CATS: Measuring Clouds and Aerosols from the International Space Station
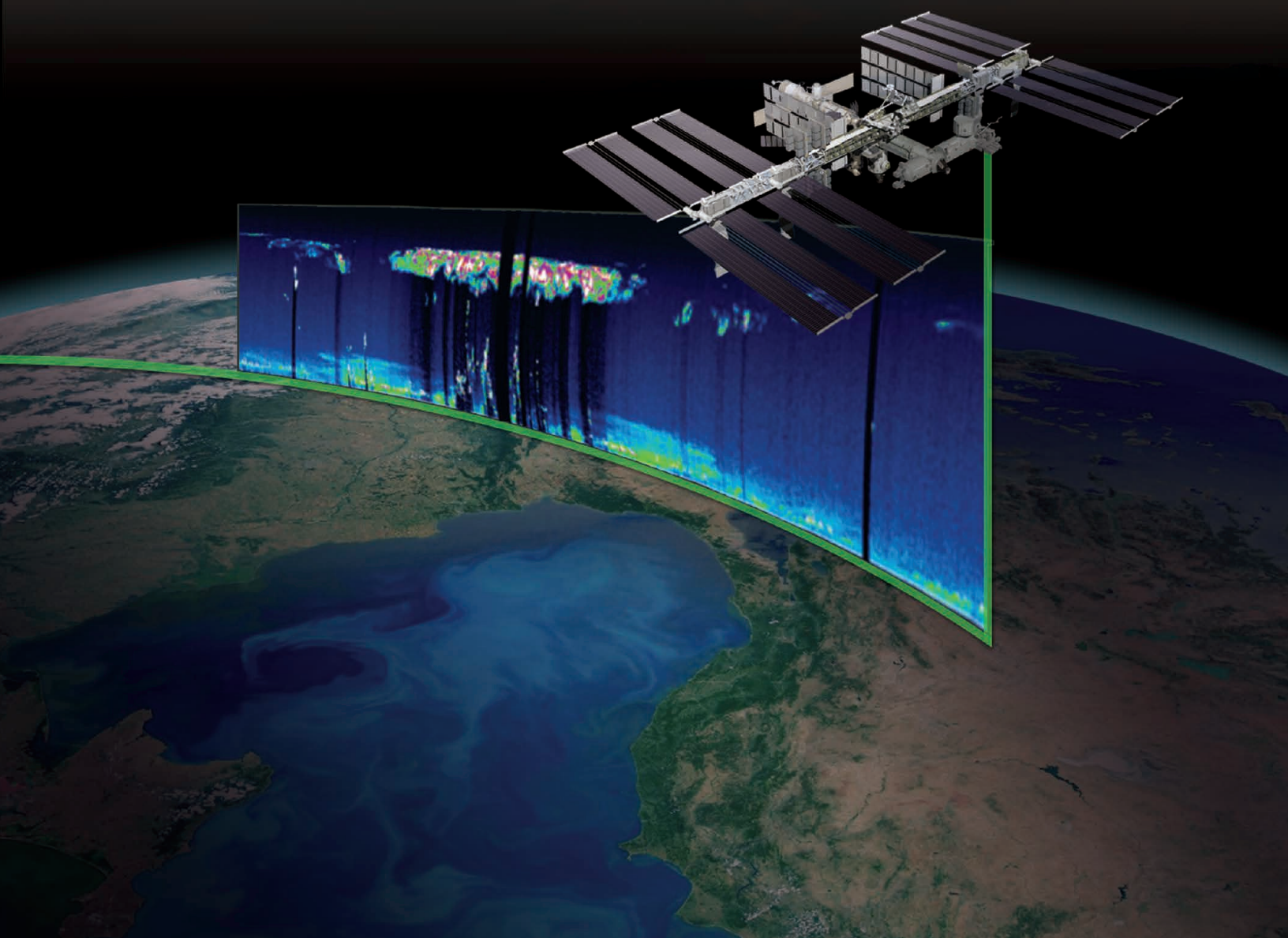
Acknowledgements

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Clouds, Aerosols, and Earth's Climate

Clouds and aerosols reflect about a quarter of the sun's energy back to space; however their impact on Earth's global energy budget and climate is not yet fully understood due to complex interactions between clouds and aerosols.

From space, streaks of white clouds can be seen swirling across Earth's surface. In addition to clouds, other tiny solid and liquid particles, invisible to our eyes, called *aerosols* are also swirling around in Earth's atmosphere. Aerosol particles are both natural and man-made, and include windblown dust from deserts, sea salt, smoke from wildfires, sulfurous particles from volcanic eruptions, and sulfurous and carbonaceous particles produced by fossil fuel combustion.

Clouds and aerosols play an important role in Earth's climate system because they reflect and absorb radiation from the sun differently. For example, when the sun's energy reaches the top of the atmosphere, clouds tend to reflect incoming sunlight, cooling Earth's surface. However, clouds also tend to absorb heat emitted from the surface and re-radiate it back down, warming Earth's surface. Therefore, the amount of warming or cooling is heavily dependent on the height, thickness, and structure of clouds in the atmosphere. Aerosols—depending upon their size, type, and location—can also either cool the surface, or
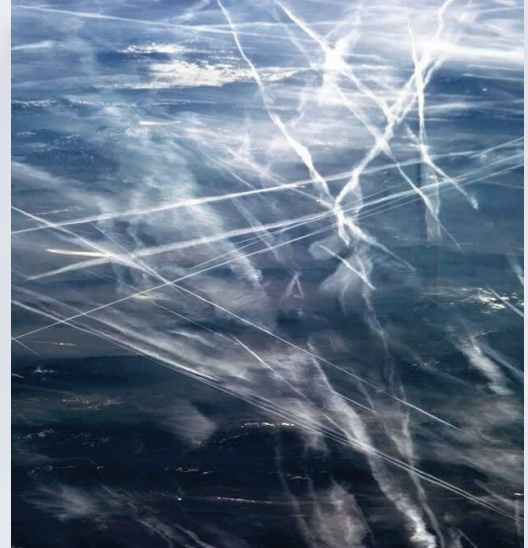
The interactions between clouds and aerosols are illustrated in this image, taken by retired astronaut Chris Hadfield onboard the International Space Station, showing contrails produced by aircraft (bright streaks) over the ocean. In the absence of aircraft exhaust, natural aerosols are required to seed upper tropospheric ice cloud particles. Image credit: NASA/Chris Hadfield

Why Do We Need Vertical Information?

Different types of clouds and aerosols can be found at varying heights in the atmosphere and depending on their properties and location, they can have varying radiative effects on Earth's climate system. To improve climate, weather, aerosol, and air quality models, scientists need to better understand these properties and cloud and aerosol vertical distribution in the atmosphere.

