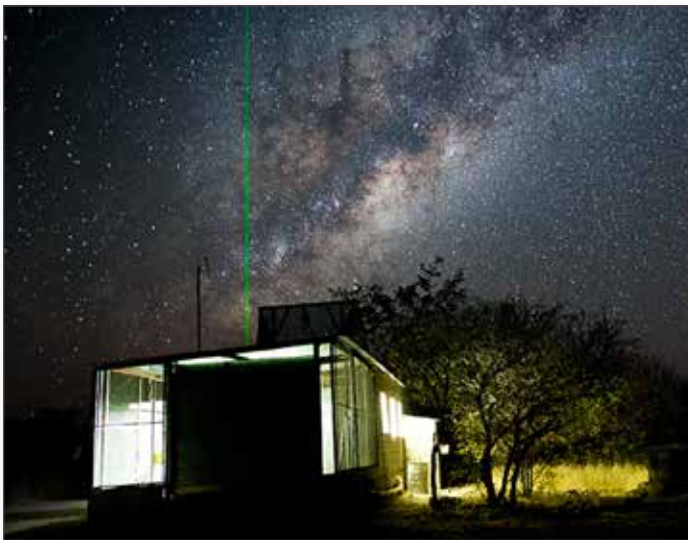
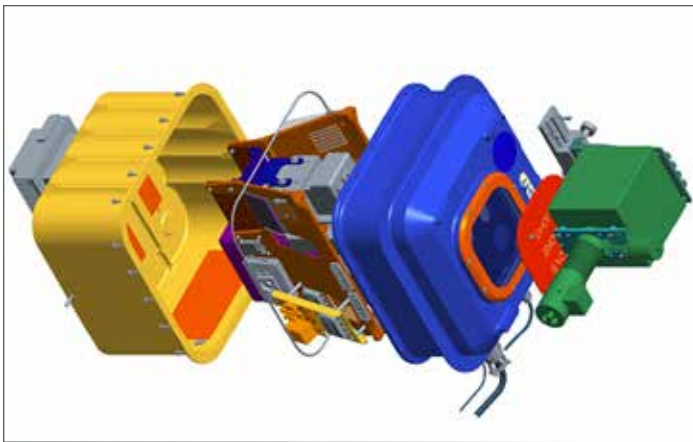


# Atmospheric Instrument Systems and Technology in the Goddard Earth Sciences Division

*Goddard Earth Sciences Division - Atmospheres*



## Cover Photo Captions

TOP LEFT,

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GCAS was developed in the IRAD program and is designed to provide high spatial resolution (< 1 km) remote-sensing observations of tropospheric- and boundary-layer pollutants and aerosols in addition to providing coastal and open-ocean color measurement capabilities. It provides broad wavelength coverage, hyperspectral radiance, it is compact and easily deployable on a variety of aircraft. It has been deployed during Discover-AQ (KingAir), NAAMES (C-130), and GOES-R validation (ER-2)

TOP RIGHT

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NASA's Goddard Space Flight Center, Wallops Flight Facility in Wallops Island, Virginia, deployed an integrated S-band (2700–2900 MHz), dual-polarized antenna system. The antenna system consists of a parabolic reflector, dual-polarized feed horn, pedestal, drive motors, and servo-amplifiers. It is capable of emitting and receiving both horizontal and vertical linearly polarized RF energy. The antenna system is used as an integrated, transportable meteorological research radar, with all of the components constructed for shipment in standard ISO sea containers with outside dimensions of 2.44 m x 2.44 m x 6.1 m (8 ft x 8 ft x 20 ft).

BOTTOM LEFT

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Located in a remote area of Namibia to the southwest of Etosha National Park, the NASA Micro-Pulse Lidar Network's (MPLNET) newest site is 100-percent solar-powered and is expected provide a long-term comprehensive dataset for the region. MPLNET is a federated network of micro-pulse lidar systems designed to measure aerosol and cloud vertical structure, as well as boundary layer heights. The data are collected continuously, day and night, over long time periods from sites around the world. Most MPLNET sites are co-located with sites in the NASA Aerosol Robotic Network.

BOTTOM RIGHT

---

NASA successfully deployed Goddard Space Flight Center's IceCube from the International Space Station at 7:55 a.m. EDT, May 16, 2017, as a spaceflight technology mission to present a new 883-GHz cloud ice radiometer. The system will demonstrate and validate the submillimeter-wave receiver developed to advance cloud ice remote-sensing and help scientists better understand the role of ice clouds in the Earth's climate system.

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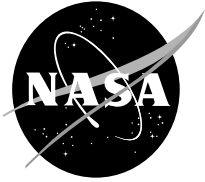
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**Level of Review:** This material has been technically reviewed by technical management.



# **Atmospheric Instrument Systems and Technology in the Goddard Earth Sciences Division**

*Goddard Earth Sciences Division - Atmospheres*

National Aeronautics and  
Space Administration

**Goddard Space Flight Center**  
**Greenbelt, Maryland 20771**

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Since its founding, NASA has been dedicated to the advancement of aeronautics and space science.

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The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

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# Executive Summary

Studies of the Earth's atmosphere require a comprehensive set of observations that rely on instruments flown on spacecraft, aircraft, and balloons as well as those deployed on the surface. Within NASA's Goddard Space Flight Center (GSFC) Earth Sciences Division-Atmospheres, laboratories and offices maintain an active program of instrument system development and observational studies that provide: 1) information leading to a basic understanding of atmospheric processes and their relationships with the Earth's climate system, 2) prototypes for future flight instruments, 3) instruments to serve as calibration references for satellite missions, and 4) instruments for future field validation campaigns that support ongoing space missions. Our scientists participate in all aspects of instrument activity, including component and system design, calibration techniques, retrieval algorithm development, and data processing systems. The Atmospheres Program has well-equipped labs and test equipment to support the development and testing of instrument systems, such as a radiometric calibration and development facility to support the calibration of ultraviolet and visible (UV/VIS), space-borne solar backscatter instruments.

This document summarizes the features and characteristics of 46 instrument systems that currently exist or are under development. The report is organized according to active, passive, or *in situ* remote sensing across the electromagnetic spectrum. Most of the systems are considered operational in that they have demonstrated performance in the field and are capable of being deployed on relatively short notice. Other systems are under study or of low technical readiness level (TRL). The systems described herein are designed mainly for surface or airborne platforms. However, two Cubesat systems also have been developed through collaborative efforts. The Solar Disk Sextant (SDS) is the single balloon-borne instrument.

The lidar systems described herein are designed to retrieve clouds, aerosols, methane, water vapor pressure, temperature, and winds. Most of the lasers operate at some wavelength combination of 355, 532, and 1064 nm. The various systems provide high sensitivity measurements based on returns from backscatter or Raman scattering including intensity and polarization. Measurements of the frequency (Doppler) shift of light scattered from various atmospheric constituents can also be made.

Microwave sensors consist of both active (radar) and passive (radiometer) systems. These systems are important for studying processes involving water in various forms. The dielectric properties of water affect microwave brightness temperatures, which are used to retrieve atmospheric parameters such as rainfall rate and other key elements of the hydrological cycle. Atmosphere radar systems operate in the range from 9.6 GHz to 94 GHz and have measurement accuracies from -5 to 1 dBZ; radiometers operate in the 50 GHz to 874 GHz range with accuracies from 0.5 to 1 degree K; conical and cross-track scan modes are used.

Our passive optical sensors, consisting of radiometers and spectrometers, collectively operate from the UV into the infrared. These systems measure energy fluxes and atmospheric parameters such as trace gases, aerosols, cloud properties, or altitude profiles of various species. Imager spatial resolution varies from 37 m to 400 m depending on altitude; spectral resolution is as small as 0.5 nm.

Many of the airborne systems have been developed to fly on multiple aircraft.

*In situ* systems provide a wide range of unique observing capabilities that are used to validate satellites measurements and to better understand the interaction among atmospheric variables through direct observations. These observing systems consist of both ground and airborne sensors. Measurements are made with instruments such as rain gauges, disdrometers, gas analyzers, and laser-based detectors. A complete mobile facility (COMMIT), housed in a 20-foot trailer, has traveled widely over the globe to support numerous field and validation campaigns.

Instrument systems evolve and change over time, and therefore this report has been updated as required, typically every three to five years. The previous report was completed in 2011; 18 new instruments programs have begun since that time and are included in this 2017 report. An electronic version of this report is posted on the Earth Sciences Division-Atmospheres Website at: <https://atmospheres.gsfc.nasa.gov/>.

We want to thank all of the Laboratory members who contributed material on the various instrument systems, and especially the efforts of Chuck Cote (SSAI) and Omega Williams (610) who managed and coordinated the report preparation as well as Judith Clark (TIMS) for formatting, proofreading, and editing support.

Sincerely,



Steven Platnick  
Deputy Director for Atmospheres



Karen Mohr  
Associate Deputy Director for Atmospheres

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## Scientific Products and Measurements Parameters

Atmospheric Scientists in the Earth Sciences Division are constantly seeking new opportunities for instrument concepts that promote NASA Earth Science objectives, leading eventually to new space-based remote-sensing systems. The approach that is used to accomplish this is the scientific process shown in Figure 1. The process begins with a scientific question raised by a NASA goal or objective and proceeds through the various phases and results in new science outcomes. This science-to-science approach is repeated with each new opportunity.

During the process, mission goals are formulated to address an important scientific problem, hypothesis, or both. Definition of the measurement requirements is a key process and identifies the geophysical parameters of specific interest to investigators. Instrument development begins with a concept definition and design followed by synthesis and fabrication. Laboratory and field models are then built and tested. Stringent requirements are placed on measurement accuracies in order to understand fully the complexity and variability of Earth science processes. This requires careful attention to calibration procedures to remove error sources and biases from instruments and data-processing algorithms. Uncertainties are uncovered and characterized through field and sub-orbital campaigns that provide feedback to hardware or software designs to improve accuracy and performance. These lead to a better understanding of physical parameters in the context of retrievals of these parameters from remote sensing. Field campaigns may be carried out jointly between government organizations, universities and other research institutions, under agency, or national or international programs. The successive feedback and refinement process continues throughout the lifetime of all atmospheric instrument systems. Calibration and Validation (CalVal) is therefore an essential element of Earth science research prior to and during flight operations. Some ground validation systems take the form of complete multi-instrument mobile vans or trailers that are never intended for space. They provide measurements to validate space-derived products, including calibration.

The final phases shown in Figure 1 are space flight and the generation of scientific outcomes (products) derived from sensor measurements. As systems migrate through the various phases of the NASA project cycle, Principal Investigators (PIs) and Instrument Scientists have the responsibility to ensure that scientific integrity is maintained throughout all development and testing phases. They are essential participants and stakeholders in any decision process that affects the performance or cost of an instrument, and are responsible to the scientific community to explain any constraints imposed by limited resources or schedule.

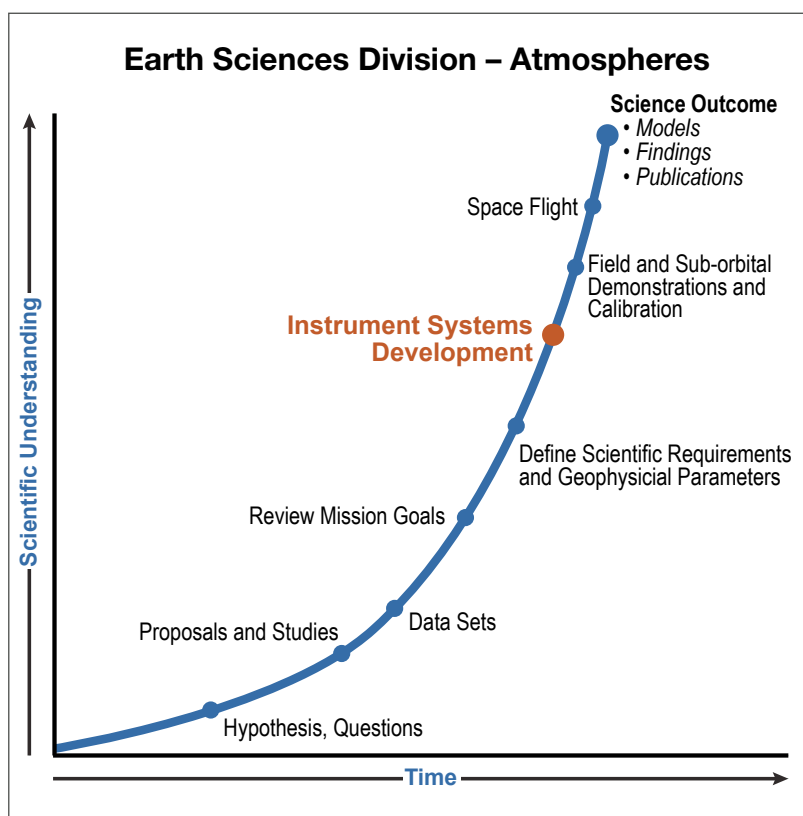


Figure 1. Instrument Systems Development (in orange) is the subject of this report.

Data are the primary product of NASA experimentation and provide the underpinnings for all scientific findings and outcomes. Raw data are transformed into products through data-processing algorithms. Design, development, and testing of retrieval algorithms is an essential aspect of the scientific measurement process. Regional or global computer models are used to place the data in a larger context and derive useful information. They add to our existing knowledge and enhance our capability to draw conclusions relative to the original scientific formulation and hypothesis.

Peer reviewed publications are essential to the success of an experimental campaign or mission. Laboratory scientists have established an impressive record of publications and citations over the years based on data products from various stages of the instrument formulation, from laboratory fabrication to space flight. A list of yearly publications can be found the Atmospheric website: <http://atmospheres.gsfc.nasa.gov/>.

Concerns over changes in aerosols, clouds, precipitation, atmospheric composition including ozone depletion/recovery, and their impacts on water and energy cycle, air quality, greenhouse gas warming, and climate change are among the many questions and issues that are addressed through these measurements and their corresponding satellite retrievals. Figure 2 shows a summary of products generated by our instrument systems that support this research on the atmosphere. Much of the data are available for scientific studies and can be found through URLs identified in the individual instrument system summaries or through direct contact with PIs and their collaborators.

