feature articles

CATS: A New Earth Science Capability

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Introduction

Aerosols are tiny atmospheric particles that are practically invisible to the naked eye, yet have a huge impact on Earth's climate. They exert a *direct effect,* as the particles scatter and absorb solar and long-wave radiation, thereby influencing Earth's radiation balance. Aerosols also exert an *indirect effect* on climate; they interact with clouds, altering the physical and chemical properties of both, and, in turn, changing their influence on the radiation balance. Indirect effects have also been shown to alter cloud formation and rainfall events. The relationship between aerosols and clouds and the resulting influence on Earth's climate is therefore complex, with impacts on Earth's energy balance, hydrologic cycle, and atmospheric circulation.

Aerosols and clouds are not homogeneously distributed in the atmosphere over the Earth's surface. They also have relatively short lifetimes, varied transport processes, and, as discussed above, complex interactions with each other. These factors have made aerosols and clouds more difficult to simulate in climate models than most other constituents. In recent years routine measurements of aerosol and cloud distributions and properties obtained from instruments from the ground, the air, and space have helped to reduce some of the uncertainties. However, despite improvements in our knowledge of their impacts and an overall downward trend in the uncertainties, aerosol and cloud direct and indirect effects remain two of the areas of uncertainty for climate models. These large uncertainties make it difficult to quantify the extent to which human activities (pollution, burning, etc.) contribute to climate change.

Figure 1. The Japanese Experiment Module–Exposed Facility (JEM-EF) on the International Space Station. Payloads, such as CATS, attach using "plug-in" ports located around the JEM-EF. **Image credit**: NASA

A Testbed for New Earth Science Technologies

The Cloud-Aerosol Transport System (CATS) is a lidar remote-sensing instrument designed to provide measurements of atmospheric particles; it is intended to help fill the anticipated "data gap" in acquiring such data—see *Mind the Gap* on page 6. The CATS instrument is funded by the International Space Station (ISS) National Laboratory program as a demonstration of ISS-based operational science capability. By allowing such payloads to be attached, the ISS provides a unique capability for demonstrating new technologies in space at a relatively low cost.

The CATS mission was therefore designed to take advantage of the ISS platform to provide new capabilities from space including operational aerosol forecasting and technology demonstration and risk reduction for future Earth science missions. The CATS payload will continue the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data record, provide observational lidar data to improve operational modeling programs, and demonstrate the direct lidar retrieval of aerosol extinction from space.

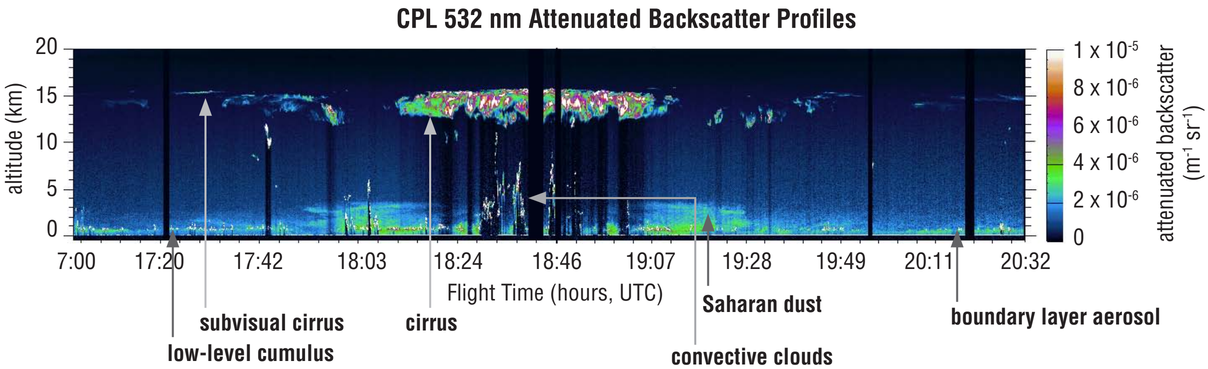

Figure 2. Example of lidar profile data from the airborne Cloud Physics Lidar (CPL) instrument. The CATS instrument is a scaled-up version of the CPL, intended to produce similar-quality data. (See Sidebar on page 7 for more details on CPL.) **Image credit**: NASA

Development of CATS also serves as a *pathfinder* for NASA, as it is the first NASA-developed payload for the Japanese Experiment Module-Exposed Facility (JEM-EF) on the ISS—see **Figure 1**. Furthermore, CATS is only the second U.S. payload ever to go to the JEM-EF. Designed to operate for at least six months and possibly for as long as five years, the CATS lidar will provide range-resolved profile measurements of atmospheric aerosol and cloud distributions and properties.

