two years, its resistance to radiation at its orbiting altitude of 438 miles (705 kilometers) and the 99.2 pounds (45 kilograms) of propellant that it carries should allow the mission to operate well beyond its nominal two-year lifetime.

Thermal Control

The thermal system maintains satellite equipment at proper temperatures. It uses a combination of active and passive components. The active components are electrical heaters, which maintain the spacecraft interior within an operational temperature range during eclipses and in the unlikely event of the satellite entering a safe hold condition. The passive components are thermal radiators (which remove excess heat from the observatory electronics), blankets and thermal paints on the observatory's external surfaces. The instrument optics will be cooled to approximately 21 degrees Fahrenheit (267 Kelvin) by a passive radiator. The focal plane arrays are cooled to approximately minus 238 degrees Fahrenheit (123 Kelvin) by a pulse tube cryocooler, which uses a passive radiator to radiate its heat to space.



The observatory's power is generated, stored and distributed by the electrical power subsystem. The power required to run the entire observatory is 815 watts, equivalent to nine common 80-watt household light bulbs. The 28-volt power comes from a pair of symmetrical solar array wings covered with gallium arsenide solar cells. The arrays are extended in orbit on opposite sides of the satellite's main platform. Two small drive motors work with the spacecraft's computer software to keep the arrays pointed at the sun so that adequate power is always available to charge the battery and run all the components and the instrument.

Each wing of the solar array consists of two panels, each measuring 26 by 58 inches (0.66 by 1.47 meters), representing a total surface area of 41.7 square feet (3.88 square meters). The observatory wingspan, when the solar arrays are fully deployed, measures approximately 29 feet (9 meters) from tip to tip. The solar arrays generate an average of 900 watts of power when in orbit.

During times when the sun is eclipsed from the satellite, power is provided by a 35-amp-hour nickel-hydrogen battery. The battery also provides power in the unlikely event the observatory goes into safe hold during the period where the solar arrays are not pointed toward the sun.

Flight Software

The observatory uses stored commands to perform its normal operations and also receives commands and sequences from Earth. The software on the flight computer translates the stored and ground commands into actions for various spacecraft subsystems. The flight software also gathers science data as well as engineering telemetry for all parts of the spacecraft and continuously monitors the health and safety of the observatory.

The flight software can perform a number of autonomous functions, such as attitude control and fault protection, which involve frequent internal checks to determine whether a problem has occurred. If the software senses a problem, it will automatically perform a number of preset actions to resolve the problem or put the spacecraft in a safe mode until ground controllers can respond.

Observatory Avionics System

The observatory avionics, consisting of a central electronic unit and the attitude and power electronics, contain all the hardware and software to manage the observatory's attitude control, power, propulsion, thermal management and telecom functions. All the satellite's computing functions are performed by the central electronics unit. The heart of this subsystem is a Rad 6000 computer, which runs the observatory's flight software and controls various other parts of the satellite. The computer is a radiation-hardened version of the PowerPC chip used on many other spacecraft, such as NASA's Mars Exploration Rovers. The central electronics unit has one gigabyte of random access memory and three megabytes of non-volatile memory, which allows the system to maintain data even if power is lost.

Among the tasks managed by the central electronics unit and attitude and power electronics are the deployment of the solar arrays; precision determination and control of the satellite's orientation, or attitude; thermal management; automated fault detection and correction; communication with the science instrument; and acquisition, storage and transmission of science data. The central electronics unit also controls a 96-gigabit solid-state recorder that continuously stores science and engineering data from the observatory for downlink to the ground.

An uplink card operates independently of the onboard computer and is responsible for receiving, validating and decoding commands from the ground. Commands are routed to three paths for execution: special commands, normal command traffic and stored commands. Special commands operate independently of the onboard computer, bypassing the processing associated with normal command traffic. Special commands are typically used for reconfiguration and/or hard resets for the command and data handling subsystem. They can also be used to place the satellite in a "safe" mode, if this is commanded from the ground. The uplink card also receives timing signals from a global positioning system receiver and synchronizes timing on all observatory subsystems.

A downlink card receives telemetry data from various spacecraft subsystems, the science instrument and the solid-state recorder, and prepares these data for transmission to ground stations.

