The Cloud-Aerosol Transport System (CATS): A Technology Demonstration on the International Space Station

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ABSTRACT

The Cloud-Aerosol Transport System (CATS) is a multi-wavelength lidar instrument developed to enhance Earth Science remote sensing capabilities from the International Space Station. The CATS project was chartered to be an experiment in all senses: science, technology, and management. As a low-cost project following a strict build-to-cost/build-to-schedule philosophy, CATS is following a new management approach while also serving as a technology demonstration for future NASA missions. This presentation will highlight the CATS instrument and science objectives with emphasis on how the ISS platform enables the specific objectives of the payload. The development process used for CATS and a look at data being produced by the instrument will also be presented.

Keywords: Cloud-Aerosol Transport System, CATS, International Space Station, ISS, JEM-EF

1. CATS PROJECT OVERVIEW

Atmospheric aerosols (suspended particles of dust, smoke, and pollution) and clouds have significant impacts on the Earth's energy balance and on air quality and human health. The impact of clouds and aerosols, and their complex interactions, 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 of the Earth system and climate feedback processes.

The Cloud-Aerosol Transport System (CATS) is a new lidar remote sensing instrument that is now operational from the International Space Station (ISS) to provide vertically resolved measurements of clouds and aerosols. The ISS orbit is particularly suited to this measurement, because the 51-degree inclination of the orbit places the ISS track over and along primary aerosol transport paths in the atmosphere. Because the ISS is in a precessing orbit using the ISS as an observation platform also permits study of diurnal changes in aerosol and cloud effects.

The CATS lidar is designed to provide range-resolved profile measurements of atmospheric aerosol and cloud distributions and properties. The CATS instrument uses a high repetition rate laser operating at up to 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.

CATS was launched to the ISS on January 10, 2015 on the SpaceX-5 launch, and was installed to the Japanese Experiment Module – Exposed Facility (JEM-EF) on January 22. First science data was obtained on February 10, 2015, and data collection has continued since. The CATS payload is designed to operate on-orbit for at least six months, and up to three years.

2. CATS AS A TECHNOLOGY DEMONSTRATOR

The CATS instrument has extensive heritage in airborne instruments built and operated on the high-altitude NASA ER-2 aircraft. Primary heritage comes from the long-standing Cloud Physics Lidar (CPL)[1] that has operated since 2000 demonstrating the capability of high repetition-rate lasers when coupled with photon-counting detection. The Airborne Cloud-Aerosol Transport System (ACATS)[2] was developed to prototype a new approach to high spectral resolution lidar, or HSRL. Because ACATS was proving successful, the ACATS HSRL receiver concept was incorporated into the CATS instrument as a demonstration.

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There are many technology "firsts" associated with the CATS payload. The CATS instrument provides a 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. Coupled with photon-counting detectors, the attainable detection sensitivity is being demonstrated on-orbit. Moreover, the temporal-spatial resolution being demonstrated is providing unprecedented detail of atmospheric structure, on par with data quality from aircraft-based instruments. The Fabry-Perot interferometer in the high spectral resolution channel will prototype high-fidelity tunable spectral filtering for future Earth Science applications.

Many of the hardware components in the CATS instrument have heritage in either NASA's Small Business Innovative Research (SBIR) program and/or NASA's Earth Science Technology Office (ESTO). The nature of the CATS project also allows use of commercial-off-the-shelf (COTS) hardware, notably the photon-counting detectors, optics, and mechanisms.

A primary aspect of the CATS project was to demonstrate the ISS as a suitable platform for NASA-developed external payloads that are intended for near-continuous operation. While the ISS platform promised a unique capability for demonstrating new technologies in space and at relatively low cost, it was up to CATS to provide proof as an end-to-end test. As one of the first NASA external payloads for ISS (and the first NASA-developed payload for the JEM-EF), and the first NASA payload to use the JEM-EF cooling loop, there was a steep learning curve. In the end, CATS has paved the way for future payloads by defining and refining ISS processes, by sorting out interface requirements, and by testing the limits of many of the ISS safety processes.