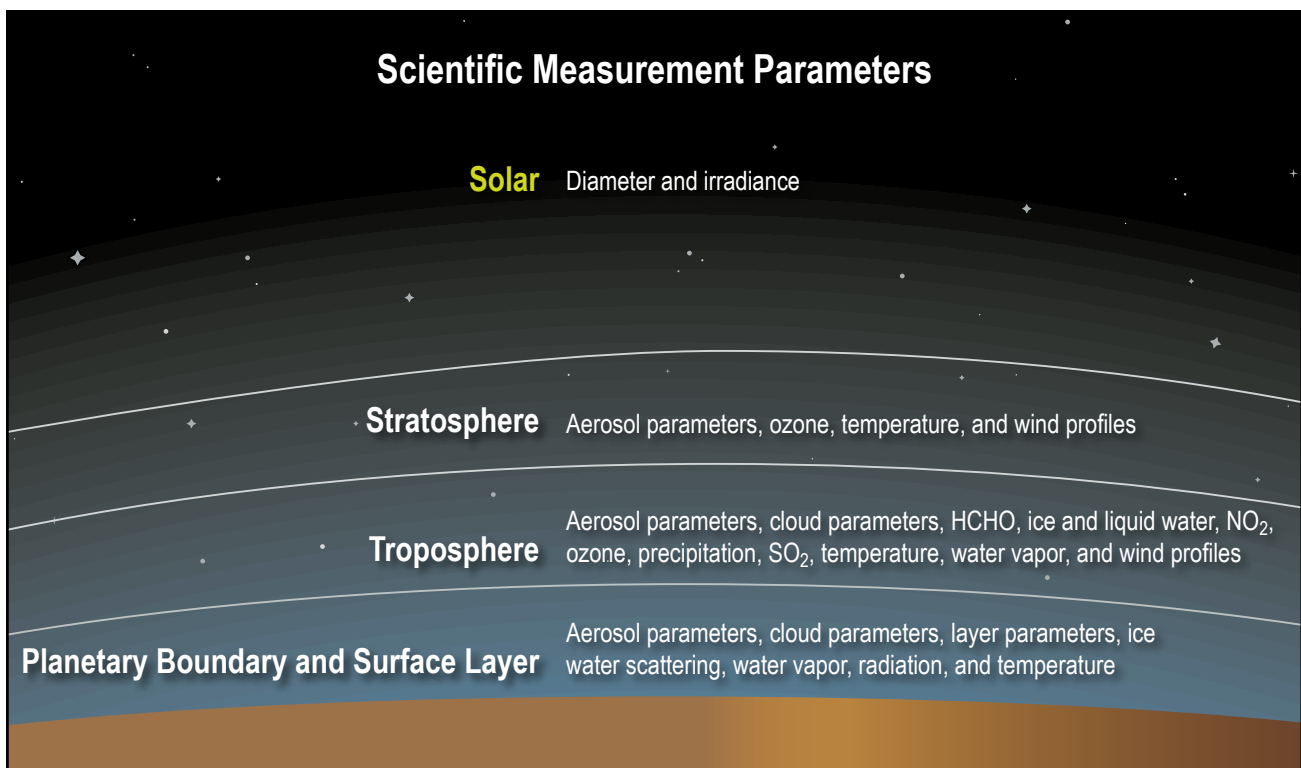


Figure 2. Summary of atmospheric research products.

Active Remote-Sensing Systems  
Lidar



# ACATS

## *Airborne Cloud-Aerosol Transport System Lidar*



A picture of (a) the current ACATS instrument includes (b) the receiver subsystem and (c) the telescope subsystem.

### Key ACATS Facts

- Heritage: Cloud Physics Lidar (CPL)
- ER-2 airborne lidar for cloud and aerosol profiling. Provides cloud/layer boundary, depolarization ratio, optical depth, and extinction ratios.
- Participated in several small field campaigns, including WAVE-2012, CCAVE, and ICESat-2 demonstration flights.
- Nominal Flight Characteristics: 65,000 ft (20 km), above 94 percent of Earth's atmosphere. Multiple 45 degree viewing angles, 8 h duration time.

### Description

Lidar remote sensing is a proven useful tool for profiling the structure of atmospheric cloud and aerosol features. In addition to basic intensity information, backscattered photons inherently possess other microphysical attributes, such as Doppler shift caused by the mean motion of the scattering medium. Thus, a lidar system capable of resolving the Doppler shifts inherent to atmospheric motions can simultaneously provide information about both the scattering intensity and the particle motion.

The Airborne Cloud-Aerosol Transport System (ACATS) is a relatively new instrument that has flown several times on NASA aircraft. The ACATS instrument is a lidar that is both a Doppler lidar and, by its very nature, a high spectral

resolution lidar (HSRL). The HSRL aspect of ACATS will provide information on cloud and aerosol height, internal structure, and optical properties (e.g., extinction). The Doppler aspect adds capability to derive wind motion, which in turn enables studies of aerosol transport and cloud motion. The technology developed has direct application to future spaceborne missions, such as the proposed Aerosol-Cloud-Ecosystems (ACE) mission and will provide critical validation capability for future missions.

The ACATS lidar is an aerosol-based fringe-imaging HSRL/Doppler lidar. The fringe-imaging method measures the Doppler shift of the spectral return by observing the signal spectroscopically (i.e., as a function of wavelength) using a spectral-resolving filter and a multi-element detector. A unique aspect of the fringe-imaging Doppler lidar concept is that it is also, by its very nature, an HSRL. Because the broad

Rayleigh-scattered spectrum is imaged as a nearly flat background (and can be characterized and removed from the total signal) the aerosol scattered signal can be directly and unambiguously measured. The integral of the aerosol-scattered spectrum is, in fact, analogous to the aerosol measurement made with a typical iodine filter HSRL instrument.

Designed for operation on high-altitude aircraft, the ACATS lidar instrument provides a combination of backscatter lidar, Doppler lidar, and HSRL. Although it is an HSRL, the single-wavelength ACATS lidar is designed to enable aerosol transport studies. In addition, the need to point off-nadir for wind measurements inherently enables cross-track cloud and aerosol measurements.

The ACATS lidar also provides an important technology demonstration for a future global wind system. Global wind measurements from space are recognized as an essential and unfulfilled measurement capability. Although different lidar techniques are being evaluated, no single method is yet mature enough to propose as a definitive space-based system. Because of the numerous difficulties inherent in the measurement, it is unknown if any of the methods currently being evaluated will result in either a successful demonstration of wind measurement technology or a system that is scalable to space platforms. Demonstration flights of the ACATS lidar will permit both science and engineering evaluation of an alternate approach to the measurement.

## ACATS Data Products

- Particulate backscatter
- Layer boundaries for aerosols and clouds
- Layer and column optical depth
- Particulate extinction profile
- Horizontal wind speed and direction

## ACATS Instrument Parameters

- Wavelength: 532 nm
- Laser repetition rate: 200 Hz
- Laser energy: 10mJ at 532 nm
- Telescope diameter: 8 in
- Total power: <1500 W
- Weight: <120 kg
- FOV: 200 microradians
- Vertical resolution: 60 m (aerosol), 450 m (wind)
- Horizontal resolution: 200 m (standard), 5 km (wind & HSRL)

## Principal Investigator

John Yorks  
NASA's Goddard Space Flight Center  
[John.E.Yorks@nasa.gov](mailto:John.E.Yorks@nasa.gov)

## Co-Investigators

Matthew McGill  
NASA's Goddard Space Flight Center  
Stanley Scott  
NASA's Goddard Space Flight Center  
Andrew Kupchock  
Science Systems and Applications, Inc.  
Scott Ozog  
University of Maryland

## Scientific Questions for Future Campaigns

- What are the fluxes of aerosols in high transport regions?
- What is the outflow speed in anvil cirrus associated with tropical and convective storms?

## Future Plans

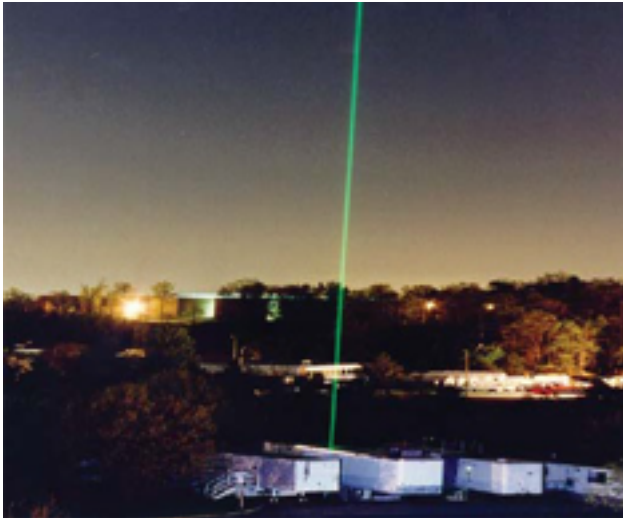
- Provide demonstration measurements for ACE and future space-based lidar missions.
- Yearly campaigns supporting various Earth Science missions or experiments.

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# AT Lidar

## *Aerosol and Temperature Lidar*



*AT Lidar operating at GSFC; 532 nm beam is clearly visible.*

### Key AT Lidar Facts

- Heritage: Originally designed for stratospheric parameters; modified to include the troposphere.
- The AT Lidar is an elastic and Raman backscatter lidar designed for aerosol and temperature profiling in the stratosphere and above; and for tropospheric water vapor and temperature, cirrus cloud parameters, and temperature within cirrus clouds.
- Nominal field configuration: The system is mobile and is housed in a large, environmentally controlled trailer.

### Description

This Lidar system has high sensitivity aerosol and temperature capabilities using two separate Nd:YAG lasers to transmit three different wavelengths: 1064, 532, and 355 nm. Returns from the spectrally narrow transmitted 1064 and 532-nm beams are used to measure aerosol backscatter into the stratosphere. The depolarization ratio of the 532-nm radiation is measured to determine the physical state of the particles. The transmitted 532-nm beam is spectrally narrow and rotational. Raman lines scattered from nitrogen can be spectrally resolved. These lines are temperature sensitive, so temperature within cirrus clouds can be retrieved. The rotational Raman detection of tropospheric temperature has been a collaboration between NASA and Germany's GKSS. Raman scattering of the transmitted 532-nm radiation from nitrogen (607-nm radiation) is also collected. Raman scattered returns from nitrogen (at 387 nm) and water vapor (at 407 nm) are also collected from the transmitted 355-nm beam. The ratio of the elastically scattered 355 or 532

nm radiation to the corresponding Raman scattered return at 387 or 607 nm, allows for the direct measure of the aerosol backscatter ratio. The ratio of the 407-nm return to the 387-nm return yields a relative water vapor profile. This can be calibrated to yield an absolute measurement of the tropospheric water vapor profile.

### AT Lidar Data Products

- Aerosol backscatter: 1064, 532, and 355 nm
- Aerosol depolarization: 532 nm
- Aerosol backscatter and extinction: 532 and 355 nm
- Stratospheric aerosol and temperature
- Tropospheric water vapor
- Tropospheric temperature (includes within clouds)

### AT Lidar Parameters

- Laser wavelengths: 1064, 532, and 355 nm at 50 Hz
- Optical returns: 1064, 532, 607, 355, 387, and 407 nm
- Vertical resolution (raw signal): 15 m
- Telescopes: far-field 36-in Newtonian; near-field: 4-in Cassegrain

### Principal Investigator

Thomas J. McGee  
NASA's Goddard Space Flight Center  
[Thomas.J.McGee@nasa.gov](mailto:Thomas.J.McGee@nasa.gov)

### Co-Investigators

John Sullivan  
NASA's Goddard Space Flight Center  
Grant Sumnicht  
Science Systems and Applications, Inc.  
Laurence Twigg  
Science Systems and Applications, Inc.

### International Collaborator

Jens Reichardt  
German Weather Service

### Science Question for Future Campaigns

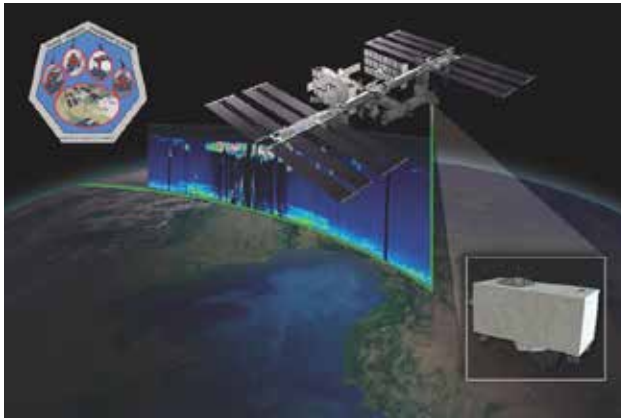
- What determines the formation of cirrus cloud particles as a function of temperature within the cloud?

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# CATS

## Cloud-Aerosol Transport System Lidar



CATS is a lidar instrument that operates on the International Space Station (ISS) and provides a combination of operational science measurements, in-space technology demonstrations, and technology risk reduction for future Earth Science missions.

### Key CATS Facts

- Heritage: Cloud Physics Lidar (CPL), Airborne Cloud-Aerosol Transport System (ACATS)
- CATS uses a 60 cm telescope, 2 high-repetition ratio lasers, and photon-counting detection to measure backscatter and depolarization ratio at 532 and 1064 nm
- CATS has operated on the ISS (altitude of 415 km) for over three years (since Feb. 05, 2015) and has fired over 200 wavelengths.
- Website: CATS URL: <http://cats.gsfc.nasa.gov>

### Description

Scientists use an array of satellite, aircraft, and ground-based instruments to measure and monitor clouds and aerosols. To better observe the vertical structure of clouds and aerosols, scientists turn to active remote-sensing instruments, such as lidar. Lidar 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.

The Cloud-Aerosol Transport System (CATS) is a lidar remote-sensing instrument designed to provide vertical profiles of clouds and aerosols while also demonstrating new in-space technologies for future Earth Science missions. CATS has been operating on the International Space Station (ISS) for over two years, beginning in early February 2015. CATS provides diurnally varying vertical profiles of clouds and aerosols in near-real-time (NRT) from the ISS to enhance our depth of understanding in the areas of aerosols (man-made pollution, smoke, dust), clouds, and hazardous events.

The CATS payload was designed to operate on-orbit for a minimum of 6 months and up to three years (with a possibility of extending to 5 years). With over 2 years of operation from the ISS, the CATS data products are enabling the science community to investigate cloud and aerosol impacts on the climate system, as well as more accurately monitor and model hazardous aerosol plumes.

CATS is primarily a technology demonstration designed to provide vertical profiles of clouds and aerosols that are similar to those provided by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission. One benefit of CATS is that the ISS orbital characteristics enable measurements that are often hours apart from CALIPSO observations, providing additional data that when combined with CALIPSO data can provide better temporal and spatial coverage over the tropics and mid-latitudes. CATS has enhanced the data record of cloud and aerosol vertical profiles by providing excellent spatial and temporal coverage over the tropics and mid-latitudes at local times not observed by CALIPSO. CATS' high detection sensitivity at the 1064 nm wavelength enables detection of the full extent of the aerosol layers above the cloud, and differentiation of these two layers so that the radiative effect of smoke and dust above clouds can be more accurately determined. Additionally, CATS data enables analysis of aerosol plume characteristics over time and space, since the ISS orbit provides comprehensive coverage of the primary aerosol transport paths.