Telecommunications

The observatory's radio system operates in both the S-band and the X-band ranges of the microwave spectrum. Commands will be uplinked to the spacecraft as required using redundant S-band receivers linked to a pair of helical omnidirectional antennas. Uplinked commands include those for mode changes, pre-planned ground contacts or orbit maintenance burns. Science and housekeeping/health status data will be downlinked at a rate of 150 megabits per second through the 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.

Science data and information about the spacecraft's health and safety stored on the observatory's solid-state recorder are downlinked once daily to the ground station at AS1 or AS3. The observatory tracks the ground station during each downlink session. Downlink opportunities exist during every orbit, but only one 10-minute pass is required each day to download all the science data and engineering telemetry.

The downlinked science data will then be transmitted to the ground data system center at JPL, which will process and analyze these data. As the data are downloaded, the Mission Operations Center at Orbital will monitor and archive real-time housekeeping data, using software that allows them to spot any problems. Science data telemetry and any additional data not contained in the science data stream will be forwarded to JPL via the Internet.

The observatory will coordinate operations with other A-Train spacecraft through the Earth Science Mission Operations office at NASA's Goddard Space Flight Center, Greenbelt, Maryland.

Attitude and Control System

The attitude and control system provides high stability for the spacecraft during science operations and points the instrument for science and calibration observations. It also points the body-mounted X-band antenna at the ground station for data downlink.

The Orbiting Carbon Observatory-2 is a "three-axis-stabilized" spacecraft, meaning it can be held in any orientation in relation to space. The system is fully autonomous, relying on onboard systems to control the satellite orientation with no intervention required from ground controllers.

Unlike some other spacecraft, the Orbiting Carbon Observatory-2 requires no thrusters to adjust its orientation. Instead, it achieves this with four devices called reaction wheels, which use the momentum of spinning wheels to nudge the satellite in one direction or another. Periodically the reaction wheels accumulate too much momentum, which requires the use of three devices called magnetic torque rods — somewhat like large electromagnets — to push against Earth's magnetic field and cancel out some of the momentum in the wheels. The torque rods use information from a device called a three-axis magnetometer that senses the orientation of Earth's magnetic field.

The satellite's orientation is sensed and verified by a star tracker, while its rotation rates are sensed by an onboard inertial measurement system. The star tracker views the sky and processes the images gathered to recognize star patterns as they pass through the tracker's field of view.

The inertial measurement system on the observatory is a three-axis laser gyroscope that senses the observatory's attitude rate and controls the observatory attitude between the star tracker updates.

Sun sensors provide a relatively coarse measure of the sun's direction if the satellite should enter safe hold mode. There are 13 sun sensors on various parts of the observatory such that more than one sensor is pointing toward the sun regardless of observatory orientation.

In addition to pointing the instrument, the spacecraft must know where on Earth the footprint of the instrument is located. An onboard global positioning system receiver provides that information.

Propulsion

The Orbiting Carbon Observatory-2 requires onboard propulsion to raise its orbit from launch vehicle separation to the operational orbit within the A-Train constellation. The propulsion system is also used to maintain the observatory in a prescribed location within the A-Train. The observatory adjusts its orbit by firing any combination of its four onboard thrusters, each of which provides about 0.1 pound (0.5 Newtons) of thrust. The thrusters use hydrazine propellant. Orbit-raising burns and inclination corrections require the spacecraft to be reoriented. The propulsion system carries 99.2 pounds (45 kilograms) of hydrazine.

Physical and Functional Redundancies

The Orbiting Carbon Observatory-2 is a single-string spacecraft. This means that most spacecraft subsystems do not have backups. However, physical functional redundancies have been incorporated whenever possible. Some of the subsystems have redundant units such as S-band receivers, solar array drive electronics, reaction wheels and thrusters. There are other subsystems whose functionality can be accomplished by other units. Examples of functional redundancy include the ability to use the coarse sun sensors to provide spacecraft attitude instead of the star tracker, and performing onboard calculation of the spacecraft's ground track instead of using the global positioning system receiver.