Although most aerosols reflect sunlight, some also absorb it. An aerosol's effect on light depends primarily on the composition and color of the particles. Broadly speaking, bright-colored or translucent particles tend to reflect radiation in all directions and back towards space. Darker aerosols can absorb significant amounts of light. Pure sulfates and nitrates reflect nearly all radiation they encounter, cooling the atmosphere. Black carbon, in contrast, absorbs radiation readily, warming the atmosphere but also shading the surface. Image credit: NASA

Composite image created from photographs by: Patrick Byrne, Carolyn Conner, Peggy Davis, Daniel Fogg, John Newman, Cyrus Reed, and Gayle Trautman

warm the atmosphere. In general, dark-colored aerosols such as black carbon from fossil fuel combustion absorb radiation, heating Earth's atmosphere, while bright-colored aerosols such as sulfates from volcanic eruptions reflect radiation, acting to cool Earth's atmosphere.

Constantly in motion, different types of clouds and aerosols can be found at varying heights throughout the atmosphere and while they have relatively short lifetimes, they often have complex interactions when mixed together. For example, aerosol particles can affect the formation and properties of clouds (e.g., by activating early growth of cloud droplets and by changing the albedo, or reflectivity, of clouds). The relationship between clouds and aerosols and the resulting influence on Earth's climate is therefore multifaceted, with impacts on Earth's energy balance, hydrologic cycle, and atmospheric circulation.

Aerosols, both natural and man-made, also affect air quality. Near Earth's surface, aerosol particles are pollutants that can exacerbate poor air quality conditions harmful to our health. For example, small aerosols can enter the human lungs and blood, where they can cause respiratory issues and even heart attacks. Higher in the atmosphere, aerosols ejected from volcanoes can disrupt air traffic—as was dramatically demonstrated during the 2010 eruption of the Eyjafjallajökull volcano in Iceland, which caused an estimated $1.7 billion dollar loss for the airline industry.

To predict changes in Earth's climate and air quality scientists use measurements of clouds and aerosols to simulate forecasts using computer models. However, due to the complexities mentioned here, there are large uncertainties in the way models handle clouds and aerosols and their radiative properties. Therefore, obtaining a better understanding of cloud and aerosol coverage, distribution, and type throughout all vertical layers of the atmosphere is critical for understanding and predicting Earth's climate as well as air quality conditions.
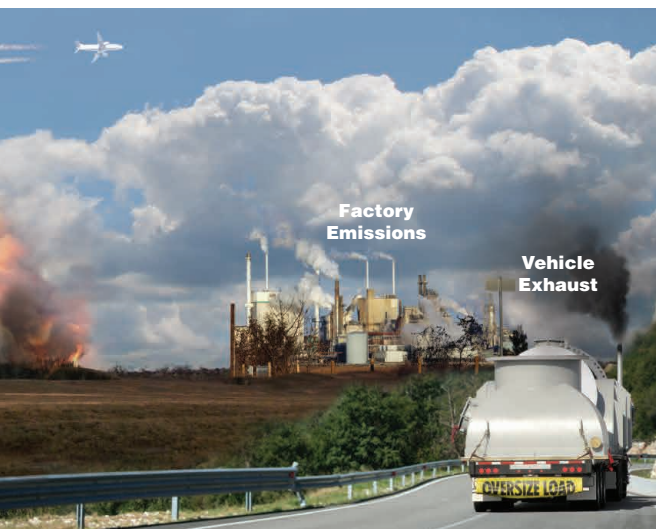
Image credit: Sydney Oats

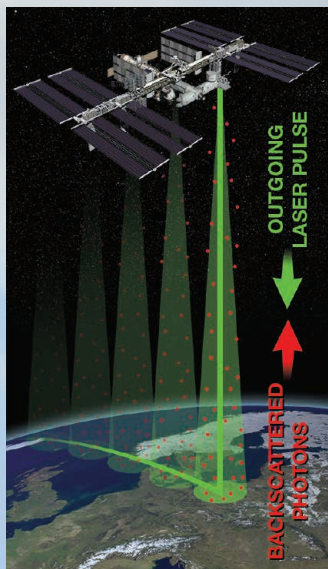Image credit: US Forest Service Gila National Forest/Kari Greer

Image credit: Thawt Hawthje

Image credit: Bojan Rantaša

Some aerosols close to the surface, such as dust, smoke from wildfires, and harmful pollutants, can cause air quality issues and impact human health.

Measuring Clouds and Aerosols

Active lidar remote sensing instruments provide information about the three-dimensional distribution of clouds and aerosols by emitting a laser pulse of light and measuring the elapsed time of the return signal. Image credit: NASA

Today scientists use an array of satellite, aircraft, and ground-based instruments to measure and monitor clouds and aerosols. For many years scientists have observed clouds and aerosols using passive remote sensors that measure the amount of radiation reflected and emitted by Earth. These sensors are important for providing information about aerosol and cloud concentrations over large areas but are not commonly used for distinguishing differences in height or type. To better observe the vertical structure of clouds and aerosols, scientists turn to another tool: active remote sensing instruments, which include lidar.

Lidar works by using a laser to send a pulse of energy through the atmosphere towards a distant object (i.e., a cloud droplet or aerosol particle). Once the energy reaches the object, some of the energy is reflected back to the lidar receiver. Scientists can calculate the distance between the lidar instrument and the object (i.e., its location in the atmosphere) based on the time it takes the reflected energy to return to the receiver. The intensity of this *return pulse* also allows scientists to infer other properties, such as the composition of clouds, the abundance and sizes of aerosols, and the altitudes of cloud and aerosol layers.

In 1999 NASA developed an airborne lidar system called the Cloud Physics Lidar, or CPL, for use on the high-altitude ER-2 aircraft. Still used

The primary capability for CATS was adapted from the CPL design. Pictured here, the Cloud Physics Lidar was designed and built by scientists and engineers at NASA's Goddard Space Flight Center. Image credit: NASA

CPL 532 nm Attenuated Backscatter Profiles
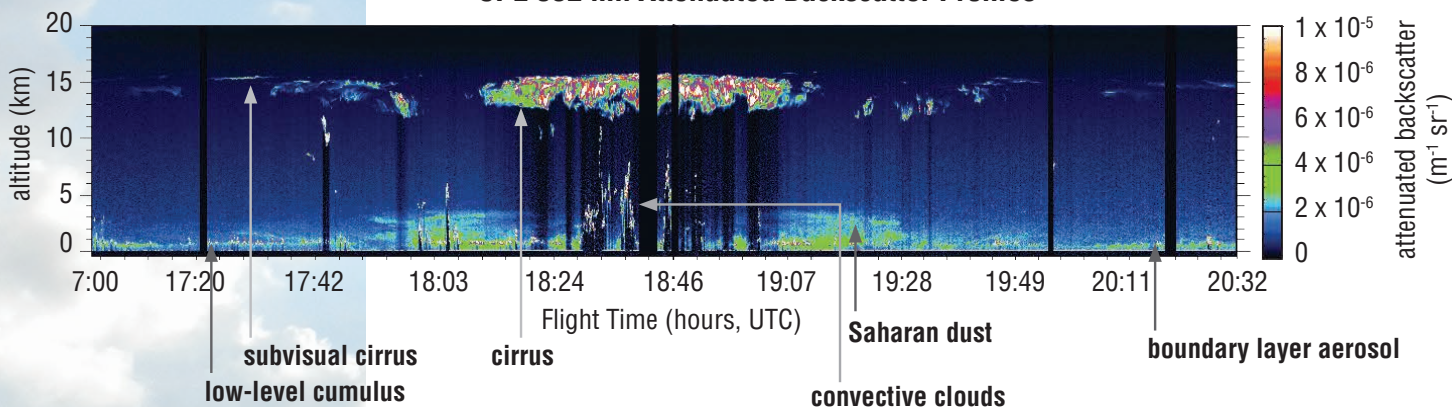
This vertical profile from the airborne CPL lidar instrument shows different cloud and aerosol types and concentrations at various heights in the atmosphere. Measurements of the vertical distribution of clouds and aerosols are useful in many diverse scientific disciplines such as climate studies, weather research and prediction, atmospheric geochemistry, aerosol impacts on the biosphere, as well as satellite and model calibration and validation. Image credit: NASA