3. THE CATS INSTRUMENT

As a payload for the JEM-EF on ISS, CATS is not overly constrained by mass or cooling concerns. The standard JEM-EF payload volume is 1.5 x 1 x 0.8 m, and is allowed up to 500 kg. Use of the JEM-EF coolant loop eliminates need for large radiators and complete reliance on conductive cooling. Having only minimal constraints on mass, power, etc., is obviously a key to keeping costs low for ISS payloads, compared to free-flyer instruments where every ounce and every Watt can be a driving consideration. In fact, the cost and complexity of an ISS payload is significantly reduced over a free-flyer satellite owing to the fact that the ISS provides the equivalent of a "spacecraft bus."

A schematic of the CATS payload is shown in Figure 1. Two lasers (partly for redundancy, partly to test different technologies), a 60-cm beryllium telescope, and detector boxes comprise the majority of the hardware.

The primary instrument parameters are given in Table 1, below. As with CPL, the field of view has to be small to avoid excessive background sunlight that would overwhelm the detectors. This necessitates good optical design and, to ensure success, an active boresight alignment mechanism is provided on each of the receiver fields of view. Active alignment is provided by pairs of counter-rotating Risley prisms mounted in COTS mechanisms.

From the outside, the payload is simply a blanketed box, as shown in Figure 2. The ISS interfaces for robotic operations and power/data are identified.

4. INITIAL DATA EXAMPLES

CATS data (at 60 m vertical resolution and ~350 m horizontal resolution), is received from the ISS continuously and in near real-time (with the exception of loss-of-signal (LOS) periods that can range from 5 to 50 minutes). Data are collected, corrected for communication artifacts (i.e. duplicate or missing data) and sorted to produce granules that span half an ISS orbit (approximately 45 minutes). The raw data is then geo-located, normalized to laser energy, and annotated with ancillary information to create the normalized relative backscatter (NRB).

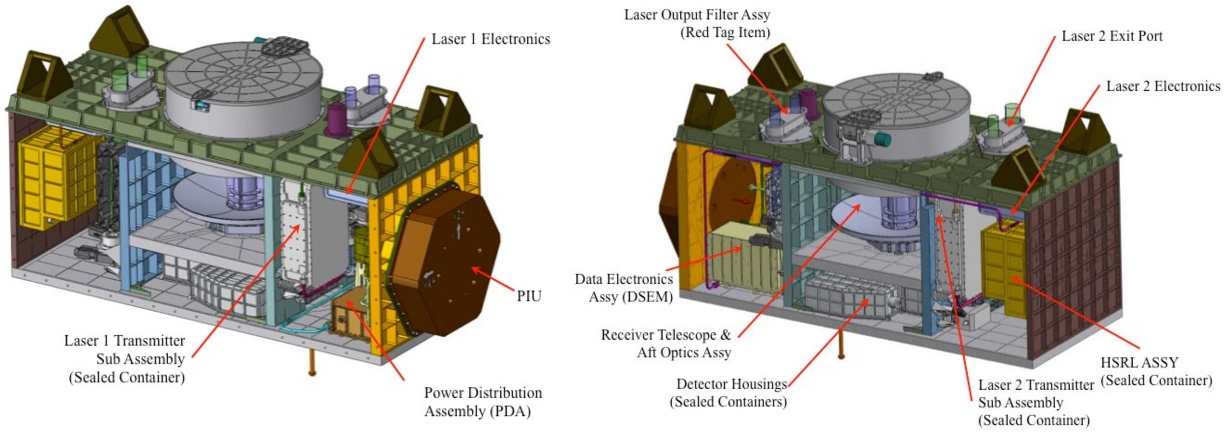

Figure 1: Schematic of CATS payload, showing primary internal components. Payload volume is 1.5 x 1 x 0.8 m.

Table 1: CATS instrument parameters

Laser 1 Type	Nd: YVO_4
Laser 1 Wavelengths	532, 1064 nm
Laser 1 Rep. Rate	5000 Hz
Laser 1 Pulse Energy	~1 mJ/wavelength
Laser 2 Type	Nd: YVO_4, seeded
Laser 2 Wavelengths	355, 532, 1064 nm
Laser 2 Rep. Rate	4000 Hz
Laser 2 Pulse Energy	~2 mJ/wavelength
Telescope Diameter	60 cm
View Angle	+/-0.5 degrees
Telescope FOV	110 microradians