Science Instrument

The Orbiting Carbon Observatory-2 will carry a single science instrument, designed by Hamilton Sunstrand, Pomona, California, for the original Orbiting Carbon Observatory mission, and built by JPL.

The instrument consists of three high-resolution spectrometers that are integrated into a common structure and fed by a common telescope. It measures 5.3 feet by 1.3 feet by 2 feet (1.6 meters by 0.4 meters by 0.6 meters), weighs 298 pounds (135 kilograms) and requires less than 125 watts of power.

The spectrometers are designed to measure how carbon dioxide and molecular oxygen absorb sunlight reflected off Earth's surface when viewed in the near-infrared part of the electromagnetic spectrum. Each spectrometer focuses on a different, narrow range of colors to detect light with the specific colors absorbed by carbon dioxide and molecular oxygen. Scientists will analyze these measurements to very precisely estimate the concentration of atmospheric carbon dioxide all over the globe. Once validated, this information will be used to infer the locations of carbon dioxide sources and sinks.

The instrument views Earth through an f/1.8 Cassegrain telescope mounted in a port in the side of the spacecraft bus. Reflected sunlight captured by the telescope is first focused at a field stop (a round aperture in an eyepiece that limits the field of view) and then realigned before entering a relay optics assembly that ensures that all three spectrometer channels view the same scene. Beam splitters separate the light by color, which is then refocused on a narrow slit that forms the entrance to each of the three spectrometers. Each slit measures only about 0.1 inch (3 millimeters) long and 0.00098 inch (25 microns) wide. The slits produce fields of view that are approximately 1/100th of a degree wide by eight-tenths of a degree long. A narrow-band filter ensures that only light from the desired spectral range reaches its particular channel, while a polarizer in front of each spectrometer slit keeps out any light that is not polarized in the desired direction.

Once light passes through each of the three spectrometer slits, it is aligned, then divided up by a diffraction grating into its different component colors, or wavelengths, traveling in different directions, in the same way that shining light through a prism creates a rainbow.

The light is then refocused by a camera lens onto each spectrometer's two-dimensional 1,024-pixel-by-1,024-pixel focal plane array, where it forms a two-dimensional image of a spectrum and is recorded. Originally designed for use in astronomy, the observatory's focal plane arrays are image sensing devices consisting of an array of light-sensing pixels. Each is designed to detect very fine differences in wavelength within its spectrometer's spectral range. The two carbon dioxide spectrometer channels use mercury cadmium telluride as their photosensitive materials, while the molecular oxygen A-band channel uses silicon.

Resembling bar codes, the spectra produced have dark lines where carbon dioxide or oxygen has absorbed specific colors. By measuring the light absorbed in each of these dark lines, scientists can count the number of carbon dioxide or oxygen molecules in the atmosphere at that location.

Design Considerations

The Orbiting Carbon Observatory-2 instrument and measurement approach are new. However, key instrument components, such as the mission's optical approach, holographic grating, cryocooler and detectors, have been flight qualified for other missions, including the Total Ozone Mapping Spectrometer, the Atmospheric Infrared Sounder on NASA's Aqua spacecraft, and the Tropospheric Emission Spectrometer on NASA's Aura spacecraft.

The need for sensitivity, stability and speed required innovations in optics, electronics, structures and thermal control. The three spectrometers incorporate an unprecedented combination of spectral resolving power and optical speed to provide the required sensitivity and short exposure times. The molecular oxygen spectrometer has a resolving power of approximately 20,000 while the carbon dioxide spectrometers have resolving powers of about 19,000. A fast (f/1.8) optical design and broad dynamic range were adopted to provide acceptable signal-to-noise ratios within the instrument's small measurement footprints over the full range of viewing conditions expected above Earth's sunlit hemisphere.

The high spectral resolution and fast optical design placed stringent constraints on the instrument structure and thermal control system, which must maintain tolerances smaller than one-tenth the thickness of a human hair through launch and the temperature variations the spacecraft will see as it travels in and out of Earth's shadow.

To minimize electronic noise that would generate measurement errors, the light detectors for each spectrometer must remain very cold. To ensure that the detectors remain sufficiently cold, the instrument uses a cryocooler, which is a refrigeration device. The cryocooler keeps the temperature of the detectors near minus 240 degrees Fahrenheit (minus 150 degrees Celsius).