In addition to their impact on the Earth's climate system, aerosols from volcanic eruptions, wildfires, man-made pollution events, and dust storms are hazardous to aviation safety and human health. The 2010 eruption of the Eyjafjallajökull volcano in Iceland grounded nearly 95,000 flights and caused an estimated \$1.7 billion loss for the airline industry. Aerosols near the Earth's surface contribute to an annual death toll of ~68,000 Americans and ~3.3 million people globally. The CATS data products are produced within 6 hours of collection, which enables assimilation of aerosol vertical profiles into models for applications such as forecasting volcanic plume transport that cost the airline industry billions of dollars and predicting air quality during hazardous events that result in millions of deaths globally.

### CATS Data Products

- Attenuated total backscatter
- Layer boundaries for aerosols and clouds
- Layer and column optical depth
- Extinction profile

- Depolarization ratio
- Cloud phase
- Aerosol type
- Ice water content/path

### CATS Instrument Parameters

- Wavelengths: 532 and 1064 nm
- Laser repetition rate: 4-5 kHz
- Laser energy: 1-2 mJ/wavelength
- Telescope diameter: 60 cm
- View angle: 0.5 degrees
- Weight: <500 kg
- FOV: 110 microradians
- Vertical resolution: 60 m
- Horizontal resolution: 350 m (Level 1), 5-60 km (Level 2)

### Principal Investigator

Matthew McGill  
NASA's Goddard Space Flight Center  
[Matthew.J.McGill@nasa.gov](mailto:Matthew.J.McGill@nasa.gov)

### Co-Investigators

John Yorks (Science Lead)  
NASA's Goddard Space Flight Center  
Stanley Scott (Instrument Lead)  
NASA's Goddard Space Flight Center  
Dennis Hlavka  
Science Systems and Applications, Inc.  
Andrew Kupchock  
Science Systems and Applications, Inc.  
Scott Ozog  
University of Maryland  
Steve Palm  
Science Systems and Applications, Inc.  
Rebecca Pauly  
Science Systems and Applications, Inc.  
Sharon Rodier  
Science Systems and Applications, Inc.  
Patrick Selmer  
Science Systems and Applications, Inc.  
Mark Vaughan  
NASA's Langley Research Center

### Science Goals for the Project

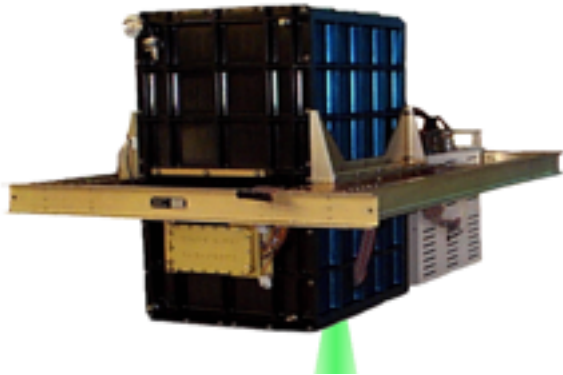
- Extend space-based lidar climate observations to include measurements at various local times and promote studies of diurnal changes in clouds and aerosols.
- Provide near real time observational data to improve operational aerosol model forecasts.
- Demonstrate new technologies for future space-based lidar missions and future Earth Science ISS payload.

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# CPL

## Cloud Physics Lidar



CPL configured to fly on the NASA ER-2.

### Key CPL Facts

- Heritage: Cloud Lidar System (CLS)
- ER-2 airborne lidar for cloud and aerosol profiling. Provides cloud/layer boundary, depolarization ratio, optical depth, and extinction ratios.
- Participated in more than two-dozen field campaigns, including SAFARI-2000, CRYSTAL-FACE, TC4, and SEAC4RS.
- Nominal Flight Characteristics: 65,000 ft (20 km), above 94 percent of Earth's atmosphere. Nadir viewing, 9-h duration time with 5-GB storage.
- CPL URL: <http://cpl.gsfc.nasa.gov>

### Description

The effect of clouds and aerosols on regional and global climate is of great scientific importance. Long-standing elements of the NASA climate and radiation science program are field studies incorporating airborne remote sensing and *in situ* measurements of clouds and aerosol. The CPL system is designed specifically for studying clouds and aerosols using the ER-2 High Altitude Aircraft. Because the ER-2 typically flies at 65,000 ft (20 km), its instruments are above 94 percent of the Earth's atmosphere, thereby allowing ER-2 instruments to function as spaceborne instrument simulators. The CPL provides a unique tool for atmospheric profiling and is sufficiently small and low cost to include in multiple instrument missions. Active lidar profiling is especially valuable because the cloud height structure is measured unambiguously, up to the limit of signal attenuation.

### CPL Data Products

- Planetary boundary layer (PBL)
- Layer boundaries for aerosols and clouds
- Layer and column optical depth

- Extinction profile
- Depolarization ratio
- Cloud phase
- Aerosol type

### CPL Parameters

- Vertical resolution: 30 m
- Horizontal resolution: 200 m
- Wavelengths: 1064, 532, and 355 nm
- Laser repetition Rate: 5000 Hz
- Laser pulse energy: 50  $\mu$ J at 1064 nm; 25  $\mu$ J at 532 nm; 50  $\mu$ J at 355nm
- Total power: 60 W to 1200 W
- Weight: 50 kg to 110Kg
- FOV: 100  $\mu$ rad

### Principal Investigator

Matthew McGill  
NASA's Goddard Space Flight Center  
[Matthew.J.McGill@nasa.gov](mailto:Matthew.J.McGill@nasa.gov)

### Co-Investigators

John Yorks (Science Lead)  
NASA's Goddard Space Flight Center

Dennis Hlavka  
Science Systems and Applications, Inc.

Andrew Kupchock  
Science Systems and Applications, Inc.

Patrick Selmer  
Science Systems and Applications, Inc.

Steve Palm  
Science Systems and Applications, Inc.

Rebecca Pauly  
Science Systems and Applications, Inc.

### Science Question for Future Campaigns

- What are the particle sizes within clouds?
- What is the effect of multiple scattered signals on estimates of extinction-to-backscatter and optical depth?

### Future Campaigns

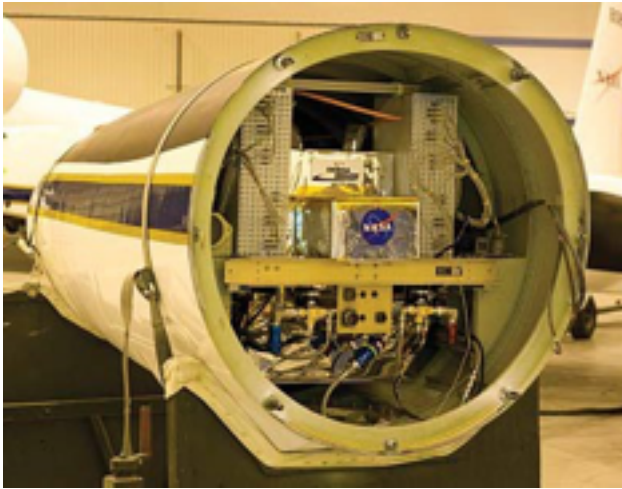
- CATS, CALIPSO and GOES-16 validation flights
- Future EVS flights
- Yearly campaigns supporting various Earth Science missions or experiments

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# MABEL

## *Multiple Altimeter Beam Experimental Lidar*



*MABEL being installed in the ER-2 nose*

### Key MABEL Facts

- Heritage : New development, as demonstration of ICESat-2 measurement capability
- MABEL is a new instrument being developed in support of the ICESat-2 mission
- Field operations (aircraft, altitude, etc.): Flies on ER-2 aircraft at >20,000 ft

### Description

The Multiple Altimeter Beam Experimental Lidar (MABEL) is a new instrument being developed in support of the ICESat-2 mission. The ICESat-2 mission is critically dependent on making cross-track measurements of surface slope. This is accomplished by using multiple independent beams, measured simultaneously, to profile the surface. Moreover, to enable this measurement concept, ICESat-2 is embracing a new approach to surface altimetry measurements by using high-repetition rate, low-pulse-energy lasers and photon-counting detection.

Because there are many engineering and science trades made possible by using the multiple beam photon-counting approach, it is essential to have an airborne simulator instrument that can be used to demonstrate the measurement concept. MABEL is an airborne demonstrator instrument that has enough design flexibility to permit exploration of engineering and science trade spaces to inform and validate the ICESat-2 instrument design. Initial plans call for deployment on the high-altitude ER-2 aircraft, with eventual adaptation to the Global Hawk unmanned platform.

The design for MABEL is two wavelength (532 and 1064 nm) with 16 beams at 532 nm and 8 beams at 1064 nm. Each transmit beam produces a 2-m diameter footprint on the surface, centered on a 4-m diameter field of view. Fiber-optic arrays coupled to the transmit and receive telescopes determine the viewing geometry. The fiber arrays, arranged similar to a telephone switchboard, permit selection of specific viewing geometry that can be varied in increments of 20 m across a 2-km swath.

### MABEL Parameters

- Wavelength: 532 and 1064 nm
- Laser repetition rate: 5 to 25 kHz
- Laser energy (per beam): ~5  $\mu$ J at 532 nm; ~5  $\mu$ J at 1064 nm
- Number of beams: up to 16 at 532 nm, up to 8 at 1064 nm
- Telescope diameter: 6 in (0.152m)
- Total Power: <1500 W
- Weight: <120 kg
- FOV: 200 microradians
- 30-m vertical resolution

### Principal Investigator

Matthew McGill  
 NASA's Goddard Space Flight Center  
[Matthew.J.McGill@nasa.gov](mailto:Matthew.J.McGill@nasa.gov)

### Science Questions

- Under formulation

### Future Campaigns

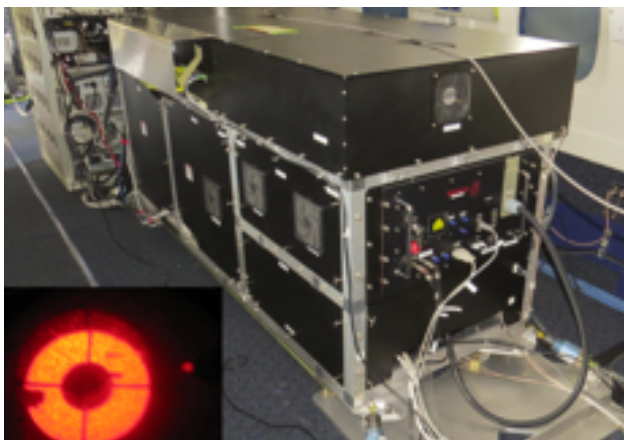
- Provide demonstration measurements in support of ICESat-2
- Provide validation measurements in support of ICESat-2

### Reference

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## MELI

### Methane Lidar



MELI transceiver and with back-illuminated transmitter and receiver images during deployment on the NASA DC-8 airborne laboratory in the fall of 2015 to measure CH<sub>4</sub> concentrations over a wide range of topography and weather conditions from altitudes of 3 km to 13 km.

### Key MELI Facts

- Heritage: The first IPDA CH<sub>4</sub> lidar, aside from the German DLR CHARM-F instrument
- Integrated Path Differential Absorption (IPDA) lidar instrument to measure CH<sub>4</sub> column concentrations
- Uses GSFC-developed 1.65- $\mu$ m laser transmitters and a sensitive avalanche photodiode detector
- Prototype R&D demonstrator for a future space mission

### Description

Methane (CH<sub>4</sub>) is the second most important anthropogenic greenhouse gas with a higher radiative forcing potential than carbon dioxide (CO<sub>2</sub>) on a per molecule basis, making anthropogenic CH<sub>4</sub> a critical target for mitigation. Anthropogenic CH<sub>4</sub> is responsible for a significant portion of the global warming produced by all well-mixed greenhouse gases. MELI is an IPDA lidar using an optical parametric oscillator (OPO) and optical parametric amplifier (OPA) laser transmitters and sensitive avalanche photodiode detector. The lidar measures atmospheric a CH<sub>4</sub> absorption at multiple, discrete wavelengths at 1650.9 nm. The lidar, along with an *in situ* spectrometer was deployed in the fall of 2015 aboard NASA's DC-8 airborne laboratory based at the Armstrong Science Aircraft Integration Facility (SAIF) in Palmdale, CA, and measured CH<sub>4</sub> column concentrations over a wide range of topography and weather conditions from altitudes of 3 km to 13 km.

### MELI Main Data Products

- CH<sub>4</sub> column concentration measurements at 1.65  $\mu$ m
- Atmospheric backscatter profile at 1.65  $\mu$ m

### MELI Parameters

- Center wavelength: 1650.958 nm
- Number of wavelengths: 5–20
- Transmitter energy/pulse: ~30–250  $\mu$ J
- Transmitter pulse rate: 5–10 kHz
- Transmitter divergence: ~150  $\mu$ rad
- Receiver field-of-view: 300  $\mu$ rad
- Receiver diameter: 20 cm
- Receiver band pass: 0.8 nm (FWHM)
- Detector: HgCdTe e-ADP
- Detector QE: ~90%
- Averaging time: 1/16 sec

### Principal Investigator

Haris Riris  
 NASA's Goddard Space Flight Center  
[Haris.Riris@nasa.gov](mailto:Haris.Riris@nasa.gov)

### Team Members

Kenji Numata, NASA's Goddard Space Flight Center  
 Stewart Wu, NASA's Goddard Space Flight Center



MELI principle of operation (left). DC-8 over the Pacific Ocean during a MELI flight in October 2015 (right).

### Scientific Questions for Future Campaigns

- What are the global, regional, and sectoral sources and sinks of CH<sub>4</sub>?
- What are the processes that drive CH<sub>4</sub> release in the Arctic and tropical wetlands and what is their contribution to climate change?

### Future Campaigns

No current campaigns planned. The previous flights were supported by IRAD.

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# MPLNET

## Micro Pulse Lidar Network



MPLNET in Doi Ang Khang, Thailand

### Key MPLNET Facts

- Heritage: GSFC Director's Discretionary Fund
- Nominal field configuration: Global ground-based sites in the NASA Micro-Pulse Lidar Network.
- Instruments are compact and eye-safe polarized lidars capable of profiling the vertical structure of aerosols and clouds up to 30 km.
- The instrument design was engineered for deployments to remote field locations requiring continuous lidar observations.
- MPLNET Website: <http://mplnet.gsfc.nasa.gov>

### Description

The NASA Micro-Pulse Lidar Network (MPLNET) is a global, federated network of polarized micro-pulse lidar (MPL) systems designed to measure aerosol and cloud vertical structure continuously, over long time-periods required to contribute to climate change studies and provide ground validation for satellite sensors and related aerosol modeling and forecasting efforts. MPLNET began in 2000, and there have been over 60 sites worldwide. There are currently 17 long-term and numerous short-term field campaign sites in operation. Seven of the long-term sites have over 10 years of data, and many more have 5+ years. There are 6 more sites in planning stages towards operational status by end of 2017 and several more at proposal stage. Most MPLNET sites are co-located with the NASA Aerosol Robotic Network (AERONET), producing both column and vertically resolved data on aerosol and cloud properties and the evolution and structure of the planetary boundary layer (PBL). MPLNET is also a member of the WMO Global Atmospheric Watch (GAW) Aerosol Lidar Observation Network (GALION).