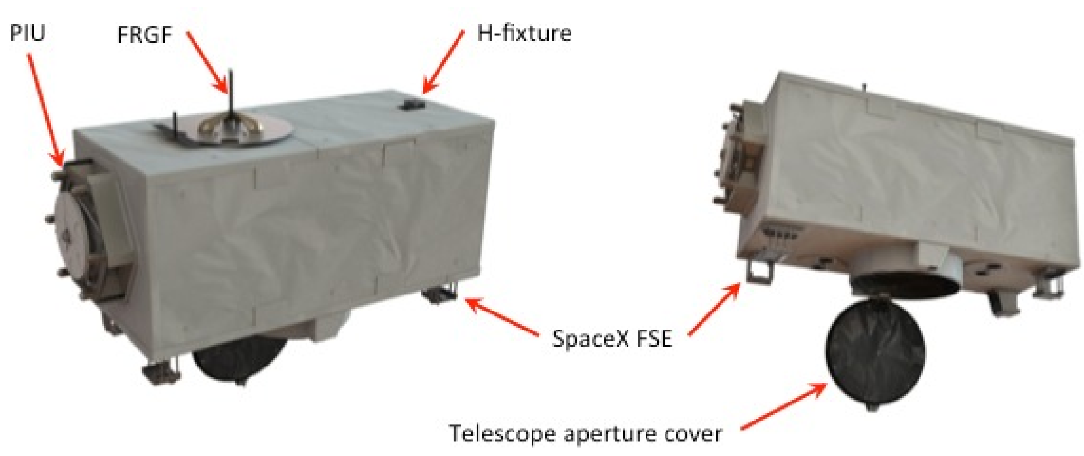

Figure 2: CATS payload exterior view, showing ISS interface hardware.

The near real time and continuous data downlinking provided by the ISS allows CATS data to be processed as quickly as 3-6 hours after collection. This allows CATS data to be incorporated into the data assimilation process of aerosol forecast models. Processing of the CATS data products in Mode 1 began in February 2015 and include:

- **Level 1B**: Data that have been calibrated, annotated with ancillary meteorological data, and processed to sensor units. The CATS Level 1B data (attenuated total backscatter and depolarization ratio) is archived as Level 1 data at the raw CATS resolutions.
- **Level 2**: Geophysical parameters derived from Level 1 data, such as the vertical feature mask, profiles of cloud and aerosol properties (i.e. extinction, particle backscatter), and layer-integrated parameters (i.e. lidar ratio, optical depth).

These products and corresponding browse images are available at the CATS website (cats.gsfc.nasa.gov).

The CATS Level 1B and 2 data processing algorithms rely heavily on heritage from existing airborne and space-based lidar systems, such as CPL, ACATS, and the Cloud-Aerosol Lidar Infrared Pathfinder Spaceborne Observations (CALIPSO) satellite.[3] Given the technology demonstration aspect of Mode 2, this data will be processed differently than the other two modes. The HSRL data processing algorithms will be very similar to those used for the ACATS instrument.[2]