The Spectrometers

The Orbiting Carbon Observatory-2's three parallel, high-resolution, near-infrared grating spectrometers make simultaneous measurements of the intensity of reflected sunlight at the same location on Earth's surface. They divide sunlight reflected from Earth's surface into a rainbow of colors, called a spectrum. The spectrometers, which use similar optical designs, are "tuned" to recognize the specific colors of infrared light absorbed by carbon dioxide and molecular oxygen. They will measure the intensity of the light in these colors with unprecedented accuracy.

As light passes through Earth's atmosphere and is reflected from the surface, molecules of each gas in the atmosphere leave their own telltale "fingerprint" on the reflected solar radiation. The Orbiting Carbon Observatory-2's spectrometers detect these molecular fingerprints. By analyzing the level of absorption displayed in these spectra, scientists can tell how much of the gas is present in the region where the measurement was taken.

Each spectrometer measures a specific wavelength band, or range of colors, within the near-infrared part of the electromagnetic spectrum. Near-infrared is invisible to the human eye. Each of these widely separated ranges of colors gives scientists a critical piece of information that contributes to the overall accuracy of the observatory's measurements.

The instrument measures the absorption of reflected sunlight by carbon dioxide in two ranges of colors, with wavelengths centered near 1.61 and 2.06 microns. The first absorbs carbon dioxide relatively weakly, but is most sensitive to the concentration of carbon dioxide near Earth's surface. This spectral region was selected for atmospheric carbon dioxide concentration measurements because other atmospheric gases do not absorb significant energy there.

The second range of colors, which absorbs carbon dioxide more strongly, provides a totally independent measure of atmospheric carbon dioxide abundance. That color range provides critical information about the pathway the light has taken and can detect clouds, aerosols and variations in atmospheric pressure and humidity, all of which can interfere with accurate measurements of carbon dioxide.

The third range of colors, the molecular oxygen A-band, with wavelengths centered near 0.765 microns (just beyond where the human eye is sensitive to red light), shows how much molecular oxygen is present in the light's pathway. To accurately derive the atmospheric concentration of carbon dioxide using instrument data, scientists first need to compare them to measurements of a second atmospheric gas. Because the concentration of molecular oxygen is constant, well-known and uniformly distributed throughout the atmosphere, it provides an excellent reference measurement. The molecular oxygen A-band spectra can assess the effects of clouds, aerosols and surface topography that can interfere with atmospheric carbon dioxide measurements. Observations from this band are also used to infer total atmospheric surface pressure and measure the length of the path of solar light as it passes through the atmosphere.

The reflection gratings used in the observatory's spectrometers consist of a very regularly spaced series of grooves that lie on a very flat surface. A good example of how the grating works can be seen by looking at the back of a compact disc under bright light. The narrow, circular tracks that record the information on the disk split light into a rainbow of different colors. The grooves in the instrument diffraction grating are very finely tuned to spread the light spectrum into a large number of very narrow wavelength bands or colors. The observatory instrument design resolves about 400 different colors in each of its three spectral ranges. In comparison, a digital camera covers a similar-sized wavelength range using just three colors.

Instrument Coverage

The observatory will orbit Earth every 99 minutes, continuously collecting 24 soundings per second while over the sunlit hemisphere. At this rate, the instrument will gather up to 69,000 individual measurements over a narrow ground track each orbit. The surface footprint of each measurement has an area smaller than just more than 1 square mile (3 square kilometers). The instrument will collect data over about 14.6 of these orbit tracks every day, each spaced about 24.7 degrees of longitude (1,600 miles, or 2,700 kilometers) apart at the equator. Over the course of each 16-day ground repeat cycle, it will collect about 8,000,000 measurements, with orbit tracks separated by less than 1.5 degrees longitude (100 miles or 160 kilometers) at the equator.