today, the CPL uses a high-repetition-rate laser to provide atmospheric profile measurements of clouds and aerosols. The ER-2 typically flies at approximately 65,000 feet (20 kilometers) above the Earth's surface, which allows the instruments onboard to function as spaceborne instrument simulators. While the CPL provides valuable data to the research community and has done so for many years, it does not provide continuous, near-global coverage like satellites can.

In 2006 NASA launched the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observa-tions, or CALIPSO, spacecraft—a joint mission between NASA and the French Centre National d'Études Spatiales (CNES). Similar to CPL's lidar, CALIPSO carries a lidar that provides vertical distributions and properties of clouds and aerosols along a flight track. However, the CALIPSO lidar has exceeded its three-year prime mission and has been using its backup laser since 2009.

It is critical to continue the measurement capabilities of CALIPSO to better assess the climatological impacts of clouds and aerosols through the use of computer models. To do so, these measurements are required over time scales that are much longer (~20-30 years) than typical mission lifetimes (~5-10 years). The next satellite mission with a lidar onboard is scheduled to launch in 2018—a joint European and Japanese spacecraft called the Earth Clouds, Aerosols, and Radiation Explorer, or EarthCARE. NASA also plans to launch the Aerosols, Clouds, and Ecosystems (ACE) mission; however, it is planned for a post-2020 launch date. As a result, the cloud and aerosol research community faces a significant data gap in terms of continuing the CALIPSO data record.

However, a unique opportunity to fill the potential data gap presented itself in 2011 when the International Space Station (ISS) NASA Research Office offered scientists at NASA's God-dard Space Flight Center a mounting location onboard the space station for a new lidar instru-ment called the Clouds and Aerosol Transport System, or CATS. Scheduled for launch in December 2014, CATS will serve as a "bridge" between CALIPSO and EarthCARE, helping to

extend the CALIPSO data record for continuity of lidar climate observations. Ideally, CALIPSO will still be operational when CATS becomes active allowing for a period of intercomparison between CATS and CALIPSO data, and likewise CATS would be operational long enough to get EarthCARE up and running.
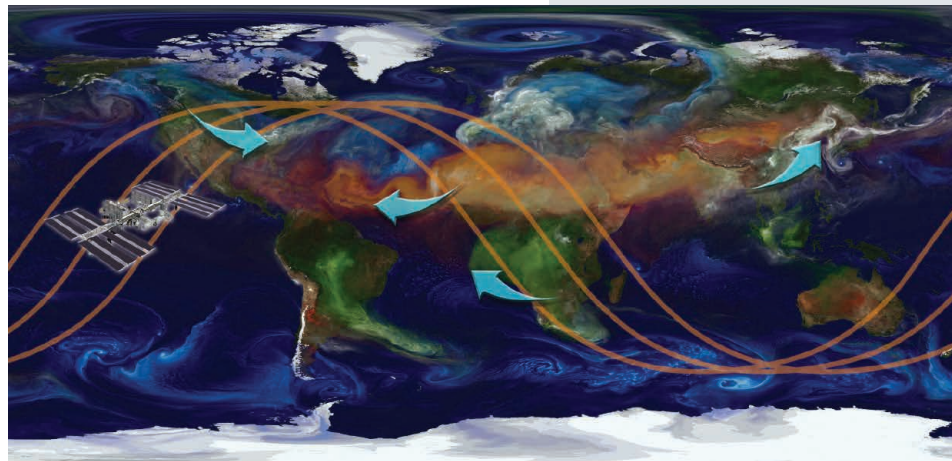
To study aerosols, researchers from NASA's Global Modeling and Assimilation Office ran a simulation of the atmosphere using the Goddard Earth Observing System Model Version 5, or GEOS-5, that captured how winds transport aerosols around the world. This image represents how sea salt (blue) and dust (orange) swirl inside cyclones, sulfates (white) stream from surface emissions and volcanoes, and carbon (green) bursts from fires. Such simulations allow scientists to better understand how these tiny particulates travel in the atmosphere and influence weather and climate. Image credit: NASA's Scientific Visualization Studio
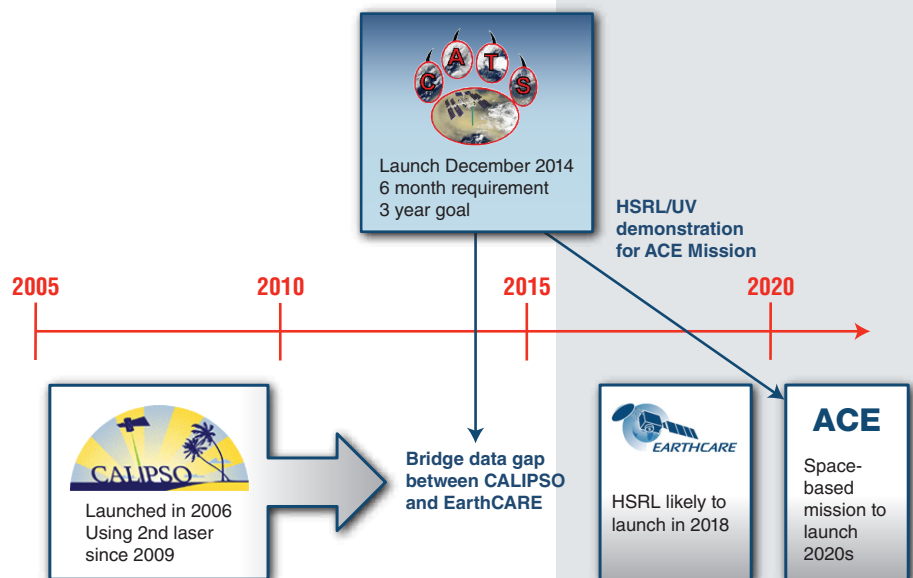
The CATS mission will help extend the CALIPSO data record to ensure continuity of lidar climate observations. Image credit: NASA
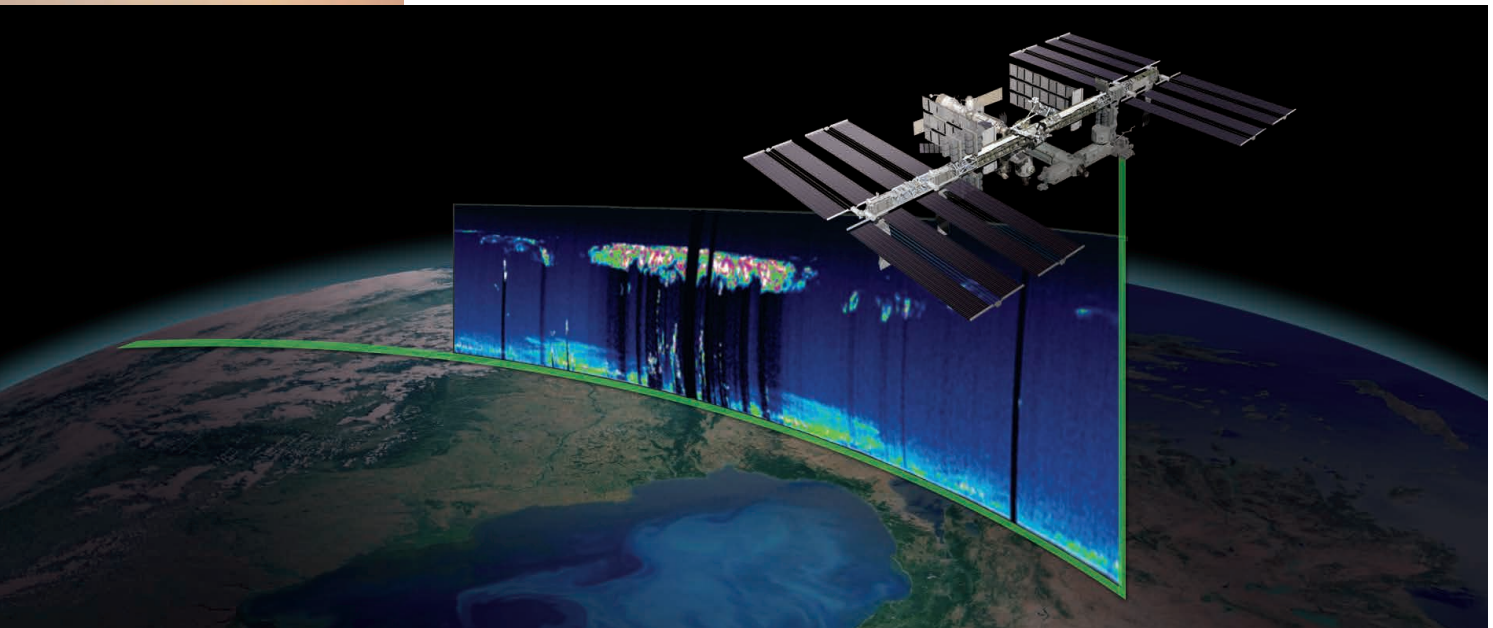
Mission Overview