CATS Science

The impact of clouds and aerosols (e.g., pollution, dust, smoke) on global energy balance and climate feedback mechanisms is not yet fully understood. Obtaining a better understanding of cloud and aerosol coverage and properties is critical for understanding the Earth's systems and their climate feedback processes.

The CATS instrument uses a laser to obtain range-resolved information about the climate impacts of clouds and aerosols on a global scale. The ISS orbit is particularly suited to this measurement because the 51-degree inclination of the orbit puts ISS tracks over and along primary aerosol transport paths. The ISS orbit also permits study of *diurnal* (day-to-night) changes in aerosol and cloud effects—something unique compared with other Earth science satellite orbits. The CATS instrument uses a high-repetition-rate laser operating at three wavelengths (1064, 532, and 355 nm) to derive properties of cloud/aerosol layers, including layer height, layer thickness, backscatter, optical depth, extinction, and depolarization-based discrimination of particle type.

An important aspect of CATS science will be to provide real-time observations of aerosol vertical distribution to serve as inputs to global aerosol transport models. Current models tend to agree on total aerosol loading, but tend to disagree on the vertical distribution of the loading and the type of aerosols present. To begin to determine how much of the total aerosol load can be attributed to natural sources (e.g., dust) and how much can be attributed to human-induced sources (e.g., pollution), it is important to know how the aerosols are distributed through the atmosphere. In particular, the vertical distribution of aerosols is highly important, because their effects differ depending on whether the aerosol layer is below, mixed with, or above cloud layers. As mentioned earlier, aerosol–cloud interactions currently comprise the largest source of uncertainty in studies of climate forcing, so it is critical to ascertain the correct vertical distribution of aerosols.

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Lidar remote sensing is particularly well-suited to profiling of aerosols and optically thin, but radiatively important, clouds—see **Figure 2**. In fact, the primary capability for CATS was adapted from the Cloud Physics Lidar (CPL) design—see *CATS Heritage: The Long-standing CPL* on page 7. The vertical profile information, particularly when determined at multiple wavelengths, and combined with depolarization information, provides height location of cloud and aerosol layers, information on particle size, and information on particle shape. The CATS instrument will provide measurements of cloud and aerosol profiles similar to CALIPSO—filling in the data gap described in the sidebar—so that this information can be used to improve climate models and our understanding of the Earth system and climate feedback processes.

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Risk Reduction and Objectives

To maximize operational lifetime, the CATS payload is designed to use two laser units[1], but with different capabilities and architecture.

One laser is based on a rugged Nd:YVO_4[2] crystal, with 1064/532-nm outputs. This laser is used for the backscatter measurements and is based on a heritage design to ensure long life. The second laser is also Nd:YVO_4-based, but incorporates two advanced features—*injection seeding* and *frequency tripling*—as demonstrations that might be incorporated in future space-based missions. Injection seeding provides narrow line-width as required for high-spectral-resolution measurements; frequency tripling permits generation of 355-nm output in addition to the 1064- and 532-nm outputs, which will enable better differentiation between aerosol types.

The CATS instrument also provides the first in-space demonstration of high-repetition-rate lasers for Earth remote sensing. Operating at 5000 pulses per second, the CATS lasers emit a pulse every 1.5 m along-track. The Fabry-Perot interferometer in the high-spectral-resolution channel also is a prototype for high-fidelity, tunable-spectral filtering for future Earth science applications.