Compensating for Clouds, Aerosols and Topography

In order to infer the presence of sources and sinks, the light detected by the instrument must penetrate through the full height of the atmosphere. Thick clouds and aerosols (smoke, smog and desert dust) can obscure the surface, reducing the number of measurements that can be used for full-atmospheric column estimates of carbon dioxide. In addition, large variations in surface elevation within individual soundings can also distort atmospheric carbon dioxide measurements. The Orbiting Carbon Observatory-2 compensates for these factors by making a large number of very densely spaced measurements, each covering an area measuring about 1 square mile (3 square kilometers) when looking straight down. The instrument can gather as many as 69,000 of these soundings on the sunlit side of any Earth orbit. With measurement footprints of this size and density, the Orbiting Carbon Observatory-2 instrument can make an adequate number of high-quality soundings, even in regions where clouds, aerosols and variations in topography are present. Existing studies suggest that at least 10 percent of the data will be sufficiently cloud-free to yield atmospheric carbon dioxide concentration estimates with accuracies of 0.3 to 0.5 percent (1 to 2 parts per million) on regional scales at monthly intervals.

The observatory's spectrometers are designed to mitigate the effects of cloud contamination in individual soundings. The oxygen A-band and 2-micron carbon dioxide channels are extremely sensitive to clouds. In fact, the oxygen A-band channel is far more sensitive to thin clouds over continents than any other existing sensor except for the lidar on NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation mission. Also, because the observatory makes closely spaced soundings, the presence of small amounts of cloud contamination in a specific sounding can often be inferred from measurements made in adjacently located soundings.

Observational Modes

To enhance the quality and verify the validity of mission data, the Orbiting Carbon Observatory-2 will collect science observations in three standard observational modes: nadir, glint and target. All three modes sample at the same rate of 12 soundings per second.

In nadir mode, the satellite points the instrument straight down to the current ground track while on the day side of Earth. Nadir mode provides the highest spatial resolution on the surface and is expected to return more usable soundings in regions that are partially cloudy or have significant surface topography. However, nadir observations may not be suitable over dark ocean surfaces or in areas covered by snow.

In glint mode, the spacecraft points the instrument toward the bright "glint" spot (the point on the surface where the sun's reflection is most intense). Glint mode observations provide up to 100 times more signal than nadir observations. Therefore, the use of glint measurements significantly improves the signal-to-noise ratio over the dark ocean. The mission plans to alternate between nadir and glint modes over each sequential 16-day global ground track repeat cycle so that the entire Earth is mapped in each mode on roughly monthly time scales.

In target-tracking mode, the observatory will lock its view onto a single specific surface location while it flies overhead. This mode allows for a more thorough analysis of the atmosphere around an individual site. A target track pass can last for up to nine minutes, during which time the observatory can acquire as many as 12,960 samples. The mission plans to conduct regular target track passes over each of the observatory's calibration sites where ground-based solar-looking Fourier Transform Spectrometers are located. Comparing space-based and ground-based measurements provides a means to identify and correct systematic and random errors in the observatory's atmospheric carbon dioxide concentration data products.

NASA's Carbon Cycle Science Program

The Orbiting Carbon Observatory-2 is part of NASA's Carbon Cycle and Ecosystems Focus Area, which addresses the distribution and cycling of carbon among the land, ocean and atmospheric reservoirs and ecosystems as they are affected by humans, as they change due to their own biogeochemistry and as they interact with climate variations. The goals of the focus area are to: quantify global productivity, biomass, carbon fluxes and changes in land cover; document and understand how the global carbon cycle, terrestrial and marine ecosystems and land cover and use are changing; and provide useful projections of future changes in global carbon cycling and terrestrial and marine ecosystems.

Throughout the next decade, research will be needed to advance our understanding of, and ability to model, human-ecosystems-climate interactions so that an integrated understanding of Earth system function can be applied to our goals. These research activities will yield knowledge of Earth's ecosystems and carbon cycle, as well as projections of carbon cycle and ecosystem responses to global environmental change.

Examples of the types of forecasts that may be possible are: the outbreak and spread of harmful algal blooms, occurrence and spread of invasive exotic species and productivity of forest and agricultural systems. This focus area also will contribute to the improvement of climate projections for 50 to 100 years into the future by providing key inputs for climate models. This includes projections of future atmospheric carbon dioxide and methane concentrations and understanding of key ecosystem and carbon cycle process controls on the climate system.