This mission provides a unique opportunity to demonstrate ISS-based operational science capabilities as well as an opportunity to demonstrate new technologies for future Earth science missions (e.g., NASA's ACE mission) at a relatively low cost.

Several aspects of CATS make the mission extraordinarily unique. To start, the CATS instrument was to be designed and built in only two years and on a much smaller budget than traditional satellite missions. Given this two-year design time—which is very short compared to most spaceborne missions—scientists and engineers at NASA's Goddard Space Flight Center needed to work quickly. To do so they leveraged existing instrument designs from the CPL and Airborne Cloud-Aerosol Transport System, or ACATS, and used commercial parts where possible. In particular, Fibertek, Inc. provided the laser units and the avionics/communications package and Design Interface, Inc. provided mechanical design services.
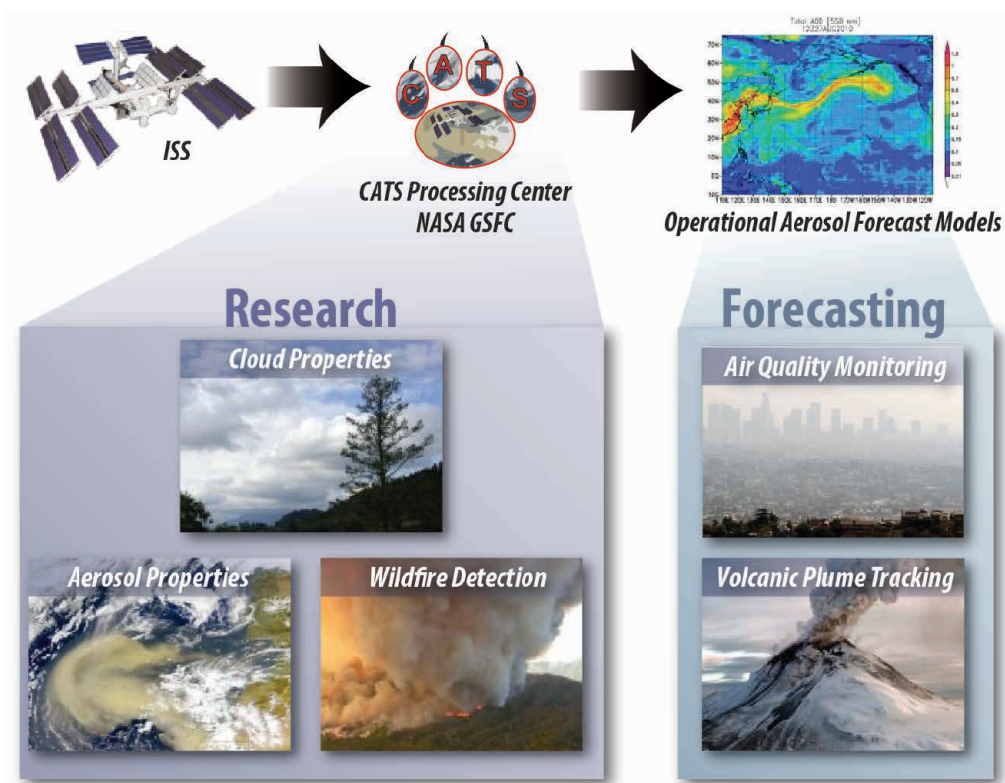
Designed to operate for at least six months—with a goal of three years, and the possibility to operate as long as five years—CATS will provide vertical profiles of cloud and aerosol properties at three wavelengths (1064, 532, and 355 nanometers). Onboard the space station, CATS will orbit between 375 kilometers (~230 miles)

and 435 kilometers (~270 miles) above Earth's surface at a 51-degree inclination with nearly a three-day repeat cycle. This unique orbit path will allow the CATS instrument to observe the same spot on Earth at different times each day, providing far more comprehensive coverage of the tropics and mid-latitudes (between 51.6 degrees north and south latitude) than sun-synchronous orbiting satellites (like CALIPSO) that observe the same Earth scene at the same local time each day. This will allow scientists to, for the first time ever, study diurnal (day-to-night) changes in cloud and aerosol effects from space.