### MPLNET Data Products

- Polarized backscatter lidar signals and volume depolarization ratio from surface to 30 km (1 min, 30 or 75 m resolutions)
- Cloud heights, phase, thin cloud extinction and optical depth
- Aerosol heights, backscatter and extinction profiles, optical depth and depolarization ratio
- Planetary Boundary Layer heights and aerosol optical depth
- Near real time delivery of all data products on public webserver, including quality assured data products

### MPL Instrument Parameters

- Laser wavelength: 523, 527, or 532 nm
- Laser pulse energy: 5–10  $\mu\text{J}$
- Pulse repetition rate: 2500 Hz
- Alternating polarized output from linear to elliptical at 10 Hz
- Telescope: 7–8-in Cassegrain
- Vertical resolution: 15–300 m
- Typical data rate: 1 s to 1 min

### Principal Investigator

Ellsworth J. Welton  
 NASA's Goddard Space Flight Center  
[Ellsworth.J.Welton@nasa.gov](mailto:Ellsworth.J.Welton@nasa.gov)

### Scientific Questions for Future Observation

- What are the distributions of aerosol layers and properties and how have they changed over the past decade?
- How can operational lidar networks improve aerosol modeling and forecasting?
- How does boundary layer height impact aerosol transport and surface pollution levels?
- How do dust, smoke, and pollution aerosols effect cloud formation and precipitation?

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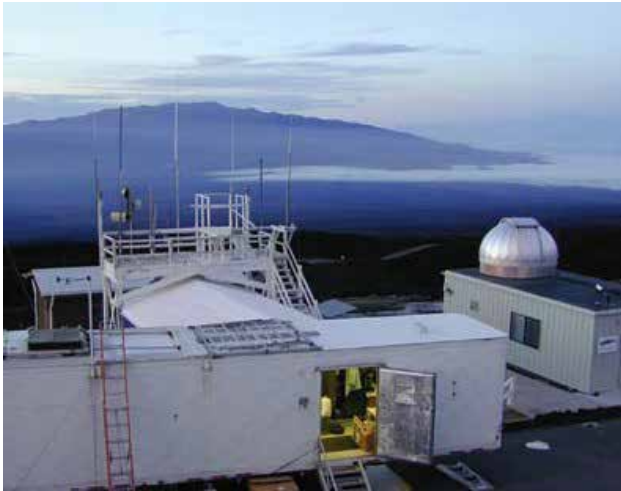
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# STROZ LITE

## *Stratospheric Ozone Lidar Trailer Experiment*



The STROZ LITE trailer deployed at the Mauna Loa Observatory in August 2013. Mauna Kea is visible in the background.

### Key STROZ LITE Facts

- Heritage: Originally designed for stratospheric ozone, then modified to include temperature, aerosols, and tropospheric water vapor.
- A differential absorption, elastic and inelastic backscatter lidar instrument that returns vertical profiles of ozone, temperature, and aerosol parameters in the stratosphere and a vertical profile of water vapor in the troposphere.
- The lidar has been involved in more than two dozen national and international campaigns supporting satellite validation, aircraft campaigns, and NDSC validation campaigns.
- Nominal field configuration: The system is mobile and housed in a large, environmentally-controlled shipping container.

### Description

The STROZ LITE lidar uses two lasers to generate the two wavelengths that are transmitted into the atmosphere: an XeCl excimer laser, emitting at 308 nm; and another laser to transmit near 350 nm with a spectrally narrow emission line. Ozone is extracted using a differential absorption (DIAL) technique—two wavelengths are transmitted into the atmosphere: one is strongly absorbed by ozone, while the other is not absorbed. Ozone can then be deduced from the difference in slope between the lidar returns at the two transmitted wavelengths. In addition to collecting the backscatter signal from each of these transmitted wavelengths, STROZ LITE collects several inelastic returns from Raman scattering from  $N_2$  and  $H_2O$ . The STROZ LITE instrument was the first to develop the Raman scatter

differential absorption technique for the measurement of ozone profiles in the presence of heavy aerosol loadings. This was put into place shortly after the eruption of Mt. Pinatubo in 1991. The success of this technique resulted in a recommendation from the NDSC Steering Committees that all ozone lidar instruments within the NDSC should incorporate the Raman channels needed for the Raman DIAL technique. NDACC ozone and temperature data from instruments around the world that have been validated by the STROZ lidar, have been shown to be in very good agreement with global data records from satellites.

### STROZ LITE Data Products

- Aerosol backscatter and extinction at 355 nm, troposphere
- Stratospheric and mesospheric temperature
- Tropospheric water vapor
- Stratospheric ozone

### STROZ LITE Parameters

- Laser wavelengths: 308 nm at 100Hz; 355 nm at 50 Hz
- Optical returns: 308, 332, 355, 387, and 407 nm
- Vertical resolution (raw signal): 15 m
- Telescopes: Far Field—30-in Dall-Kirkham; Near field:—4-in Cassegrain

### Principal Investigator

Thomas J. McGee  
NASA's Goddard Space Flight Center  
[Thomas.J.McGee@nasa.gov](mailto:Thomas.J.McGee@nasa.gov)

### Co-Investigators

John Sullivan  
NASA's Goddard Space Flight Center  
Grant Sumnicht  
Science Systems and Applications, Inc.  
Laurence Twigg  
Science Systems and Applications, Inc.

### Science Questions for Future Campaigns

- Has ozone begun its recovery from the losses because of chlorine destruction?
- What are the variability and abundance of water vapor just above the tropopause?

### Future Campaigns

- Observatoire de Haute Provence, France: July–November, 2017

- Hohenpeissenberg, Germany: February, 2018
- Maitoa Observatory, Reunion Island, France: July – October, 2018
- Lauder, New Zealand: January, 2019

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# TROPOZ

## *Tropospheric Ozone Differential Absorption Lidar*



TROPOZ trailer deployed to Ft. Collins, CO, during the 2014 DISCOVER-AQ campaign. The NASA P3-B flies overhead as the TROPOZ team prepares to launch an ozonesonde.

### Key TROPOZ Facts

- Heritage: Trailer and laser were originally used for stratospheric ozone measurements. The telescope and optical assemblies were largely repurposed from the AROTAL instrument; modified to include tropospheric ozone.
- An ultraviolet lidar for tropospheric ozone measurements from near 200 m to 18 km agl. Used to investigate boundary layer (air quality) and upper tropospheric/lower stratospheric ozone dynamics.
- Participated in the 2014 DISCOVER-AQ campaign and 2016 KORUS-AQ campaign.
- Nominal field configuration: The system is mobile and is housed in a large, environmentally controlled trailer.
- TROPOZ URL: <https://www-air.larc.nasa.gov/missions/TOLNet/>

### Description

Although tropospheric ozone is a critical measurement for climate and air quality studies, it is difficult to accurately measure with current space-based instrumentation. For this reason, the TROPOZ was constructed in a transportable trailer and has been deployed to provide high-resolution time-height measurements of tropospheric ozone from near-surface to the lower stratosphere for air quality/chemical-transport-model improvement and satellite validation/assessment. Because of the lack of historic diurnal information in the lower troposphere, TROPOZ advances the understanding of atmospheric processes controlling regional air quality and chemistry.

TROPOZ is made up of three major components: the transmitter, the receiver, and the data acquisition system.

The transmitter comprises an Nd:YAG laser, transmitting two parallel beams at 266 nm, which are then shifted using Stimulated Raman Scattering to 289 and 299 nm using deuterium and hydrogen, respectively. The primary receiver used for far field (upper tropospheric returns) is a 16-in Newtonian telescope and near field signal is collected using four isolated 1-in receivers. Real-time data acquisition and analysis programs provide information that is relayed to flight planners in order to improve measurement strategies during NASA campaigns.

### TROPOZ Data Products

- O<sub>3</sub> vertical profiles from 0.2 –18 km
- Surface: O<sub>3</sub>, NO<sub>2</sub>, and meteorology (P, T, RH, Winds)

### TROPOZ Parameters

- Laser wavelengths: 289 and 299 nm
- Laser pulse energy: 18 mJ and 24 mJ
- Pulse rate: 50 Hz
- Field of view: 4.5 mrad (near field), 1.0 mrad (far field)
- Optical channels: 289, 299 nm
- Vertical resolution: 0.1–1.5 km

### Principal Investigator

Thomas J. McGee  
NASA's Goddard Space Flight Center  
[Thomas.J.McGee@nasa.gov](mailto:Thomas.J.McGee@nasa.gov)

### TROPOZ Team Members

John T. Sullivan  
NASA's Goddard Space Flight Center

Laurence Twigg  
Science Systems and Applications, Inc.

Grant K. Sumnicht  
Science Systems and Applications, Inc.

### Science Questions for Future Campaigns

- What is the validity of the ozone products from future geostationary satellites (such as TEMPO)?
- How does urban pollution and ozone interact with complex terrain (such as mountains or coastal transitions)?
- What are the local and regional air quality impacts of biomass burning entering the urban environment?

### Planned Campaigns

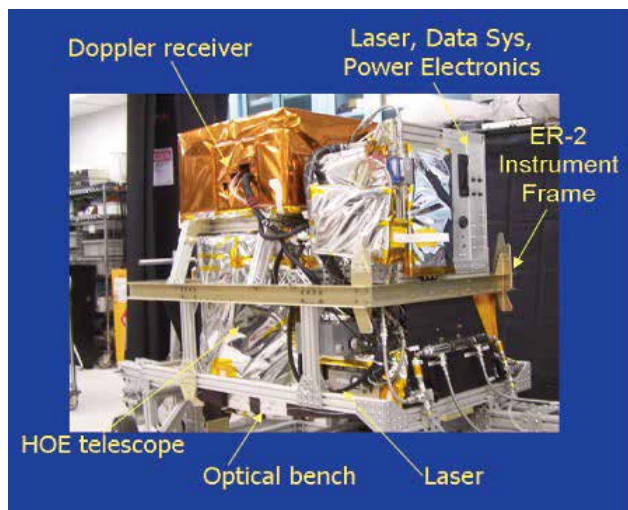
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## TWiLiTE

### *Tropospheric Wind Lidar Technology Experiment*



The Tropospheric Wind Lidar Technology Experiment (TWiLiTE) lidar configured for flight on the NASA ER-2

### Key TWiLiTE Facts

- Heritage: Double-Edge Wind Lidar, GLOW, ESTO Instrument Incubator Program
- An autonomous airborne Doppler lidar system for measuring vertical profiles of wind from the Doppler-shifted frequency of the laser signal scattered back towards the instrument by air molecules.
- Demonstrates key technologies needed for space-based Global Tropospheric Wind Mission
- Nominal Field Configuration: Airborne scanning Doppler lidar system designed to operate autonomously on NASA high-altitude research aircraft, including the DC-8, ER-2 and Global Hawk. Step-stare scanning in azimuth (0 to 360 degrees) with 45-degree elevation angle.

### Description

The TWiLiTE Doppler lidar measures vertical profiles of wind by transmitting a short laser pulse into the atmosphere, collecting the laser light scattered back to the lidar by air molecules and measuring the Doppler-shifted frequency of that light. The magnitude of the Doppler shift is proportional to the wind speed of the air in the parcel scattering the laser light. TWiLiTE was developed with funding from the Earth Science Technology Office's Instrument Incubator Program (IIP). The primary objectives of the TWiLiTE program are twofold: First, to advance the development of key technologies and subsystems critical for a future space based Global Wind Sounding Mission, as recommended by the National Research Council in the recent Decadal Survey

for Earth Science and second, to develop for the first time a fully autonomous airborne Doppler wind lidar instrument to demonstrate tropospheric wind-profile measurements from a high-altitude, downward-looking, moving platform to simulate spaceborne measurements.

### TWiLiTE Data Products

- Range-resolved conical scans of radial wind speed
- Vertical profiles of u-, v-, and w-component winds, and wind-speed and direction
- Coverage: 20 km to the surface
- Nominal vertical resolution: 250 m
- Accuracy: 0.5 to 3 m/s

### TWiLiTE Parameters

- Laser wavelength: 355 nm
- Laser energy/pulse: 35 mJ at 355nm
- Pulse repetition rate: 200 Hz
- Telescope/scanner aperture: 40 cm
- FOV: 0.2 mrad

### Principal Investigator

Bruce Gentry  
NASA's Goddard Space Flight Center  
[Bruce.M.Gentry@nasa.gov](mailto:Bruce.M.Gentry@nasa.gov)

### Co-Investigators

Huailin Chen  
Science Systems and Applications, Inc.

### Science Questions for Future Campaigns

- Can wind observations in and around a tropical cyclone improve the prediction of hurricane intensity and track?
- Can wind profile observations through the tropopause improve understanding of tropospheric/stratospheric exchange?

### References

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# UAV CPL

## Unmanned Aerial Vehicle Cloud Physics Lidar



The NASA Global Hawk aircraft.

### Key UAV CPL Facts

- Heritage: ER-2 Cloud Physics Lidar (CPL)
- NASA's first lidar instrument for the new Global Hawk platform
- Nominal flight characteristics: 65,000 ft (20 km), nadir viewing, up to 36-hour duration, real-time command and control, and data downlinking
- URL: <http://cpl.gsfc.nasa.gov>

### Description

Based on the success of the ER-2 Cloud Physics Lidar, or CPL (see <http://cpl.gsfc.nasa.gov>), a similar instrument, termed UAV-CPL, has been constructed for use on the Global Hawk unmanned platform. NASA now has two Global Hawks and UAV-CPL is the first lidar to fly on the new aircraft. Global Hawk is a large aircraft, and the UAV-CPL instrument package fits nicely into the nose section.

Data products and data quality are similar to the current ER-2 CPL instrument. Using the proven ER-2 instrument as a design base has permitted easy and inexpensive construction of the UAV-CPL. The long duration flights possible with the Global Hawk will prove useful in future science campaigns allowing, for example, study of cyclogenesis life cycle, from formation up through dissipation. Validation of satellite sensors in regions previously inaccessible by manned aircraft will also be enabled through use of Global Hawk.