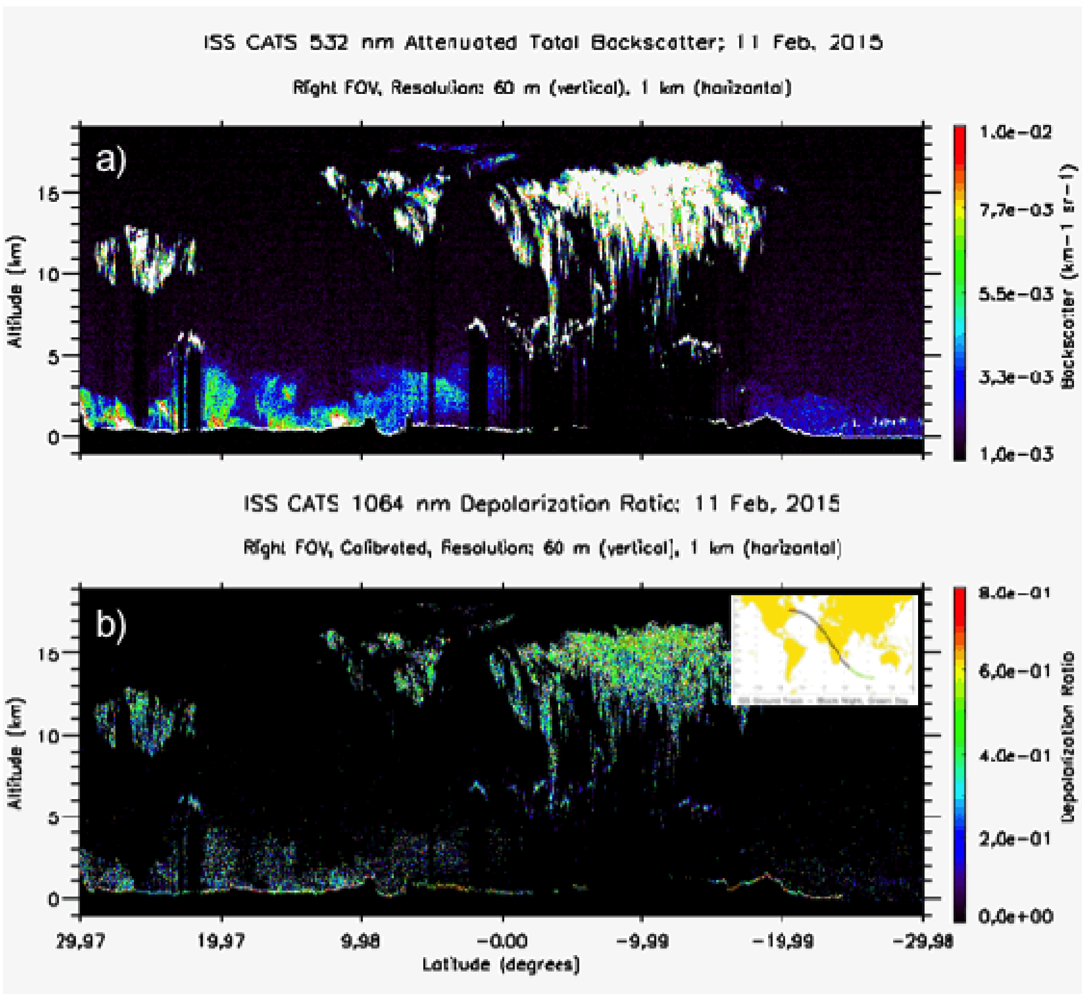

Figure 3: CATS 532 nm attenuated total backscatter (top panel) and 1064 nm depolarization ratio (bottom panel) from 11 February 2015 as the ISS passed over Africa. This is the first science image from CATS.

The 532 nm CATS data is calibrated by normalizing the NRB signal to the 532 nm molecular backscatter signal in a fixed calibration region.[4,5] The CATS calibration region is 23-27 km, starting 1 km below the top of the CATS data frame (28 km). The aerosol loading in this region is computed using CALIPSO data and applied to the calibration. The CATS NRB signal is averaged to 3 minutes at night and 20 minutes during daytime operation to reduce uncertainty in the calculation. During nighttime data collection, the 1064 nm calibration constant can be computed using an identical approach as the 532 nm calculation. However during daytime operation, the 1064 nm signal is calibrated using the 532 nm signal and backscatter from ice clouds, similar to CALIPSO at 1064 nm.[6] The depolarization gain ratio, which describes the relative gain between polarization channels, is computed for both 532 and 1064 using the same algorithms as CALIPSO.[7]

The CATS laser was first operated on-orbit on 5 February 2015. After initial telescope alignment procedures, semi-continuous CATS operation began 10 February 2015, with occasional interruptions due to spacecraft dockings at the ISS. One of the first orbits of CATS data collection occurred as the ISS flew over Africa on 11 February 2015 during local nighttime hours (00:59 to 01:19 UTC). Figure 2 shows the CATS 532 nm attenuated total backscatter (km^{-1} sr^{-1}) with Saharan dust as high as 5 km (30N to 5N), thin cirrus clouds that extend above 17 km (12N to 1S), and smoke from biomass burning (20S to 30S) in South Africa. The 1064 nm depolarization ratio values of ~0.30 for dust and ~0.50 for cirrus are consistent with CALIPSO and CPL historical data.

During the first week of CATS operations, the CPL instrument was flying on the NASA ER-2 out of Palmdale, CA. Several CATS validation flights were coordinated such that the ER-2 was flying under the ISS ground track. Validation flights were conducted during local twilight hours (10 February), daytime hours (17 and 20 February) and night (21 February). Cirrus clouds were present during the 10 and 21 February flights, while low-level stratocumulus clouds were observed during the two daytime flights. Figure 4 shows a comparison of the CATS and CPL 1064 nm backscatter profiles from the 21 February flight. Agreement of layer boundaries and surface return indicates the CATS ranging is working properly.