CATS will also provide a continuous stream of data from the ISS and, unlike CALIPSO and other Earth-observing satellites, does not rely on ground stations to downlink data once or twice daily. In addition, this mission provides a unique opportunity to demonstrate ISS-based operational science capabilities as well as an opportunity to demonstrate new technologies for future Earth science missions (e.g., NASA's ACE mission) at a relatively low cost.


Artist's rendition of CATS collecting a swath of data from the ISS. Image credit: NASA

ISS → **CATS Processing Center NASA GSFC** → **Operational Aerosol Forecast Models**

Research
Cloud Properties
Aerosol Properties
Wildfire Detection

Forecasting
Air Quality Monitoring
**Volcanic Plume Tracking**

Onboard the ISS, CATS will provide a continuous stream of data that can be used for research applications such as studying cloud and aerosol properties and detecting wildfires. CATS will also provide data that can be used in near real-time for several forecasting applications including plume tracking and air quality monitoring. Image credit: NASA

Due to the unique orbit path of the ISS, CATS will observe the same spot on Earth at different times each day. In addition, the low-inclination orbit permits extensive measurements over aerosol source and aerosol transport regions. Image credit: NASA
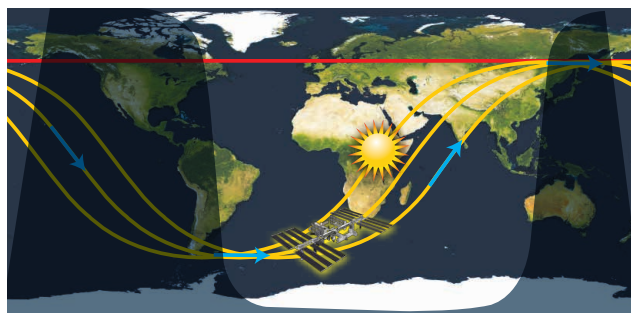
The space station revisits the same latitude at slightly different local times on each orbit. In general, this means it covers all points on Earth's surface between 51.6 degrees north and south latitude at all times of day in roughly two months. Image credit: NASA

CATS-ISS Monthly Coverage: September 2012 (0-24 hrs local time)
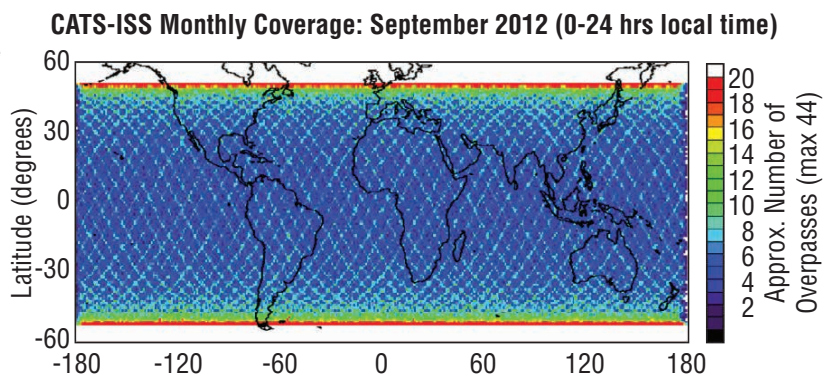
Science Goals

1. CATS will help extend the global lidar data record for continuity of climate observations. In particular, CATS will:

- Continue the data record of vertical profiles of cloud/aerosol properties;

- Improve our understanding of aerosol and cloud properties and interactions; and

- Improve model estimates of climate forcing and predictions of future climate change.

2. Data from CATS will improve operational aerosol forecasting programs. In particular, the data will:

- Improve model performance through assimilation of near-real-time cloud/aerosol data;

- Enhance air quality monitoring and prediction capabilities by providing vertical profiles of pollutants; and

- Improve strategic and hazard-warning capabilities of events in near real-time (e.g., dust storms and volcanic eruptions).

3. The CATS payload will serve as a technology demonstration for future space-based lidar missions. In particular, the payload will:

- Demonstrate High Spectral Resolution Lidar (HSRL) aerosol retrievals and 355 nanometer (ultraviolet) data for future mission development.
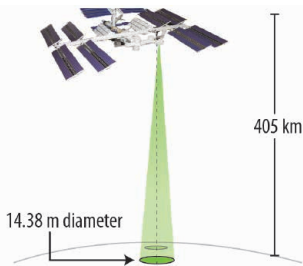
Instrument Overview

Mode 1: Multi-Beam

Backscatter: 532, 1064 nm
No HSRL
Depolarization: 532, 1064 nm
Science Goals: 1, 2
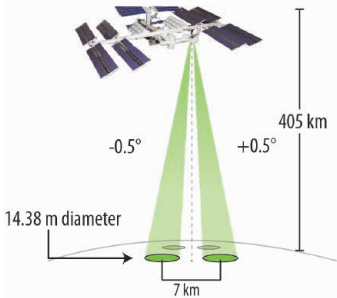
Mode 2: HSRL Demo

Backscatter: 532, 1064 nm
HSRL: 532 nm
Depolarization: 1064 nm
Science Goals: 1, 3

Mode 3: UV Demo

Backscatter: 355, 532, 1064 nm
No HSRL
Depolarization: 532,1064 nm
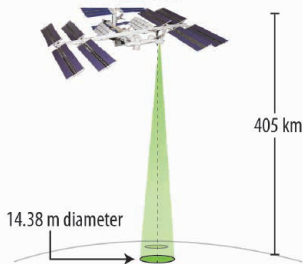Science Goals: 1, 2, 3