The UAV-CPL is a backscatter lidar designed to operate simultaneously at three wavelengths: 1064, 532, and 355 nm. The lidar uses state-of-the-art technology with a high repetition rate, low pulse-energy laser, and photon-counting detection. Vertical resolution of the measurements is fixed at 30 m; horizontal resolution is variable but is typically 1 s. Primary instrument parameters are listed below.

### UAV-CPL Parameters

- Laser wavelengths: 1064, 532, and 355 nm
- Laser type: solid-state Nd:YVO4
- Laser repetition rate: 5 kHz
- Laser output energy: 50  $\mu$ J at 1064 nm, 25  $\mu$ J at 532 nm, and 50  $\mu$ J at 355 nm
- Telescope: 20-cm diameter, off-axis parabola
- Telescope FOV: 100  $\mu$ rad, full angle
- Raw data resolution: 1/10 s (30 m  $\times$  200 m horizontal)
- Processed data resolution: 1 s (30 m  $\times$  200 m horizontal)
- Instrument weight: approximately 350 lbs
- Duration: Up to 36 h
- Flight altitude: 50,000–60,000 ft

### Principal Investigator

Matthew J. McGill  
 NASA's Goddard Space Flight Center  
[Matthew.J.McGill@nasa.gov](mailto:Matthew.J.McGill@nasa.gov)

### Co-Investigators

John Yorks  
 NASA's Goddard Space Flight Center  
 Dennis Hlavka  
 Science Systems and Applications, Inc.  
 Andrew Kupchock  
 Science Systems and Applications, Inc.  
 Patrick Selmer  
 Science Systems and Applications, Inc.  
 Steve Palm  
 Science Systems and Applications, Inc.  
 Rebecca Pauly  
 Science Systems and Applications, Inc.

### Science Questions for Future Campaigns

- How are clouds, particularly cirrus and subvisual cirrus, affecting radiative balance?
- How are aerosols transported from the source region to other areas?
- How are clouds and aerosols interacting?

### Campaigns

GloPac was the first field campaign for the NASA Global Hawk during February – March 2010. UAV-CPL was a critical component of the GloPac campaign, as well as HS3 and ATTREX EVS projects.

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# GLOW

## *Goddard Lidar Observatory for Winds*



The GLOW mobile Doppler lidar measures wind profiles from the surface into the stratosphere. The two-axis scanner (on the roof) allows full-sky scanning of the lidar

### Key GLOW Facts

- Heritage: Double Edge Wind Lidar, and ZEPHYR New Millennium Program.
- GLOW is a mobile system for determining vertical profiles of wind from the Doppler-shifted frequency of the laser signal scattered back towards the lidar. Profiles of wind speed and direction are produced.
- GLOW participated in several field experiments including the International H<sub>2</sub>O Project (IHOP) and Plains Elevated Convection at Night (PECAN).
- GLOW currently operates at the Howard University Research Facility in Beltsville, Maryland.
- Nominal Field Configuration: Step stare scanning in azimuth (0–360 deg) with fixed elevation angle (0–90 deg).
- GLOW URL: <http://glow.gsfc.nasa.gov>

### Description

The Goddard Lidar Observatory for Winds (GLOW) is a mobile wind lidar system utilizing direct detection Doppler lidar techniques for measuring wind profiles up to 35 km. The GLOW mobile lidar system has a twofold purpose: First, to provide wind profile measurements from the surface into the stratosphere for use in scientific measurement programs, and second, as a testbed for validating the performance of new technologies and measurement techniques proposed for use in future spaceborne applications.

### GLOW Data Products

- Range resolved scans (PPI, RHI) of radial wind speed
- Vertical Profiles of u, v, w component winds and wind speed, and direction

- Coverage: 0.1 to 30 km
- Minimum range resolution: 40 m
- Accuracy: 0.5 to 3 m/s

### GLOW Parameters

- Laser Wavelengths 355 nm
- Laser Energy/Pulse: 50 mJ @ 355nm
- Pulse Repetition Rate: 50 Hz
- Telescope/scanner aperture: 45 cm
- FOV: 0.2 mrad

### Principal Investigator

Bruce Gentry  
NASA's Goddard Space Flight Center  
[Bruce.M.Gentry@nasa.gov](mailto:Bruce.M.Gentry@nasa.gov)

### GLOW Team Members

Huailin Chen  
Science Systems and Applications, Inc.  
Belay Demoz  
UMBC JCET  
Gerry McIntire  
SGT  
Kevin Vermeesh  
Science Systems and Applications, Inc.

### Science Questions for Future Campaigns

How do clouds and aerosols impact the molecular Doppler lidar wind measurement?

Can wind profile observations through the tropopause improve understanding of tropospheric/stratospheric exchange?

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Active Remote-Sensing Systems  
Radar



# CRS

## Cloud Radar System



CRS instrument and antenna located in the tail section of an ER-2 SuperPod. The antenna points at nadir.

### Key CRS Facts

- Heritage: Second generation ER-2 instrument based on the ER-2 Doppler Radar (EDOP). Several other ground-based and lower-altitude airborne W-band radars are present in the community.
- A Doppler cloud radar system at W-band (94 GHz) developed for the ER-2 aircraft. Vertical profiles of radar reflectivity and hydrometeor motions are produced.
- The first deployment of CRS was in CRYSTAL–FACE during Summer 2002. Participated in TCSP, TC4, and CLASIC.
- Nominal aircraft configuration: The CRS system is configured for operation in the unpressurized tailcone of an ER-2 wing SuperPod. The single nadir antenna radiates through a 20 in × 20 in opening in the SuperPod.
- CRS URL: <http://har.gsfc.nasa.gov>

### Description

Cloud radars at millimeter wavelengths have demonstrated high sensitivity to clouds. These radars, at frequencies above 35 GHz, have been used in various ground-based and airborne studies that focus on the effect of clouds on the Earth's radiation budget. The CloudSat mission has 94 GHz cloud radar as its primary instrument. Cloud radars have strong synergism with profiling backscatter lidars which have higher sensitivity to cirrus and other clouds, but whose signal becomes considerably more attenuated in thicker, more opaque clouds. The ER 2 platform provides the best satellite-like view of the tropospheric clouds and along with CRS, has a powerful suite of cloud remote-sensing instruments. CRS is a W-band (94 GHz) cloud radar that is a fully coherent Doppler system with a fixed nadir pointing beam, which maps

out Doppler winds and reflectivities in the vertical plane. CRS, combined with the existing CPL backscatter lidar system on the ER-2, provided a testbed for algorithms and a validation platform for the CloudSat and Calipso missions, as well as for the future ACE Decadal Survey Mission.

### CRS Data Products

- Vertical profiles: radar reflectivity, hydrometeor and air vertical motions, ice and liquid water content, cloud layer locations
- Measurement interval: 37.5 m vertical, 100 m along track
- Measurement accuracy: reflectivity of 1.0 dBZ; winds at 0.5 m/s

### CRS Parameters

- Transmitter peak power: 30 W
- Frequency: 94.155 GHz
- Pulse repetition frequency: 4000/5000 Hz (staggered)
- Pulse width: 20  $\mu$ s (pulse compression), 0.5  $\mu$ s (short pulse)
- Receiver IF: 60 MHz
- Dynamic range: 80 dB
- Minimum detection signal:  $-28$  dBZ (at 10 km range)

### Principal Investigator

Gerald M. Heymsfield  
 NASA's Goddard Space Flight Center  
[Gerald.M.Heymsfield@nasa.gov](mailto:Gerald.M.Heymsfield@nasa.gov)

### CRS Team Members

Matthew McLinden  
 NASA's Goddard Space Flight Center  
 Lihua Li  
 NASA's Goddard Space Flight Center  
 Michael Coon  
 NASA's Goddard Space Flight Center

### Science Questions for Future Campaigns

- What are the particle sizes and ice contents in thunderstorm-generated cirrus?
- What is relation between convective intensity and the extent and depth of cirrus anvils generated by the convection?
- What are the growth mechanisms in cirrus clouds?

- What is the best approach for obtaining information on the cirrus properties using radar, lidar, and microwave, and visible, near-infrared radiometers?

## Future Campaigns

- GOES-16 validation flights
- Future EVS flights
- Future Decadal Mission and other Earth Science missions

## References

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## D3R

### *Dual-polarization, Dual-frequency, Doppler Radar*



NASA's Dual-polarization, Dual-frequency, Doppler Radar (D3R), currently deployed at NASA's Wallops Flight Facility on Wallops Island, VA.

### Key D3R Facts

- The dual-frequency, dual-polarized Doppler radar (D3R) was jointly developed by NASA's Goddard Space Flight Center, Colorado State University, and Remote Sensing Solutions specifically for NASA's Precipitation Measurement Mission.
- D3R utilizes the same bands (Ka and Ku) as the Dual-frequency Precipitation Radar (DPR) onboard the Global Precipitation Measurement (GPM) satellite.
- D3R consists of a solid-state transmitter and receiver, which allows full tuning of the generated signal.
- D3R is an easily transportable radar as it resides on a trailer, but is usually located at a single site for specific campaigns.
- D3R has supported several GPM field campaigns, including: the Iowa Flood Studies (IFLOODS, 2013); Integrated Precipitation/Hydrology Experiment (IPHEX; 2014) and the Olympic Mountain Experiment (OLYMPEX; 2015-2016).
- D3R URL: <https://wallops-prf.gsfc.nasa.gov/Radar/D3R>

### Description

The D3R employs a frequency-diversity waveform consisting of three frequency-spaced sub-pulses to achieve its sensitivity and minimum range. The three pulses and their associated pulse duration are long (40 s), medium (20 s), and short (1 s). The long and medium pulses are nonlinear frequency-modulated signals with an overall signal bandwidth of 3.6 MHz [Vega *et al.*, 2014]. The D3R frequency diversity waveforms have a restriction requirement on the transmit waveforms spectra to avoid overlapping of

the sub-pulse frequency bands. The digital receiver filter utilizes a minimum integrated side lobe level (ISL) filter which has been shown to be excellent for weather radar applications [Bharadwaj and Chandrasekar, 2012]. This is a mobile, surface-based radar that has been deployed in numerous field campaigns in Canada, Iowa, South Carolina, Washington, and Wallops Flight Facility.

### D3R Data Products

- Radar Reflectivity
- Radial Velocity
- Differential Reflectivity
- Differential Phase
- Cross-correlation
- Derived products: precipitation rate, hydrometeorID, rain type

### D3R Parameters

- Frequency: Ku (13.91 GHz), Ka (35.56 GHz)
- Parabolic reflector: Ku (1.83 m); Ka (0.71 m)
- Beam width: Ku (0.85°); Ka (0.90°)
- Scan patterns: PPI, RHI, vol & sector, vertical
- Pulse width: 0.8 or 2.0 s, selectable
- Peak Power: Ku (200 W); Ka (40 W per H/V)
- Transmitter/Receiver: Solid-state

### D3R Team Members

Manuel Vega  
 NASA's Goddard Space Flight Center  
[Manuel.Vega@nasa.gov](mailto:Manuel.Vega@nasa.gov)  
 V. Chandrasekar  
 Colorado State University  
[Chandra@colosate.edu](mailto:Chandra@colosate.edu)  
 David B. Wolff  
 NASA's Wallops Flight Facility  
[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

### Science Questions for Future Campaigns

- What is the particle size and velocity distribution of remotely sensed volumes of precipitation?
- How do ground-based observations of precipitation at Ka- and Ku-band compare to those made by the GPM DPR?

### Future Campaign

D3R has supported several GPM field campaigns, including: the Iowa Flood Studies (IFLOODS, 2013); Integrated

Precipitation/Hydrology Experiment (IPHEX; 2014) and the Olympic Mountain Experiment (OLYMPEX; 2015-2016). When not deployed for remote field campaigns, D3R is deployed and operated to support the GV activities of the Wallops Precipitation Research Facility on the main base of NASA Wallops Flight Facility. D3R is also available for other studies and collaborations.

D3R will be deployed in South Korea to support the Interactive Collaborative Experiment – Pyeongchang Olympic & Paralympic Games 2018 (ICE-POP 2018) for the winter of 2018.

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## EXRAD

### ER-2 X-Band Radar



Aft view of EXRAD nose showing transmitter and data system.

### Key EXRAD Facts

- Heritage: EXRAD is an updated scanning version of the ER-2 Doppler Radar (EDOP) that participated in CAMEX 1, 2, 3, and 4; Houston Precipitation Experiment (HOPEX); Texas and Florida Underflight Experiment (TEFLUN) A and B, TRMM LBA, CRYSTAL-FACE, TCSP, and TC4.
- EXRAD was originally designed for the NASA Global Hawk and then was reconfigured to fly on NASA ER-2 in 2014.
- The first science campaign was in the Integrated Precipitation and Hydrology Experiment (IPHEX) sponsored by GPM Ground Validation.
- Nominal aircraft configuration: The EXRAD system is configured for operation in a refurbished military radar nose for the ER-2. One scanning and one fixed beam are used; one is pointing at nadir and the other is conical or cross-track scanning.
- EXRAD URL: <http://har.gsfc.nasa.gov>

### Description

Airborne weather radar systems have played an important role in studying mesoscale convective systems (MCSs) and other mesoscale and cloud-scale phenomenon. These radars have provided important information on kinematic and dynamical aspects of isolated thunderstorms, MCSs, and hurricanes.

Mesoscale phenomena often have long lifetimes (12–24 h), have large spatial extent (several hundred kilometers), and advect considerable distances over their lifetime. As a result, ground-based radars may not be suitably located for high-resolution measurements of MCSs and hurricanes because of either large radar slant ranges, or from the radars or that the MCSs are located over open ocean. In addition, most airborne

weather radars are side-looking and do not provide coverage of the top portions of weather systems.

The system operates at X-band (9.6 GHz) and is a conventional short-pulse coherent Doppler weather radar with fixed nadir and scanning beams. The nadir beam maps out Doppler winds and reflectivities in the vertical plane along the aircraft motion vector, the scanning beam provides horizontal winds in the cross-track direction. Wind retrieval methods for the scanning beam are similar to those used for the HIWRAP radar.

### EXRAD Data Products

- Vertical profiles: Radar reflectivity, hydrometeor vertical motions, u, w wind components, rain rate, hail, and melting layer discrimination.
- Measurement interval: 37.5 m vertical, 100 m along-track
- Measurement accuracy: Reflectivity at 0.5 dBZ; winds 0.5 m/s

### EXRAD Parameters

- Transmitter peak power: 10 kW
- Split between two antennae
- Radio Frequency: 9.6 GHz
- Pulse repetition frequency: 4000/5000 Hz
- Pulse width: 1  $\mu$ s
- Receiver IF: 60 MHz
- Dynamic range: >90 dB

### EXRAD Field Campaigns

- Future EVS flights
- Future Decadal Mission and other Earth Science missions

### Principal Investigator

Gerald M. Heymsfield  
NASA's Goddard Space Flight Center  
[Gerald.M.Heymsfield@nasa.gov](mailto:Gerald.M.Heymsfield@nasa.gov)

### EXRAD Team Members

Lihua Li  
NASA's Goddard Space Flight Center

Matthew McLinden  
NASA's Goddard Space Flight Center

Michael Coon  
NASA's Goddard Space Flight Center

Lin Tian  
GESTAR

## Science Questions for Future Campaigns

What is the relation between convective intensity and the extent and depth of cirrus anvils generated by the convection?