The CATS Payload, Inside and Out

All lidar remote-sensing instruments consist of a laser transmitter to generate probe photons, a receiver subsystem with a telescope to collect photons that backscatter from the atmosphere, and a data system to provide timing of the return photon events. Beyond that generalization, there are choices to be made in type of laser

[1] Fibertek Inc—an advanced laser technology company—provided both of the lasers.
[2] The neodymium doped yttrium orthovanadate (Nd:YVO_4) crystal is considered the most efficient laser host crystal currently existing for diode laser-pumped solid-state lasers. See *www.u-oplaz.com/crystals/crystals20-1.htm* to learn more.

Mind the Gap

In 2006 NASA launched the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) spacecraft. A joint mission between NASA and the French Centre National d'Études Spatiales (CNES), CALIPSO is an Earth System Science Pathfinder mission designed to provide unique atmospheric profile measurements to improve our understanding of the roles played by aerosols and clouds in Earth's climate system. The CALIPSO lidar provides vertical distributions and properties of aerosols and optically thin clouds along the nadir flight track; the top heights of thicker clouds are also determined, but not profiled. CALIPSO provides two-wavelength (532- and 1064-nm) elastic-backscatter lidar profiling with linear polarization at 532 nm. 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 impact of aerosols and clouds. Such measurements are required over time scales that are much longer than a typical mission lifetime (~5–10 years). This is especially true for active sensors such as lidar, which have inherently shorter lifetimes than passive sensors. At the moment, there is no NASA mission in development to replace CALIPSO. The next mission contemplated—the Aerosols, Clouds, and Ecosystems (ACE) mission—is still in the pre-formulation and study phase, and is planned for a post-2020 launch date. As a result, the aerosol and cloud research community is facing a significant "data gap" in terms of continuing the CALIPSO data record. CATS will help mitigate this gap.

CATS Heritage: The Long-standing Cloud Physics Lidar (CPL)

The CPL was developed in 1999 at the specific request of the Earth Observing System (EOS) program. At the time, EOS was preparing for the Southern African Regional Science Initiative (SAFARI) field campaign, and wanted a new-generation lidar remote-sensing instrument for use on the high-altitude ER-2 aircraft. The CPL concept uses a high-repetition-rate laser and photon-counting detectors (see text for details on these terms), and set the stage for developing and flying a series of low-cost, fast-turnaround airborne lidar instruments over the next decade. "The CPL is an outstanding addition to airborne missions that focus on aerosols and clouds in the troposphere and lower stratosphere…Operating a high-powered laser with a fast detection system autonomously in the upper atmosphere is a significant engineering challenge," said **David Fahey** [National Oceanic and Atmospheric Administration].

August 2012 will mark the twelfth anniversary of the SAFARI campaign. Many instruments don't live more than a decade, owing to several issues—e.g., harsh treatment in the aircraft environment, or loss of interest by the scientific community—but the CPL continues to provide valuable data to the research community. In fact, the CPL has proven so reliable and so important that another CPL was built for use on the unmanned Global Hawk aircraft. "CPL has clearly stood the test of time, and a new data user like myself reaps the benefits of the hard work over the years by the CPL team," said **Tom Neumann** [NASA's Goddard Space Flight Center (GSFC)].

Hal Maring [NASA Headquarters] noted that CPL data continue to be heavily used. "Measurements of the vertical distribution of aerosols and clouds 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," said Maring. The longevity and demonstrated performance of the CPL instruments provided the basis for the CATS design. Leveraging the CPL heritage will provide maximum on-orbit lifetime to provide continuous measurements that benefit the Earth science community.