Both physical and biological processes in the ocean affect the carbon cycle. In addition, physical processes influence the net production of biological oceanography.

NASA Missions to Study the Global Carbon Cycle and Climate

Over the years, several NASA missions have studied various aspects of biology and climate. These studies have been augmented by data from operational weather satellites of the National Oceanic and Atmospheric Administration.

The Landsat series of satellites, beginning in 1972, is the United States' oldest land-surface observation system. Landsat images have been used to study a wide range of processes, such as urban sprawl, deforestation, agricultural land-use trends, glaciation and volcanic activity. The latest in the series, Landsat 8, launched in February 2013. Formerly known as the Landsat Data Continuity Mission, Landsat 8 is NASA's eighth satellite in the Landsat series and continues the Landsat program's critical role in monitoring, understanding and managing the resources needed for human sustainment such as food, water and forests. Landsat 8 joined the Landsat 7 satellite in orbit and produces stunning pictures of Earth's surface along with a wealth of essential land surface data to the scientific community.

The launch of the Advanced Very High Resolution Radiometer on TIROS-N in 1978, and on subsequent NOAA operational satellites, permitted the global mapping of sea surface temperature and vegetation. The launch of the Coastal Zone Color Scanner on Nimbus-7, also in 1978, made mapping of oceanic chlorophyll and phytoplankton possible. The first step of photosynthesis both on land and in the ocean is the absorption of the sun's energy by the chlorophyll in leaves and phytoplankton. Scientists can measure the absorption of the sun's energy from space with satellites and consequently estimate the rates of carbon dioxide uptake by photosynthesis. Scientists at NASA's Goddard Space Flight Center produced the "First Picture of the Global Biosphere" using images from 15,000 orbits of the NOAA-7/AVHRR (for estimating land chlorophyll) and 66,000 images from the Nimbus-7/CZCS (for estimating oceanic phytoplankton chlorophyll, referred to as "ocean color").

The first global image of Earth's biosphere was created by NASA scientists using ocean data from the Coastal Zone Color Scanner and land data from the Advanced Very High Resolution Radiometer. Altogether, the data took almost eight years to compile. Current satellite instruments like the Sea-viewing Wide Field-of-view Sensor and the Moderate Resolution Imaging Spectroradiometer can produce images like this roughly once a week.

Launched in August 1997 as a successor to the Coastal Zone Color Scanner, the Sea-viewing Wide Field-of-view Sensor instrument onboard the OrbView-2 satellite acquires ocean color data to study the role of the ocean in the global carbon cycle, fluxes of trace gases at the air-sea interface and ocean primary productivity (rate of carbon fixation from the atmosphere). As was learned from the Coastal Zone Color Scanner, subtle changes in ocean color signify various types and quantities of marine phytoplankton. Ocean color data from the Sea-viewing Wide Field-of-view Sensor are helping scientists identify ocean "hot spots" of biological activity, measure global phytoplankton biomass and estimate the rate of oceanic carbon uptake. This information will yield a better understanding of the sources and sinks of the carbon cycle and the processes that shape global climate and environmental change.

Synthetic aperture radars on European, Japanese and Canadian satellites monitor deforestation and surface hydrological states and processes, as did such radars on NASA's space shuttle. The ability of synthetic aperture radars to penetrate cloud cover and dense plant canopies make them particularly valuable in rainforest and high-latitude boreal forest studies.

With the launch of the flagship Earth Observing System satellite in 1999 — Terra — NASA extended measurements of ocean color and land vegetation with advanced spaceborne instruments. Earth Observing System instruments such as the Multi-Angle Imaging SpectroRadiometer and the Moderate-Resolution Imaging SpectroRadiometer are providing global maps of surface vegetation so that scientists can model the exchange of trace gases, water and energy between vegetation and the atmosphere. The Enhanced Thematic Mapper Plus (ETM+) onboard Landsat 7 and the Advanced Spaceborne Thermal Emission and Reflection Radiometer onboard Terra are providing simultaneous multi-spectral, high-resolution observations of surface composition and natural hazards (volcanoes, floods, drought, etc.). In addition, the Multi-Angle Imaging SpectroRadiometer's ability to correct land surface images for atmospheric scattering and absorption and sun-sensor geometry will allow better calculation of vegetation properties. The Measurements of Pollution in the Troposphere instrument on Terra is providing global measurements of tropospheric methane and carbon monoxide.