What is the distribution of rainfall in landfalling hurricanes?

How well are hydrometeor particle-size distributions represented in TRMM algorithms?

How does overshooting convection interact with the lower stratosphere?

## References

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# HIWRAP

## High-altitude Imaging Wind and Rain Airborne Profiler



Caption

### Key HIWRAP Facts

- Heritage: HIWRAP is a completely new instrument developed under the NASA IIP. It was designed specifically for the Global Hawk.
- It is a conical scanning Doppler radar with two frequencies (Ku- and Ka-band) and two incidence angles (30 and 40 degrees).
- The first deployment of HIWRAP was for the Genesis and Rapid Intensification Processes (GRIP) campaign in 2010.
- Nominal Aircraft Configuration: HIWRAP is configured for operation in the zone 25 unpressurized radome area in the Global Hawk. The single dual-frequency, dual-beam aperture views through the Global Hawk deep radome. HIWRAP will be reconfigured for a nadir-pointing mode on the NASA ER-2.
- HIWRAP URL: <http://har.gsfc.nasa.gov/>

### Description

Wind measurements are crucial for understanding and forecasting tropical storms since they are closely tied to the overall dynamics of the storm. The High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) is a dual-frequency (Ka- and Ku-band), dual-beam (300 and 400 incidence angle), conical scan, solid-state transmitter-based system, designed for operation on the high-altitude (20 km) Global Hawk UAV. With the inclusion of Ka-band, HIWRAP will be able to image the winds through volume backscattering from clouds and precipitation, enabling it to measure the tropospheric winds above heavy rain at high levels. It will also measure ocean surface winds through scatterometry, similar to QuikScat. These measurements from higher altitudes above storms, are useful for providing higher spatial and temporal resolution than obtained by current satellites and

lower-altitude instrumented aircraft. HIWRAP is configured for flying autonomously on the NASA Global Hawk. It completed its first deployment during the GRIP field campaign in 2010.

### HIWRAP Data Products

- 3D structure below aircraft: radar reflectivity, horizontal winds, ice and liquid water content.
- Ocean surface winds: over conical scan swath
- Measurement interval: 150 m in range initially, 37.5 m future, 600 m along-track
- Measurement accuracy
- Reflectivity: 1.0 dBZ; winds 0.5 m/s

### HIWRAP Parameters:

#### Ku-band

- Radio frequency: inner beam 13.91 GHz; outer beam 13.47 GHz
- Peak transmit power: 25 W
- 3 dB beamwidth: 3.0 degrees
- Polarization: V (outer beam), H (inner beam)
- Dynamic range: >65 dB
- Min. detect. reflectivity: 0 dBZe (60 m res 10 km range)
- Doppler velocity: 0-150 m/s (uncertainty <2 m/s for SNR>10)
- Scanning: conical scan 10–30 rpm

#### Ka-band

- Radio frequency: inner beam 35.56 GHz; outer beam 33.72 GHz
- Peak transmit power: 8 W
- 3 dB beamwidth: 1.2 degrees
- Polarization: V (outer beam), H (inner beam)
- Dynamic range: >65 dB
- Min. detect. reflectivity: -5 dBZe (60-m res 10-km range)
- Doppler velocity: 0–150 m/s (uncertainty <2 m/s for SNR>10)
- Scanning: conical scan 10–30 rpm

### Principal Investigator

Gerald M. Heymsfield  
 NASA's Goddard Space Flight Center  
[Gerald.Heymsfield@nasa.gov](mailto:Gerald.Heymsfield@nasa.gov)

## HIWRAP Team Members

Lihua Li

NASA's Goddard Space Flight Center

Matthew Mclinden

NASA's Goddard Space Flight Center

Michael Coon

NASA's Goddard Space Flight Center

Lin Tian

University of Maryland, Baltimore County Goddard Earth Sciences and Technology Center

Stephen Guimond

Earth System Science Interdisciplinary Center

### Science Questions

- How does hurricane vortex spin-up during rapid intensification?
- Where does vortex originate during genesis of tropical cyclones?
- Do convective bursts and hot towers help intensify tropical storms?
- What are best algorithms for dual-frequency microphysics retrievals?

## Field Campaigns

- Future EVS flights
- Future Decadal Mission and other Earth Science missions

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Li, Lihua, G. Heymsfield, J. Carswell, D. Schaubert, M. McLinden, J. Creticos, S. Guimond, M. Vega, M. Perrine, and M. Coon, J.I. Cervantes, M. Vega, S. Guimond, Lin Tian, and A. Emory, 2015: Development of the NASA High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP). *IEEE Transactions on Geosci. and Remote Sens.*, 54, 298–310.

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# MRR

## *Micro Rain Radar*



*Small, portable K-band radar*

### Key MRR Facts

- The Micro Rain Radar (MRR) is a small and easy to operate K-Band Radar
- Vertical profiles of rain rate and liquid water content up to 6 km (3.7 miles)
- Computes detailed drop size and distribution output
- User adjustable averaging intervals and height resolution
- Adjustable averaging intervals 10–3600 s
- Height range steps between 10 m to 200 m (600 ft) with 30 range gates
- MRR URL: [www.biral.com/product/micro-rain-radar/](http://www.biral.com/product/micro-rain-radar/)

### Description

The Micro Rain Radar (MRR) is a small, portable, and easy to operate. It can be used for now-casting of precipitation, i.e., it will detect the start of rain from ground level to high above the radar several minutes before the start of rain at ground level. It is a highly reliable system suitable for use in remote and extreme environments, requiring minimal maintenance, and is well adapted for long term unattended operation.

Statistically stable drop size distributions can be derived within a few seconds due to the size of the scattering volume. The MRR can detect very small amounts of precipitation (below the threshold of conventional rain gauges) detecting drop sizes between 0.25 mm and 4.53 mm. This covers the size range of atmospheric precipitation drops as larger

drops in the atmosphere are affected by the air resistance as they fall and will split into smaller drops. The droplet number concentration in each drop-diameter bin is derived from the backscatter intensity in each corresponding frequency bin

### MRR Parameters

- Vertical profiles of rain rate and liquid water content up to 6 km (3.7 miles)
- Computes detailed drop size and distribution output
- User adjustable averaging intervals and height resolution
- Adjustable averaging intervals 10–3600 s
- Height range steps between 10–200 m (600 ft) with 30 range gates

### Support and Future Plans

The MRR2 owned by NASA's Wallops Flight Facility currently supports GPM Ground Validation. It has been used in numerous GPM and other field campaigns and is deployed at the Wallops Precipitation Research Facility when not sent elsewhere.

### Instrument Science Team Members

David B. Wolff  
NASA's Wallops Flight Facility  
[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

Walter A. Petersen  
NASA's Marshall Space Flight Center  
[Walt.Petersen@nasa.gov](mailto:Walt.Petersen@nasa.gov)

# NPOL

## NASA dual-POLarization Radar



NASA's NPOL radar deployed during the Iowa FLOODs Study (IFLOODS) in central Iowa (May–June 2013). The antenna's diameter is 8.5 m (28 feet) and operates at S-band (10 cm) with an output power in excess of 800 kW

### The Key NPOL Facts

- NPOL was built by NASA using some parts from the “mile-high” radar previously owned by the National Center for Atmospheric Research (NCAR).
- The antenna was built specifically for NASA and is capable of pointing accuracies of nearly  $0.1^\circ$ .
- The entire NPOL system can be packed into four sea-containers and shipped for remote operations using five 18-wheeler trucks.
- NPOL can run on commercial power, but has its own generator that can be used for particularly remote operations, as was done during a field campaign in Washington State during the winter of 2015–2016.
- NPOL is the only currently active, transportable S-band radar of its size in the world.
- NPOL URL: <https://wallops-prf.gsfc.nasa.gov/Radar/NPOL>

### Description:

The National Aeronautics and Space Administration, Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, Virginia has deployed an integrated S-band (2700–2900 MHz) dual-polarized antenna system. The antenna system consists of a parabolic reflector, dual-polarized feed horn, pedestal, drive motors, and servo-amplifiers. The system is capable of emitting and receiving both horizontal and vertical linearly polarized RF energy.

The antenna system is used as an integrated transportable meteorological research radar, and all of the components were constructed so that they can be shipped in standard

ISO sea-containers with outside dimensions of  $2.44\text{ m} \times 2.44\text{ m} \times 6.1\text{ m}$  ( $8\text{ ft} \times 8\text{ ft} \times 20\text{ ft}$ ). The primary objective of the radar system is to collect meteorological research quality reflectivity, Doppler and polarimetric data at various locations in the world. The radar system is capable of handling up to 1.0 megawatts of peak pulsed power with pulse widths up to 2 microseconds and pulse recurrence frequencies up to 1200 pulses per second. The antenna can be scanned in both the azimuth and elevation planes.

This high-performance radar is required for accurate measurements of dual-polarimetric quantities and will be used to provide accurate estimates of precipitation rates and hydrometeor types that in turn will be used to help validation space-based retrievals from the GPM-core and other satellites.

### NPOL Observables

- Radar reflectivity
- Radial velocity
- Differential reflectivity
- Differential phase
- Cross-correlation
- Derived products: precipitation rate, hydrometeor ID, rain type

### NPOL Parameters

- Frequency: 2700–2900 MHz tunable
- Reflector type: 8.5 m prime-focus parabolic
- Beam width: 0.93 (0.94) @ +3 (+4) dB H (V)
- Scan patterns: PPI, RHI, col & sector, vertical
- Pulse width: 0.8 or 2.0 s, selectable
- Peak Power: 425 kW H & V channel
- PRF: 250–1200 Hz

### Participating Team Members

David B. Wolff  
NASA's Wallops Flight Facility  
[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

Walter A. Petersen  
NASA's Marshall Space Flight Center  
[Walt.Petersen@nasa.gov](mailto:Walt.Petersen@nasa.gov)

David A. Marks  
Science Systems & Applications, Inc.  
[David.A.Marks@nasa.gov](mailto:David.A.Marks@nasa.gov)

## Science Questions

- What are the rain rates of remotely observed precipitation systems?
- What are the particle types (e.g. snow, hail, graupel, large drops, etc.)?
- Are there tornadoes or other dangers in a remotely sensed storms?
- What is the vertical distribution of hydrometeors and how do the ground-based radar rain rate estimates compare to GPM satellite estimates?

## Previous and Future Campaigns

NPOL has supported several GPM field campaigns, including:

- Mid-Continental Convective Cloud Experiment (MC3E, 2011)
- Iowa Flood Studies (IFLOODS, 2013);
- Integrated Precipitation/Hydrology Experiment (IPHEX; 2014)
- Olympic Mountain Experiment (OLYMPEX; 2015-2016).  
When not deployed for remote field campaigns

NPOL is currently deployed and operates to support the ground validation activities at the Wallops Precipitation Research Facility from a field in Newark, MD, which is about 38 km north-northeast from NASA's Wallops Flight Facility. NPOL is also available for other studies and collaborations.

# X-BADGER

## *X-Band Atmospheric Doppler Ground-based Radar*



The X-BADGER radar system with digital receiver on top, data system on the middle rack, and transmitter on the bottom with copper waveguide for the two beams on the left.

### Key X-BADGER Facts

- Heritage: X-BADGER began as the ER-2 Doppler (EDOP) radar (PI Gerald Heymsfield). The system was updated to include a solid-state power amplifier and digital receiver and then moved to a research trailer to transmit up from the surface instead of down from a high-altitude aircraft.
- Two fixed beams are used: one points vertically and the other is 20 deg forward of the vertical beam. Profiles of radar reflectivity, Doppler velocity, and spectrum width are produced. The forward beam can also provide measurements of the linear depolarization ratio.
- Participated in PECAN (2015) and is currently deployed at the Precipitation Research Facility at NASA WFF.

### Description

From 2013 to 2015, the X-BADGER system was built at NASA's Goddard Space Flight Center primarily for long-term precipitation and microphysics studies for the Global Precipitation Measurement (GPM) mission ground validation, but also for short-term field campaign deployments. The 9.6 GHz radar is housed in a custom-built research trailer that is lightweight, rugged, and mobile for easy field campaign deployment. The radar has two beams: one zenith and one dual-polarized 20 deg off-zenith "forward-pointing" beam for comparison of radar reflectivity and cloud microphysics. The radar evolved from the ER-2 Doppler (EDOP) radar design, but has been upgraded to include a 1000W GaN solid-state power amplifier and a Remote Sensing Solutions iRAP digital receiver. X-BADGER addresses the absence of 3-cm wavelength radars, and in particular relatively non-attenuating precipitation profiling radars, in the current NASA ground validation radar suite. The team incorporated innovative

methods to keep costs low while at the same time developing a state-of-the-art profiling radar.

The system operates at X-band (9.6 GHz) and is a fully developed, coherent Doppler weather radar with fixed vertical- and forward-pointing beams that map out Doppler winds and reflectivities in the vertical plane. In addition, the forward beam provides linear depolarization measurements, which are useful in discriminating microphysical characteristics of the precipitation

### X-BADGER Data Products

- Vertical profiles: Radar reflectivity, hydrometeor vertical motions, rain rate, hail, and melting layer discrimination.
- Vertical resolution: 37.5 m
- Measurement accuracy: Reflectivity 1 dBZ; winds 1 m/s

### X-BADGER Parameters

- Transmitter peak power: 900 W
- Split between 2 antennae
- Radio Frequency: 9.6 GHz
- Pulse repetition frequency: 4400 Hz
- Pulse width: 0.5  $\mu$ s
- Receiver IF: 60 MHz
- Dynamic range: >90 dB

### Principal Investigator

Amber E. Emory  
NASA's Goddard Space Flight Center  
[Amber.Emory@nasa.gov](mailto:Amber.Emory@nasa.gov)

### X-BADGER Team Members

Michael Coon  
NASA's Goddard Space Flight Center  
Stephen Nicholls  
University of Maryland Baltimore County, JCET

### Science Questions for Future Campaigns

- How does the melting layer evolve in time?
- What differences can be detected with elevated convection?
- How well are hydrometeor particle-size distributions represented in satellite precipitation algorithms?
- What type/amount of precipitation do horizontally scanning radars miss in mountain valleys due to beam blockage?