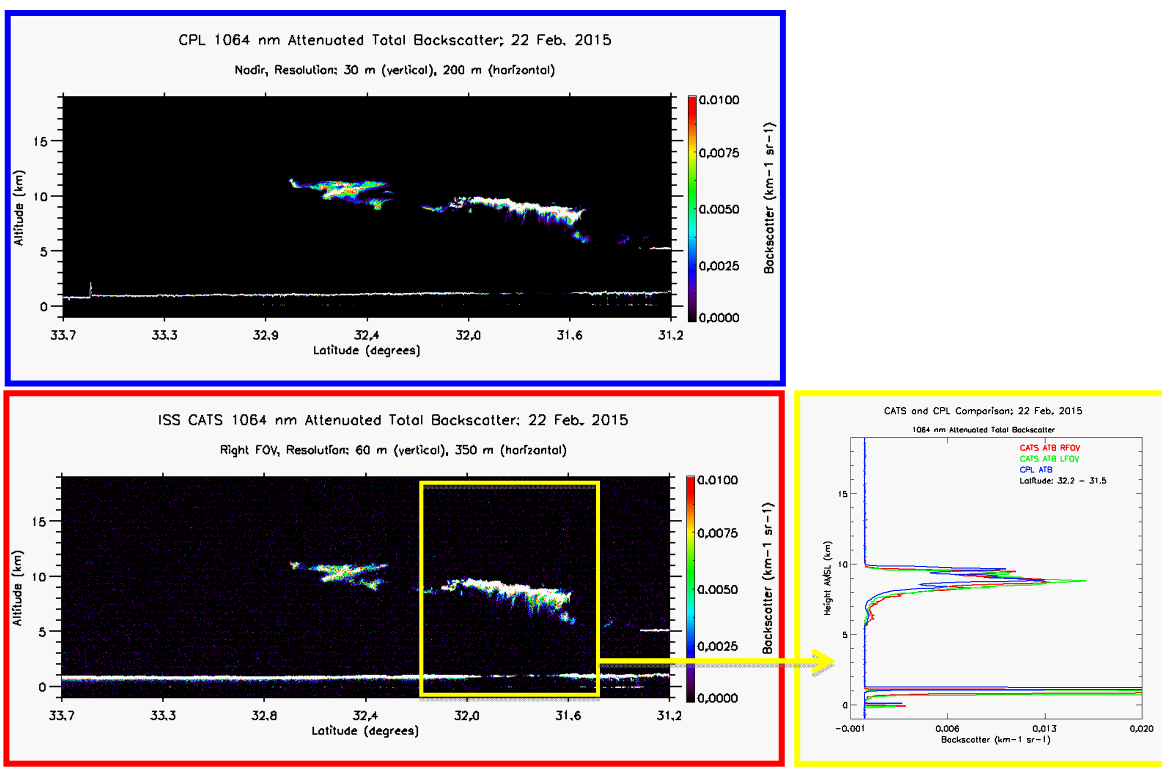

Figure 4: Data from 21 February 2015 over the Pacific Ocean at night. Top image is 1064 nm backscatter profiles from the airborne Cloud Physics Lidar (CPL) on the ER-2. Bottom image is coincident 1064 nm backscatter from CATS. The cloud boundaries and ocean surface heights agree well, as shown in the average profile on the right.

5. CONCLUSION

Launched on January 10, 2015, and first operated on February 5, the CATS instrument is now on-orbit and operating from the ISS. Data is collected near-continuously, within limits of ISS operational constraints.

As a demonstration of a build-to-cost/build-to-schedule instrument development CATS succeeded and is delivering useful science data for low cost. As a first demonstration of spaceborne high repetition rate, photon-counting atmospheric lidar CATS has succeeded. The data and data quality from CATS is meeting expectations compared to modeled performance and as validated using aircraft instruments. As a pathfinder for NASA-developed ISS payloads CATS also succeeded, as demonstrated by selections of new ISS payloads via the Earth Venture solicitations. These new payloads are all benefitting from the process improvements made possible by CATS.

Operation to-date clearly demonstrates that the CATS experiment in managing a small project has succeeded. Similarly, many of the technology aspects of the payload are proving successful. Data quality is good and is demonstrating the high spatial-temporal resolution possible with use of high repetition-rate lasers.

More information and access to CATS data can be found at the CATS web page: http://cats.gsfc.nasa.gov

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