Image credit: NASA

The CATS instrument can operate in three different *modes* and uses two high-repetition-rate lasers. Data from CATS will be used to derive a variety of properties of cloud and aerosol layers including: backscatter, layer height, layer thickness, extinction (how much light is lost due to scattering and absorption), optical depth (the total loss of light through a layer), and at least a coarse discrimination of aerosol and cloud type (e.g., smoke, dust, pollution, water droplet, ice crystal) using a technique called *depolarization-based discrimination* of particle type.
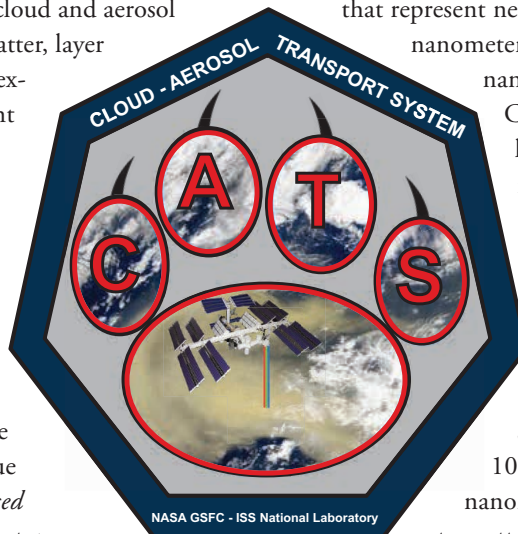
CATS will operate in Mode 1 for the majority of the mission, as Modes 2 and 3 will be used intermittently to test new technologies for future missions (e.g., ACE). Mode 1, also referred to as the *multi-beam mode*, splits the energy from the first laser into two wavelengths that represent near infrared radiation (1064 nanometers) and visible light (532 nanometers)—similar to CALIPSO. This two-wavelength mode is necessary for determining *layer type* (i.e., cloud and aerosol composition) since different particles reflect the two wavelengths differently. For example, water particles tend to scatter more "light" at 1064 nanometers than at 532 nanometers, while aerosols tend to scatter more at 532 nanometers than at 1064 nanometers. Ice particles, on the other hand, tend to scatter the same amount of light at both wavelengths.
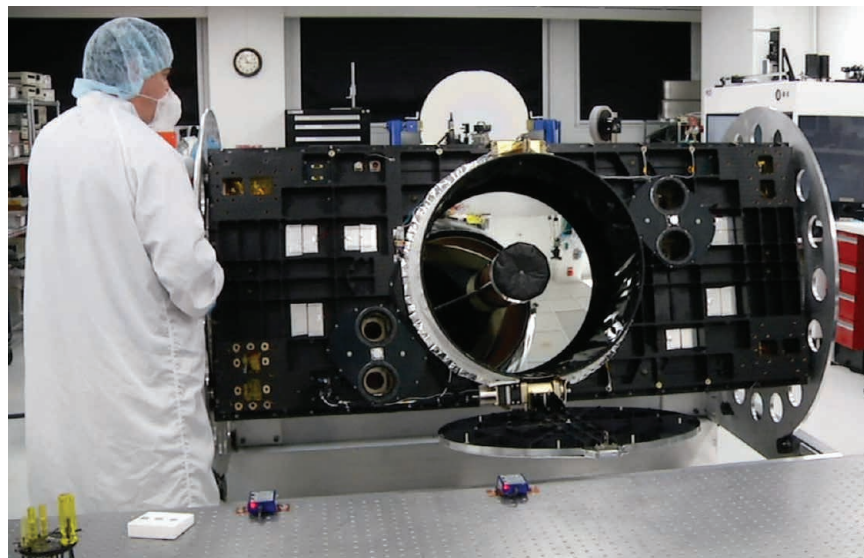
Engineers at NASA's Goddard Space Flight Center assemble the CATS payload inside the cleanroom. The instrument payload weighs 494 kilograms (~1100 pounds). Image credit: NASA
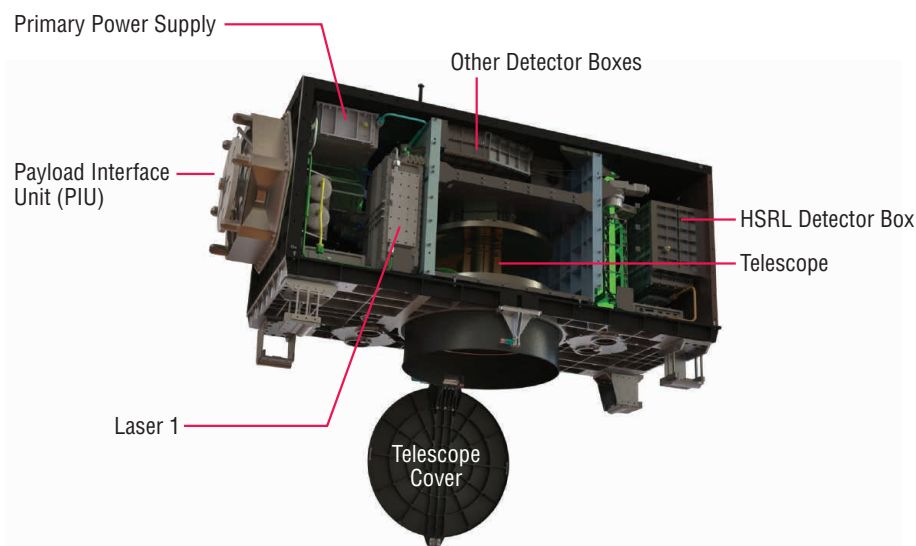
Instrument parts are labeled in this diagram of the CATS payload. (Note, Laser 2 does not appear in this view and is therefore not labeled in this image.) Image credit: NASA

Determining layer type is important because different clouds and aerosols have different radiative properties that impact Earth's radiative balance in a variety of ways. Current climate models do not accurately predict the vertical distribution of clouds and aerosols or their layer type. To reduce these uncertainties, scientists will use lidar data from CATS to initialize forecast models, subsequently producing more accurate results. Additionally, determining layer type is important for forecasting air quality conditions. In particular, aerosol types that consist of small particles, such as sulfates and carbons, are more dangerous to human health than larger aerosols such as dust.

Operational Mode 2 uses the second laser and will demonstrate a new technology called *High Spectral Resolution Lidar* (HSRL). This new technique uses a narrower wavelength interval at 1064 and 532 nanometers to provide more

precise measurements. In particular, Mode 2 will provide better estimates of extinction, which is extremely important for model applications since it is an important variable in determining the radiative effects of clouds and aerosols on the climate system.

Mode 3 also uses the second laser and in addition to operating at 1064 and 532 nanometers, adds a third wavelength at 355 nanometers. The shorter wavelength of 355 nanometers lies in the ultraviolet region of the electromagnetic spectrum and will therefore interact with particles differently than 1064 and 532 nanometer wavelengths. Scientists are eager to learn more about the use of this new wavelength and look forward to what this new capability might mean for future space-based lidar mission development, especially the EarthCARE mission.

Current climate models do not accurately predict the vertical distribution of clouds and aerosols or their layer type. To reduce these uncertainties, scientists will use lidar data from CATS to initialize forecast models, subsequently producing more accurate results.

Launch and Installation

The CATS instrument is scheduled to launch on the SpaceX Cargo Resupply-5, or SpaceX-5, mission to the ISS in December 2014. SpaceX-5 consists of a Dragon cargo spacecraft mounted atop a Falcon-9 launch vehicle. Prior to launch, the CATS instrument will be strategically mounted inside the Dragon's unpressurized trunk, which will provide power to the payload's survival heaters from launch until it is removed for installation to the ISS.

Once launched, the instrument will be installed on the International Space Station's Japanese Experiment Module – Exposed Facility (JEM-EF)—the first NASA-developed payload to ever fly on the JEM-EF. When it reaches the space station, the Dragon spacecraft will be robotically berthed. A robotic arm on the space station called the Space Station Remote Manipulator System,

or SSRMS, controlled by ground controllers at NASA, will then extract the instrument from the trunk and pass it to a second robotic arm called the Japanese Experiment Module Remote Manipulator System, or JEMRMS, controlled by the Japan Aerospace Exploration Agency that will attach the instrument to the JEM-EF.