## Future Campaigns

Northern Vietnam in late December 2017, integrated into ACHIEVE trailer, located in the aerosol-cloud confluence region, together with various regional contributing UAVs and IMPACT in profiling and *in situ*, respectively, the atmospheric state parameters and aerosol distribution.

## References

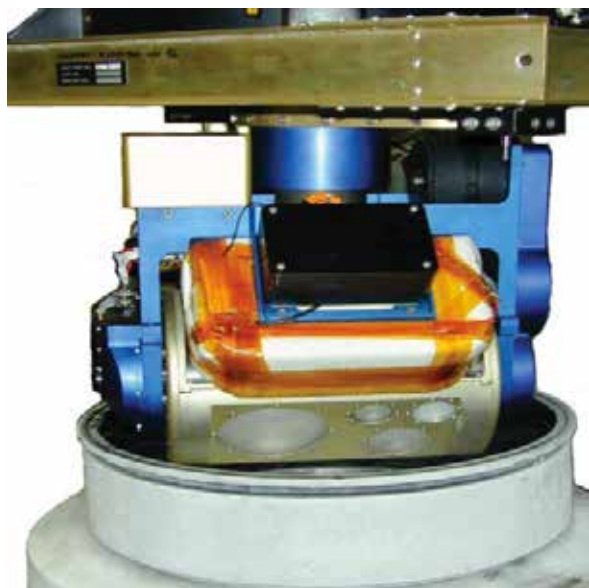
Preliminary Data Analysis from the Plains Elevated Convection At Night (PECAN) field campaign using NASA's X-Band Atmospheric Doppler Ground-based Radar (X-BADGER) System—Poster presented at the 37th AMS Radar Meteorology Conference

Passive Remote-Sensing Systems  
**Microwave**



# CoSMIR

## *Conical Scanning Millimeter-wave Imaging Radiometer*



*CoSMIR shown in laboratory calibration with liquid nitrogen. The four antennae apertures correspond to the four visible receivers.*

### Key CoSMIR Facts

- Heritage: An improved version of GSFC airborne MIR (Millimeter-wave Imaging Radiometer), capable of acquiring radiometric data over the frequency range of 50–183 GHz in conical or across-track scan modes or both.
- Onboard the NASA ER-2 aircraft, performed calibration/validation of the high-frequency channels of the Special Sensor Microwave Imager/Sounder (SSMIS), a new generation orbiting microwave imager/sounder for the DMSP (Defense Meteorological Satellite Project) F-16 satellite during 2004–2005.
- Modified to conform to high-frequency channels of the GMI (Global Precipitation Measurement mission Microwave Imager) and to acquire data in field campaigns for algorithm development of precipitation retrievals.
- Flew in GPM field campaigns MC3E in 2011, GCPEX in 2012, IPHEX in 2014, and OLYMPEX in 2015.
- Nominal Field Configuration: CoSMIR was designed to operate onboard the NASA ER-2 aircraft but has been installed and flown on the DC-8 aircraft and may be flown in other aircraft with an appropriate nadir port. As the GMI airborne simulator for GPM field campaigns, a new scan mode to acquire both conical and across-track scan data simultaneously in a given flight was implemented to satisfy the requirements of the PMM algorithm development team.

### Description

CoSMIR is an airborne, nine-channel, total power radiometer that was originally developed for the calibration/validation of the SSMIS. When first completed in 2003, the system had four receivers near 50, 91, 150 and 183 GHz that measured horizontally polarized radiation at the frequencies of 50.3, 52.8, 53.6, 150, 183.3±1, 183.3±3, and 183.3±6.6 GHz, and dual-polarized radiation at 91.665 GHz from onboard the high-flying NASA ER-2 aircraft. All receivers and radiometer electronics are housed in a small cylindrical scan head (21.5 cm in diameter and 28 cm in length) that is rotated by a two-axis gimballed mechanism capable of generating a wide variety of scan profiles. Two calibration targets, one maintained at ambient (cold) temperature and another heated to a hot temperature of approximately 328 K, are closely coupled to the scan head and rotate with it about the azimuth axis. Radiometric signals from each channel are sampled at 0.01-second intervals. These signals and housekeeping data are fed to the main computer in an external electronics box.

In 2004–2005 CoSMIR flew for calibration/validation of the SSMIS off the coastal areas of California. From 2011 to 2015 CoSMIR served as an airborne high-frequency simulator for GMI in four GPM field campaigns. This required changing the frequency and polarization for some channels to more closely match GMI. After modification, the nine channels are at center frequencies of 50.3, 52.6, 89, 165.5, 183.3±1, 183.3±3, and 183.3±7 GHz. 89 and 165.5 channels are dual-polarized (V and H) while the other channels are horizontal (H) polarized only

### CoSMIR Data Products

- Well-calibrated radiometric data between 50 and 183 GHz with accuracy on the order of ±1 K
- Through various retrieval algorithms, the acquired data can be used to estimate snowfall rates, water vapor profiles (with known temperature profiles), light precipitation, and shallow snow cover on the ground

### CoSMIR Parameters

- Frequencies: 9 channels at 50.3, 52.6, 89 (H & V), 165.5 (H & V), 183.3±1, 183.3±3, and 183.3±7 GHz
- Scan mode: Programmable for conical scan at angles between 0–53.6°, across scan, or a combination of both
- In-flight calibration: two external targets at ~328 K and at ambient temperature (~ 250 K at ER-2 aircraft cruising altitudes)

- Scan head: a cylinder 21.5 cm in diameter and 28.0 cm long
- FOV:  $\sim 4^\circ$  beam width (gives a nadir footprint at the surface of about 1.4 km at ER-2 cruising altitude of 20 km)

### Principal Investigator

Rachael Kroodsmas  
ESSIC, University of Maryland  
NASA's Goddard Space Flight Center  
[Rachael.A.Kroodsmas@nasa.gov](mailto:Rachael.A.Kroodsmas@nasa.gov)

### Co-Investigators/Team Members

Matthew Fritts  
SGT, Inc.  
[Matthew.A.Fritts@nasa.gov](mailto:Matthew.A.Fritts@nasa.gov)

Paul Racette  
NASA's Goddard Space Flight Center  
[Paul.E.Racette@nasa.gov](mailto:Paul.E.Racette@nasa.gov)

### Science Questions

- What advances can be made in snowfall retrieval algorithms for GPM, particularly with the 166 GHz dual-polarization channel?
- How can we improve cloud and precipitation studies by combining CoSMIR measurements with submillimeter-wave frequencies (e.g. CoSSIR)?

### Planned Campaigns

There are no campaigns currently scheduled.

### References

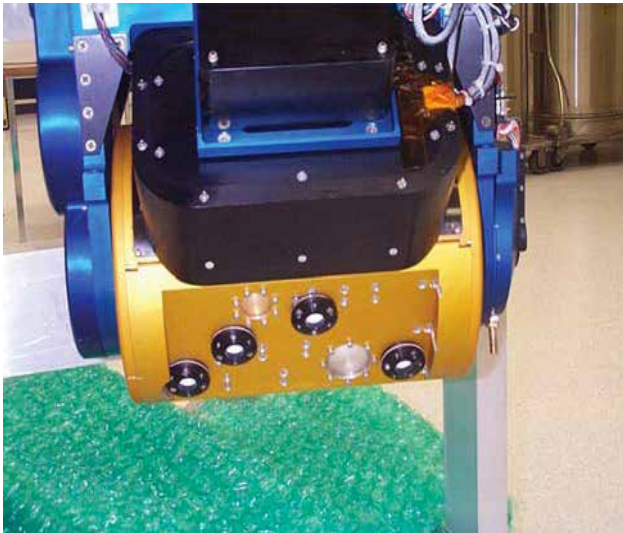
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Wang, J.R., G.M. Skofronick-Jackson, M.R. Schwaller, C.M. Johnson, W.B. Monosmith, and Z. Zhang, 2013: Observations of storm signatures by the recently modified conical scanning millimeter-wave imaging radiometer, *IEEE Trans. Geosci. Remote Sens.*, 51, 411-424.

# CoSSIR

## Compact Scanning Submillimeter-wave Imaging Radiometer



CoSSIR shown in system functional check. The five antenna apertures corresponding to the five receivers are clearly displayed

### Key CoSSIR Facts

- **Heritage:** An instrument implemented for the measurements of ice clouds. It has five receivers covering the frequency range of 183-874 GHz, that are housed in a compact cylinder 21.5 cm in diameter and 28.0 cm long. All receivers at frequencies > 183 GHz were developed under the Small Business Innovation Research (GSFC SBIR) program.
- Flown on the NASA ER-2 aircraft during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers– Florida Area Cirrus Experiment (CRYSTAL–FACE) in 2002 and the Tropical Composition, Cloud and Climate Coupling (TC4) experiment in 2007.
- Modified to serve as an airborne simulator for the Submillimeter-Wave and Infrared Ice Cloud Experiment (SIRICE) and to acquire data in field campaigns for algorithm development of ice-cloud parameter retrievals.
- **Nominal Field Configuration:** CoSSIR is designed to operate onboard the NASA ER-2 aircraft, but it has also been installed in WB-57 aircraft. In both CRYSTAL–FACE and TC4, the system acquired data mainly in conical scan mode. After these experiments, a new scan mode to acquire both conical and across-track scan data simultaneously during a given flight was successfully implemented and tested to satisfy future science requirements.

### Description

CoSSIR is an airborne, twelve-channel total power imaging radiometer that was mainly developed for the measurements of ice clouds. However, it can be used for estimation of water vapor profiles and snowfall rates. When first completed and flown in the CRYSTAL–FACE field campaign during July 2002, the system had 15 channels at different frequencies from those listed above. All the receivers and radiometer electronics are housed in a small cylindrical scan head (21.5 cm in diameter and 28 cm in length) that is rotated by a two-axis gimballed mechanism capable of generating a wide variety of scan profiles. Two calibration targets, one maintained at ambient (cold) temperature and another heated to a hot temperature of about 328 K, are closely coupled to the scan head and rotate with it about the azimuth axis. Radiometric signals from each channel are sampled at 0.01 second intervals. These signals and housekeeping data are fed to the main computer in an external electronics box.

### CoSSIR Data Products

- Well-calibrated radiometric data between 183 and 874 GHz with accuracy on the order of  $\pm 1$  K.
- Through various retrieval algorithms, the acquired data can be used to estimate ice cloud parameters (ice water path and mean particle size), snowfall rates, and water vapor profiles (with known temperature profiles).

### CoSSIR Parameters

- **Frequencies:** 12 channels at  $183.3\pm 1$ ,  $183.3\pm 3$ ,  $183.3\pm 325\pm 1.5$ ,  $325\pm 3.5$ ,  $325\pm 9.5$ ,  $448\pm 1.4$ ,  $448\pm 3$ ,  $448\pm 7.2$  642 (H and V), and 874 GHz
- **Scan modes:** programmable for conical scan at angles between  $0$ - $53.6^\circ$ , across scan, or a combination of both
- **In-flight Calibration:** two external targets at  $\sim 328^\circ$  K and at ambient temperature ( $\sim 250$  K at ER-2 aircraft cruising altitudes)
- **Scan head:** a cylinder 21.5 cm diameter and 28.0 cm long
- **FOV:**  $\sim 4^\circ$  beam width (gives a nadir footprint at the surface of about 1.4 km at ER-2 cruising altitude of 20 km)

## Principal Investigator

Rachael Kroodsma  
ESSIC, University of Maryland  
NASA's Goddard Space Flight Center  
[Rachael.A.Kroodsma@nasa.gov](mailto:Rachael.A.Kroodsma@nasa.gov)

## Co-Investigators / Team Members

Matthew Fritts  
SGT, Inc.  
Paul Racette  
NASA's Goddard Space Flight Center

## Science Questions

How can we improve cloud and precipitation studies by combining CoSSIR measurements with lower frequencies (e.g. CoSMIR)?

What advances can be made in ice cloud modeling using submillimeter-wave measurements?

What is the validity of ice cloud products from future spaceborne instruments with CoSSIR-like frequencies (e.g. METOP-SG)?

## Planned Campaigns

There are no campaigns currently scheduled.

## References

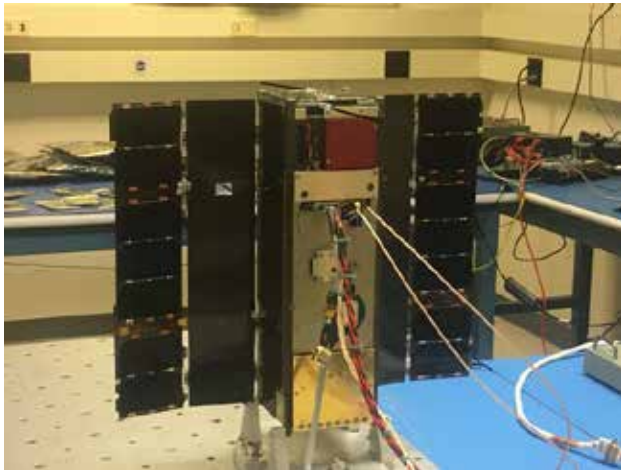
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# IceCube

## 883-GHz Cloud Ice Radiometer on CubeSat



*IceCube with solar panels deployed during its final I&T and system functional check in late 2016 at Wallops Flight Facility*

### Key IceCube Facts

- Heritage: Built upon NASA's ER-2 aircraft sensor, the Compact Scanning Submm-wave Imaging Radiometer (CoSSIR), IceCube seeks to raise the technology readiness level (TRL) of 883-GHz radiometer for future spaceflight mission. It is the first end-to-end CubeSat experiment led by GSFC.
- IceCube employs a novel radiometric calibration scheme involving a noise source in the receiver. Its goal is to achieve radiometric accuracy of 2K in a spaceflight environment using only space views and the pre-launch gain model.
- IceCube has no scanning mechanisms. It relies on the cubesat spin around the Sun vector ( $1.2^\circ$  per second) to provide periodic views between the Earth (atmosphere and clouds) and cold space (calibration). Having its solar panels facing the Sun all the time produces the maximum power for operation.
- To thermally stabilize the 883-GHz receiver temperature, IceCube attaches several paraffin packs around the instrument such that excessive heat is stored during daytime and released at night by the packs.
- IceCube is on a rideshare to the International Space Station (ISS), followed by a subsequent release from ISS for nominal 28-day mission operation.
- EoPortal Overview: IceCube  
<https://directory.eoportal.org/web/eoportal/satellite-missions/i/icecube>

### Description

Global cloud ice amount is important for understanding atmospheric radiation, dynamics, and precipitation processes, and yet it remains challenging to measure cloud ice accurately from space. Submillimeter (submm) wave remote sensing has great capability of penetrating ice clouds for mass measurements. IceCube is spaceflight demonstration of 883-GHz cloud ice radiometer on a 3U CubeSat, with a goal to mature the submm wave remote-sensing technology for future NASA's missions. The 883-GHz frequency is a spectral window whereby the radiation is highly sensitive to ice cloud scattering and interacts in depth with volume ice mass inside the cloud. IceCube is a collaborative endeavor between NASA's Goddard Space Flight Center and Virginia Diode Inc. (VDI), funded by NASA's Science Mission Directorate (SMD) and Earth Science Technology Office (ESTO).