New satellite sensors provide new ways of looking at Earth. In addition to measuring vegetation density, the Moderate Resolution Imaging Spectroradiometer can also measure photosynthetic activity. This provides a more accurate estimate of the amount of carbon absorbed by plants.

The measurement of land biomass by Moderate Resolution Imaging Spectroradiometer instruments on Aqua and Terra complement Orbiting Carbon Observatory-2 measurements by documenting the surface types associated with carbon dioxide sources and sinks. Because carbon dioxide absorption is directly proportional to net ecosystem productivity, Orbiting Carbon Observatory-2 measurements of carbon dioxide can be combined with Moderate Resolution Imaging Spectroradiometer observations to improve its estimates of this and other key land processes. Similarly, comparisons of ocean color and ocean temperature measurements from the Moderate Resolution Imaging Spectroradiometer with carbon dioxide measurements from the Orbiting Carbon Observatory-2 will help scientists better understand the relative roles of upwelling and local respiration on carbon dioxide emitted by the ocean.

The Atmospheric Infrared Sounder instrument on NASA's Aqua spacecraft is providing high-quality global measurements of carbon dioxide distribution at altitudes in the mid-troposphere, between 3 and 8 miles (5 and 13 kilometers) above Earth's surface. The sounder also measures temperature, water vapor, carbon monoxide, methane and other trace gases. The sounder's carbon dioxide measurements complement those from the surface carbon dioxide network by providing global maps of carbon dioxide concentrations at altitudes where this gas makes its largest contributions to greenhouse warming. Because the sounder's measurements have little sensitivity near Earth's surface, they cannot be used to locate and quantify the emission and absorption of carbon dioxide by processes there. The Orbiting Carbon Observatory-2 will fly in formation with Aqua, allowing both spacecraft to make measurements over the same locations within about three minutes of each other. By combining simultaneous, coincident observations of the Atmospheric Infrared Sounder with the Orbiting Carbon Observatory-2, scientists will be able to infer the altitude distribution of carbon dioxide and improve their understanding of how it mixes vertically in the atmosphere.

The Tropospheric Emission Spectrometer instrument on NASA's Aura spacecraft measures carbon dioxide at much higher altitudes, in Earth's stratosphere. Analyses of carbon dioxide from the Tropospheric Emission Spectrometer will be of keen interest to the Orbiting Carbon Observatory-2 science team.

Program/Project Management

The Orbiting Carbon Observatory-2 mission is managed for NASA's Science Mission Directorate, Washington, by NASA's Jet Propulsion Laboratory, Pasadena, California.

At NASA Headquarters, John Grunsfeld is the associate administrator for the Science Mission Directorate. Charles J. Gay is deputy associate administrator for the Science Mission Directorate. Mike Freilich is the Earth Science Division director within the Science Mission Directorate. Jack Kaye is associate director for research within the Earth Science Division. Betsy Edwards is the Orbiting Carbon Observatory-2 program executive. Ken Jucks is the Orbiting Carbon Observatory-2 program scientist.

At JPL, Ralph Basilio is the Orbiting Carbon Observatory-2 project manager, and Said Kaki is the Orbiting Carbon Observatory-2 deputy project manager. The project scientist is Michael Gunson, and the deputy project scientist is Annmarie Eldering. The Orbiting Carbon Observatory-2 Science Team is led by David Crisp of JPL, who guides the selected science team members. JPL is responsible for overall project management, system engineering management, mission design, instrument integration and test, mission assurance management, mission operations management and the ground data system. The California Institute of Technology, Pasadena, California, manages JPL for NASA.

At NASA's Kennedy Space Center, the NASA Launch Services Program is responsible for government oversight of launch vehicle preparations at Vandenberg; the engineering, certification and testing of the Delta II launch vehicle; spacecraft ground support and integration with the Delta II; the Space Launch Complex 2W pad facilities; countdown management; launch vehicle tracking; data acquisition; and telemetry monitoring.