Once the instrument is successfully attached to the JEM-EF, all onboard operations will be conducted through ground control at NASA's Goddard Space Flight Center using real-time commands. Onboard the space station, CATS is intended to operate continuously, or as near-continuously as possible, except during periods when the instrument needs to be turned off for safety reasons such as during an extra-vehicular activity (i.e., a spacewalk).

SpaceX Dragon cargo spacecraft. Image credit: NASA

Image credit: NASA/Tony Gray and Tim Powers
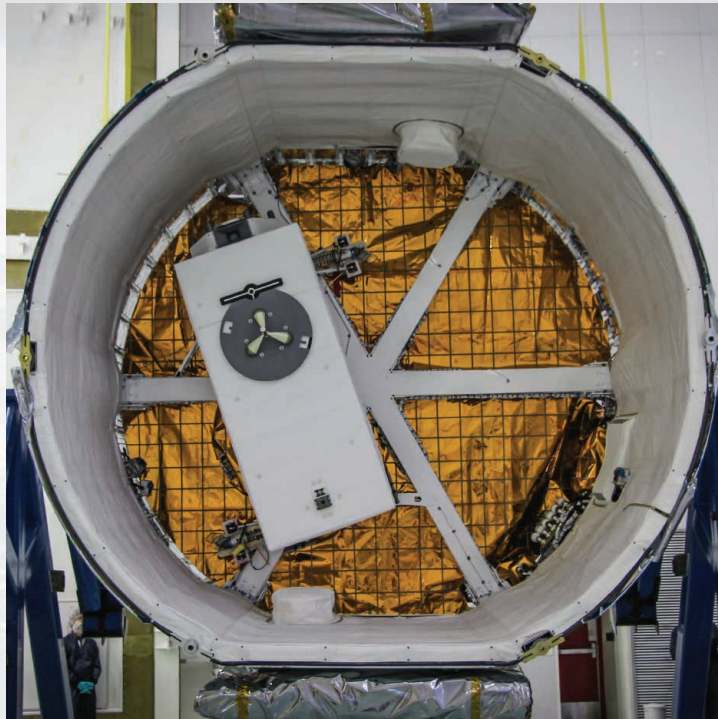
Prior to launch, the CATS instrument will be strategically mounted inside the Dragon trunk on SpaceX. Image courtesy: SpaceX

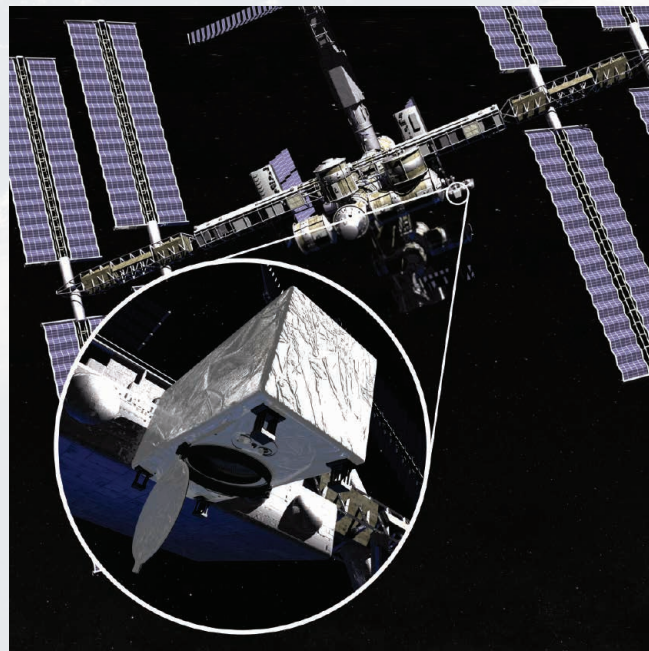Pictured here, CATS will be fully exposed to the space environment once mounted on the JEM-EF. Image credit: NASA

Onboard the space station, CATS is intended to operate continuously, or as near-continuously as possible, except during periods when the instrument needs to be turned off for safety reasons such as during an extra-vehicular activity (i.e., a spacewalk).

Image credit: NASA
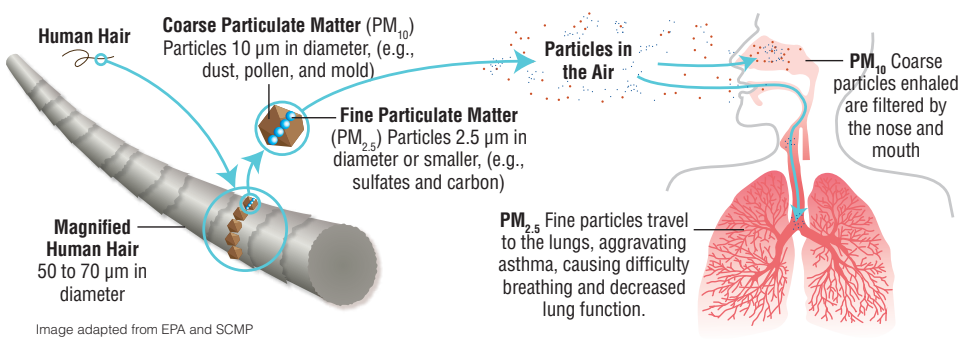
Benefits to Society and Technology

Air, or the atmosphere, is essential for life on Earth. It protects life by absorbing ultraviolet solar radiation, warming the surface through heat retention (greenhouse effect), and reducing temperature extremes between day and night. In addition to protecting us, the quality of Earth's air, or *air quality*, impacts the health of all living things from humans to plants.

Air quality fluctuates from day to day for a number of reasons. Most obviously, air quality changes if more pollutants are put into the atmosphere. Large events such as dust storms, wildfires, volcanic eruptions, and days with high-energy demands can dramatically influence air quality and impact human health and activities.

Currently, scientists get a broad picture of air quality conditions in the atmosphere and generate air quality forecasts by combining satellite, aircraft, and ground-based data with sophisticated computer models. However, most datasets do not provide information about the vertical structure of clouds and aerosols and their layer type. Incorporating the near real-time vertical data that CATS will produce is expected to improve our ability to track different cloud and aerosol types at all layers of the atmosphere. These datasets will be used to improve strategic and hazard-warning capabilities of events in near real-time (e.g., plume tracking for dust storms, volcanic eruptions, and wildfires), which ultimately impact our daily lives.

Provided here are just a few examples of recent events where air quality impacted daily life. Data from CATS can make a difference in predicting, responding to, and mitigating the impact of similar events in the future.

- **Volcanic Eruptions.** On June 4, 2011, the Puyehue-Cordón Caulle volcano in Chile experienced its first major eruption in decades. The volcano sent an ash plume eastward, disrupting air traffic, threatening water supplies, and even dropping golf ball-sized pumice on parts of Argentina. Volcanic ash (very different from ash from ordinary fires) is made of tiny, jagged particles of rock and glass that are very abrasive and slightly corrosive, and can even conduct electricity when wet. In addition to disrupting air traffic, it can irritate respiratory systems, coat vegetation and leave it inedible to wildlife and livestock, and destroy machinery.