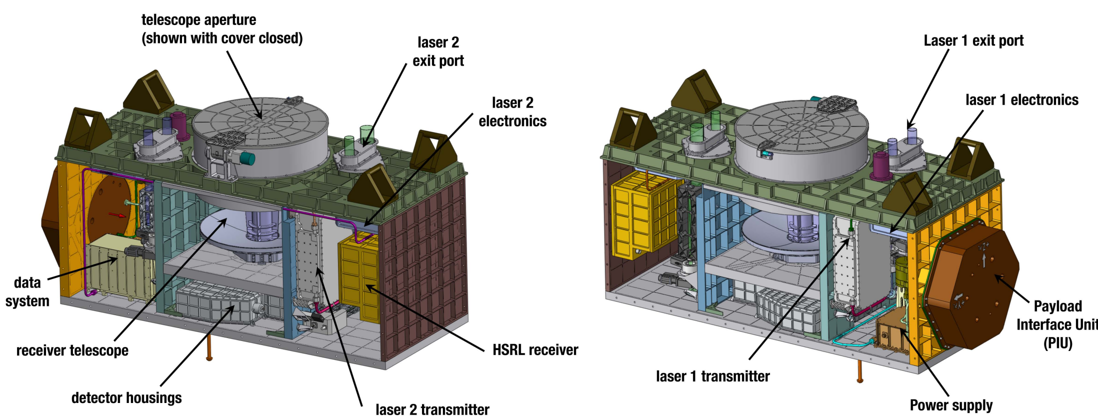

Figure 3. The CATS payload with primary components identified. The payload fits within a standard JEM-EF attached payload volume. **Image credit:** Design Interface, Inc.

(e.g., wavelength, repetition rate, etc.) and complexity of receiver, which is dependent on the variables to be measured. There is also a fundamental choice for detection type, either by *analog detectors* or *photon-counting detectors*. Photon-counting detection generally drives requirements for receiver field-of-view to limit the solar background signal and laser pulse energy to avoid saturating the detector(s). In CATS, photon-counting and high-repetition-rate lasers are used; a narrow 100-microradian field-of-view minimizes the impacts of solar background. In airborne instrument use, the photon-counting detectors have proven easy to use and allow smooth calibration and thus quick turn-around of data products.

The CATS payload is based on existing instrumentation operated on the high-altitude NASA ER-2 aircraft. The payload is housed in a 1.5-m x 1-m x 0.8-m envelope that attaches to the JEM-EF. The allowed volume limits the maximum size for the collecting telescope to a 60-cm diameter. **Figure 3** shows the layout of the CATS payload, with the primary instrument components identified.

The ISS and, in particular, the JEM-EF is an exciting new platform for spaceborne Earth observations. The ability to leverage existing aircraft instrument designs, coupled with the lower cost possible for external attached payloads, permits rapid and cost-effective development of spaceborne sensors.

There are three different operational modes for CATS:

- *Backscatter detection only, at 1064 and 532 nm, with depolarization measurement at both wavelengths*. The laser output is split into two transmit beams, one aimed 0.5° to the left and one 0.5° to the right, effectively making two tracks separated by 7 km (~4.3 mi) at Earth's surface. This operational mode will be used to ensure that minimum science requirements can be met for the maximum mission duration.

- *Demonstration of high-spectral-resolution aerosol measurements*. This mode uses the injection-seeded laser operating at 1064 and 532 nm to demonstrate a high-spectral-resolution measurement using the 532-nm wavelength.

- *Demonstration of 355-nm profiling*. This mode uses the injection-seeded laser operating at 1064, 532, and 355 nm to demonstrate 355-nm laser performance. Similar to the backscatter detection mode, there are depolarization measurements at each wavelength.

The CATS payload is being built on a 24-month schedule, with payload delivery targeted for April 2013. The current launch target is to be the Japanese H-II Transfer Vehicle, with launch in the early-2014 timeframe.

Conclusion

The CATS payload, currently under development for deployment to the ISS, will help bridge the looming data gap for NASA's program in active remote sensing of the Earth's atmosphere. The ISS—in particular the JEM-EF—is an exciting new platform for spaceborne Earth observations. The ability to leverage existing aircraft instrument designs, coupled with the lower cost possible for external attached payloads, permits rapid and cost-effective development of spaceborne sensors. Data from the CATS instrument will be used to improve aerosol transport models while simultaneously providing risk reduction for future Earth science missions. The downlink capability of the ISS will permit near-real-time assimilation of the CATS lidar data into numerical models. The ISS orbit over major aerosol transport routes and the ability to observe diurnal changes will provide new observations for Earth science applications.

Acknowledgements

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