- **Dust Storms.** In mid-October 2012, the Great Plains of the United States endured a widespread dust storm due to months of drought and searing heat. Severe winds blew soil and sediment across hundreds of miles causing near blackout conditions in some places. Authorities had to close portions of Interstate 35 in Kansas and Oklahoma, as well as Interstate 80 in Wyoming, due to accidents and poor visibility. More common

Human Hair

Coarse Particulate Matter (PM$_{10}$) Particles 10 μm in diameter, (e.g., dust, pollen, and mold)

Fine Particulate Matter (PM$_{2.5}$) Particles 2.5 μm in diameter or smaller, (e.g., sulfates and carbon)

Magnified Human Hair 50 to 70 μm in diameter

Particles in the Air

PM$_{10}$ Coarse particles enhaled are filtered by the nose and mouth

PM$_{2.5}$ Fine particles travel to the lungs, aggravating asthma, causing difficulty breathing and decreased lung function.

Image adapted from EPA and SCMP

Fine, airborne particulate matter (PM) that is smaller than 2.5 microns (about one thirtieth the width of a human hair) is considered dangerous because it is small enough to enter the passages of the human lungs. Most PM$_{2.5}$ aerosol particles come from the burning of fossil fuels and biomass (wood fires and agricultural burning).

are dust storms that originate over large deserts such as the Gobi and Taklimakan.

- **Pollution Outbreaks.** Residents of Beijing and many other cities in China are used to having their lives impacted by poor air quality. Like many times before, a thick layer of haze blanketed the North China Plain on October 9, 2014. That same day, measurements from ground-based sensors at the U.S. Consulate in Beijing reported $PM_{2.5}$ measurements of 334 micrograms per cubic meter of air. The World Health Organization considers $PM_{2.5}$ to be safe when it is below 25 micrograms per cubic meter of air.

- **Forest Fires.** Smoke from the California Rim Fire in September 2013 choked Yosemite National Park during the busy Labor Day weekend. The fire started on August 17, 2013, and was the third largest wildfire in California's history. The smoke caused poor air quality from Yosemite National Park to the San Joaquin Valley and people were advised to avoid strenuous outdoor activity or to remain indoors since smoke can irritate the eyes and respiratory system and aggravate chronic heart and lung disease.

In addition to anticipated improvements to operational forecasting programs, CATS will also demonstrate new technologies for observing and measuring clouds and aerosols. The HSRL technique (described in the *Instrument Overview* section) is expected to provide more precise measurements from space than ever before. Scientists will also get a first-ever, space-based look at cloud and aerosol retrievals in the ultraviolet—355 nanometers.

In summary, the CATS mission seeks to build on the CALIPSO data record, provide observational lidar data to improve research and operational modeling programs, and demonstrate new lidar retrievals of clouds and aerosols from space. These technologies and the science gained from the CATS mission will be used to design future missions that will study clouds and aerosols and their affects on Earth's climate and air quality for years to come.

Data from CATS will be freely available at *cats.gsfc.nasa.gov*.

Volcanic Eruptions
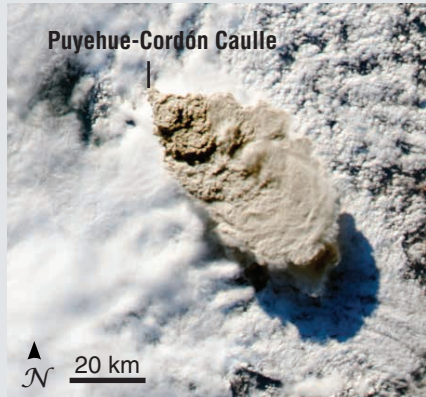
This image shows the volcanic plume coming from Puyehue-Cordón Caulle in Chile on June 4, 2011 shortly after the eruption began. The brown ash plume reaches high above the clouds and casts a shadow towards the southeast. Along the leading edge of the plume, it appears that heavier material has fallen out of the ash cloud, while finer particles remain suspended in the atmosphere. Credit: NASA's Earth Observatory

Dust Storms
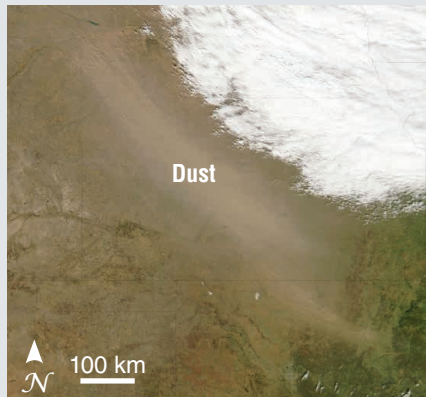
NASA's Aqua satellite captured this natural-color image of dust storms in the prairies of the United States on October 18, 2012. Gale-force northwest winds blew along the western edge of a storm system that stretched from the Canadian border to Kansas. High winds carried dust and dirt as much as 900 to 1200 meters (3000 to 4000 feet) into the atmosphere, according to local weather reports. Credit: NASA's Earth Observatory

Pollution Outbreaks
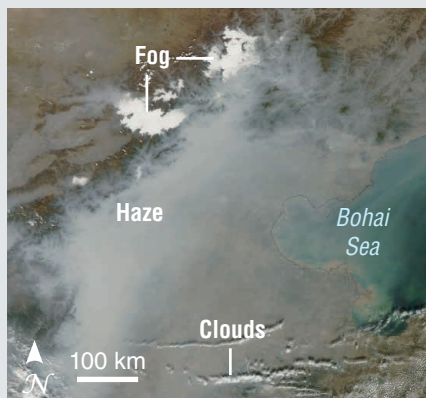
NASA's Terra satellite acquired this natural-color image of northeastern China on October 9, 2014. The image shows extensive haze, low clouds, and fog over the region. The haze obscured many features usually visible in satellite imagery of the area, including China's largest city, Beijing. Credit: NASA's Earth Observatory

Forest Fires
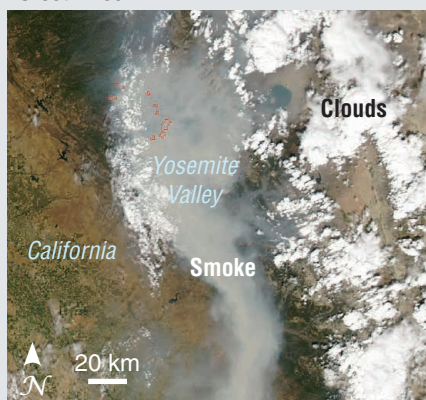
Officially contained on Thursday, October 24, 2013, the California Rim Fire burned approximately 257,314 acres (~402 square miles)—the largest wildfire on record in the Sierra Nevada. NASA's Aqua satellite acquired this view of the fire on August 31, 2013. The smoke is brown and smooth in texture compared to the bright white clouds. Credit: NASA's Earth Observatory

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