### IceCube Data Products

- 883-GHz radiances with accuracy of  $\pm 2$  K
- Cloud-induced radiances
- Cloud ice above  $\sim 12$  km

### Cloud Radiometer Parameters

- Frequency: 883 GHz
- Channel bandwidth: 6 GHz
- Radiometric accuracy: 2K
- Radiometric precision:  $\sim 1$ K (1-s integration)
- Power/Mass/Volume: 7.8W / 0.9 kg / 1.3 U
- FOV:  $1.8^\circ$  beam width (13 km footprint at nadir)

### CubeSat Information

- Development period: 4/2014 – 12/2016
- Power/Mass/Volume: 20W max / 4.3 kg / 3 U
- Payload duty-cycle: 50% (day-on, night-off)
- Data rate: 70 MB/day
- Data downlink: UHF at WFF
- Attitude control: 11 arcsec (2 axes), 25 arcsec (3rd axis), star-tracker (night), sun sensor (day)
- Battery: 40 Wh
- Launch date: April 2017
- Orbit: ISS ( $\sim 405$  km,  $51.6^\circ$  inclination)
- Lifetime:  $\sim 1$  year

## Principal Investigator

Dong L. Wu  
NASA's Goddard Space Flight Center  
[Dong.L.Wu@nasa.gov](mailto:Dong.L.Wu@nasa.gov)

## Co-Principal Investigators

NASA's Goddard Space Flight Center  
Jaime Esper, [Jaime.Esper-1@nasa.gov](mailto:Jaime.Esper-1@nasa.gov)  
Negar Ehsan, [Negar.Ehsan@nasa.gov](mailto:Negar.Ehsan@nasa.gov)  
Matt McLinden, [Matthew.L.Mclinden@nasa.gov](mailto:Matthew.L.Mclinden@nasa.gov)  
Jeff Piepmeier, [Jeffrey.R.Piepmeier@nasa.gov](mailto:Jeffrey.R.Piepmeier@nasa.gov)  
Paul Racette, [Paul.E.Racette@nasa.gov](mailto:Paul.E.Racette@nasa.gov)

## Payload Team Members

NASA's Goddard Space Flight Center  
Du Toit, Nelis  
Fetter, Lula (Lu)  
Hersey, Ken  
Horgan, Kevin  
Lu, Daniel  
Lucey, Jared  
Pellerano, Armi  
Ortiz-Acosta, Melyane  
Solly, Michael  
Wong, Mark (Englin)

Virginia Diode Inc.  
Hesler, Jeff  
Bryerton, Eric  
Retzloff, Steven

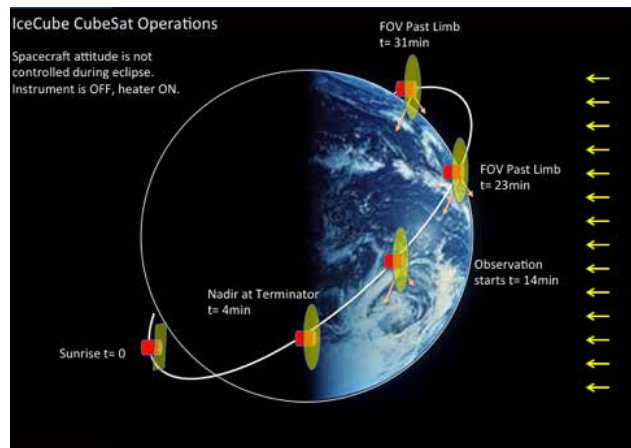
## CubeSat Team Members

Abresch, Brian  
Choi, Michael K.  
Coleman, Alexander  
Corbin, Brian  
Duran-Aviles, Carlos  
Daisey, Ted  
Flaherty, Brooks  
Hart, Henry  
Heatwole, Scott  
Hudeck, John  
Johnson, Tom  
Lewis, Christopher  
Mast, William  
Purdy, Christopher  
Reddersen, Kurt

Rodriguez-Ruiz, Juan  
Stancil, Robert K.

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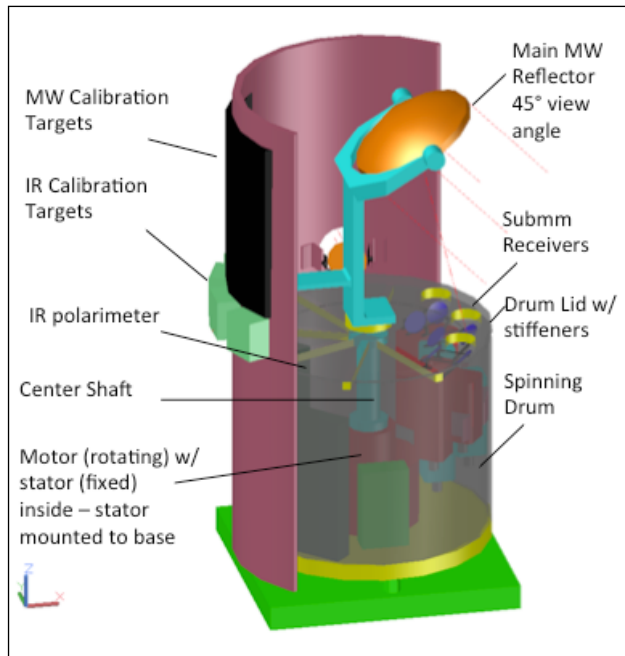
Wu et al. (2016), IceCube: 883-GHz Cloud Radiometer Ready for its Space Journey  
[https://esto.nasa.gov/forum/estf2016/PRESENTATIONS/Wu\\_A1P3\\_ESTF2016.pdf](https://esto.nasa.gov/forum/estf2016/PRESENTATIONS/Wu_A1P3_ESTF2016.pdf)



Schematic drawing of IceCube operation in space. Solar panels face the Sun with the instrument day-on and night-off.

# SWIRP

## Compact Submm-Wave and LWIR Polarimeters for Cirrus Ice Properties



SWIRP is a lab prototype of miniaturized ( $20 \times 20 \times 40$  cm) conically-scanning polarimetric radiometer system for ice cloud observations. Development period: Jan 2017–Dec 2019.

### Key SWIRP Facts

- Objectives: 1) Observe global cloud ice and microphysical properties accurately; 2) Substantiate size, mass, and power of combined mm/submm-wave, LWIR polarimetric-radiometer systems, scan and calibration mechanism; 3) Mature the 220 and 680-GHz direct detection technology with narrow band filters; 4) Design and develop a compact, multi-channel LWIR spectro-polarimeter.
- Heritage: Microwave (MW) polarimetric receivers (220 and 680 GHz) benefit from an earlier development in IIP-13, successful designs of Bearing and Power Transfer Assembly (BAPTA), and the new technology for 25 nm InP HEMT low-noise amplifier (LNA).
- Key subsystems: Two 680 GHz and one 220 GHz polarimetric receivers; an InfraRed Channeled Spectro-Polarimeter (IRCSP), min-BAPTA, drum structure, radiometric and polarimetric calibration assembly, RF instrument control and data acquisition, and power distribution unit.
- Partnership: NASA's Goddard Space Flight Center, Northrop Grumman Corp, University of Arizona, and Texas A&M University.

### Description

Clouds remain as a major source of uncertainty in climate models. Ice clouds, in particular, are poorly constrained and have been used as a tuning parameter in the models to balance radiation budget at the top of atmosphere and precipitation at the surface. Lack of accurate cloud ice and its microphysical property measurements has led to large uncertainty about global clouds and their processes within the atmosphere.

The SWIRP instrument, funded by NASA's and Earth Science Technology Office (ESTO) Instrument Incubator Program, is to enable accurate measurements of cloud ice and microphysical properties (particle size and shape) with a compact conically-scanning submm and IR polarimeters for future remote sensing from space. Radiometric and polarimetric measurements from the SWIRP submm (220 and 680 GHz) and IR (8.6, 11, and 12  $\mu\text{m}$ ) bands provide the needed sensitivity over a full dynamic range of cloud ice. The SWIRP conical scanning configuration will preserve horizontal and vertical polarization information for bulk cloud particle shape retrievals while the matched submm and LWIR footprints allow determination of cloud particle size from the scattering radiances at these frequencies. The compactness of SWIRP design enables cost-effective, flexible deployment of such radiometers-polarimeters in future spaceflight missions (e.g., ACE) for rapid update and frequent revisit sampling to study fast atmospheric processes.

### SWIRP Data Products

- Cloud ice water path (IWP)
- Cloud bulk particle size (Deff) and shape (Aspect Ratio)

### SWIRP Parameters

- Frequency: 220 and 680 GHz, 8-12  $\mu\text{m}$
- Channel bandwidth: 10 and 17 GHz, 0.3-1  $\mu\text{m}$
- Power/Mass/Volume: 16W/ 12 kg /  $20 \times 20 \times 40$  cm<sup>3</sup>
- Radiometric precision: 1K (MW), 0.5 K (IR)
- FOV: 15 km footprint at 220 GHz from 400 km orbit; 7.5 km at 680 GHz and LWIR

### Science Questions

- How much cloud ice is in the atmosphere?
- What are the microphysical properties of cloud ice particles?
- How do cloud microphysical properties vary in different cloud-precipitation systems?

## SWIRP Principal Investigator

Dong L. Wu  
NASA's Goddard Space Flight Center  
[Dong.L.Wu@nasa.gov](mailto:Dong.L.Wu@nasa.gov)

## Co-Principal Investigators

NASA's Goddard Space Flight Center:

Giovanni De Amici, [Giovanni.Deamici@nasa.gov](mailto:Giovanni.Deamici@nasa.gov)  
Negar Ehsan, [Negar.Ehsan@nasa.gov](mailto:Negar.Ehsan@nasa.gov)  
Jeff Piepmeier, [Jeffrey.R.Piepmeier@nasa.gov](mailto:Jeffrey.R.Piepmeier@nasa.gov)

Northrop Grumman Corp.:

William Gaines, [William.Gaines@ngc.com](mailto:William.Gaines@ngc.com)  
William Deal, [William.Deal@ngc.com](mailto:William.Deal@ngc.com)

University of Arizona

Russell Chipman, [RChipman@optics.arizona.edu](mailto:RChipman@optics.arizona.edu)

Texas A&M University

Ping Yang, [PYang@tamu.edu](mailto:PYang@tamu.edu)

## Team Members

Cornelis Du Toit  
Carlos Duran  
Don Jennigns  
Victor Marrero  
Michael Solly  
Manuel Vega

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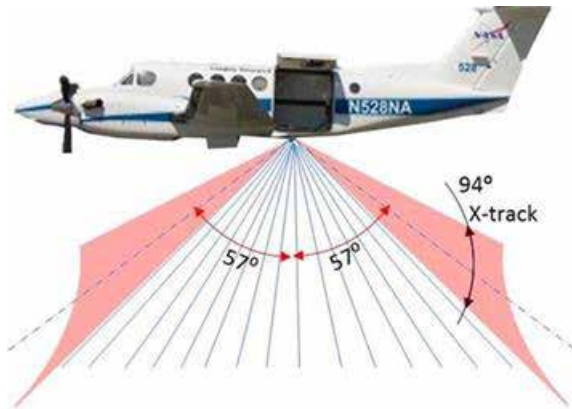
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Passive Remote-Sensing Systems  
Optical



# AirHARP

## *Airborne Hyper-Angular Rainbow Polarimeter*



*Air-HARP has been integrated and flown in the Langley UC-12 aircraft, and has also been approved to fly in the NASA ER2.*

### Key AirHARP CubeSat Facts

- Heritage: AirHARP is a fully autonomous airborne copy of the HyperAngular Rainbow Polarimeter Instrument (HARP CubeSat), built at the Laboratory for Aerosols Clouds and Optics at UMBC in collaboration with GSFC through the Joint Center for Earth Systems and Technology (JCET). The spacecraft was built at the Space Dynamics Lab (SDL) in Utah.
- Wide field of view hyperangular polarization with no moving parts.
- Versatile, small, low power system.
- Angles and sampling wavelengths are selectable within pre-defined values
- Other wavelength modules can be added from UV to shortwave infrared (SWIR).

### Description

AirHARP is a fully autonomous airborne copy of the HyperAngular Rainbow Polarimeter Instrument (HARP CubeSat) built at the Laboratory for Aerosols Clouds and Optics at UMBC, in collaboration with NASA GSFC through the Joint Center for Earth Systems and Technology (JCET). The Spacecraft was built at the Space Dynamics Lab (SDL) in Utah.

AirHARP is a compact, robust and accurate, multiwavelength, hyperangular polarimeter with no moving parts. The built-in hyperangular properties of AirHARP allow for the direct measurement of the angular scattering properties aerosol and cloud particles which contain information about their size, shape, refractive index and amount. As the aircraft moves, each angle and each wavelength are to cover the same

region on the ground with multiple push-broom systems, producing continuous multi-angle observations for each scene. Although the current version of AirHARP only covers the visible to NIR spectral range, this concept represents a very modular design which allows easy expansion to other wavelength ranges (already designed from 360 to 2250 nm).

This current version AirHARP is flying in the NASA's Langley UC12 airplane but has already been approved to fly in the NASA ER2 and is also expected to fly in other airplanes.

### AirHARP Future Data Products

- Aerosol optical thickness and microphysics
- Cloudbow phase function from water droplets
- Hyperangular phase function of ice clouds
- Cloud droplet effect radius and variance
- Surface BRDF

### AirHARP Visible and Near-Infrared Parameters

- Wavelengths: 440, 550, 670, 865nm
- Pixel Resolution from 20 km: 19.5m
- Cross track swath: 94°
- 2048 pixels cross track (un-binned)
- Up to 20 along track view angles at 440, 550, and 865 nm
- Up to 60 along track view angles at 670 nm



*Photograph of the AirHARP structure and doghouse. Everything is contained within the doghouse, including the data system. The pen on the left hand side shows the scale of the system*

### AirHARP Principal Investigator

J. Vanderlei Martins  
 University of Maryland Baltimore County/JCET  
 NASA's Goddard Space Flight Center  
[Martins@umbc.edu](mailto:Martins@umbc.edu)

## **AirHARP Team Members**

Roberto Fenandez-Borda  
University of Maryland Baltimore County/JCET

Lorraine Remer  
University of Maryland Baltimore County/JCET

Lerroy Sparr  
NASA's Goddard Space Flight Center

## **Science Questions for Future Campaigns**

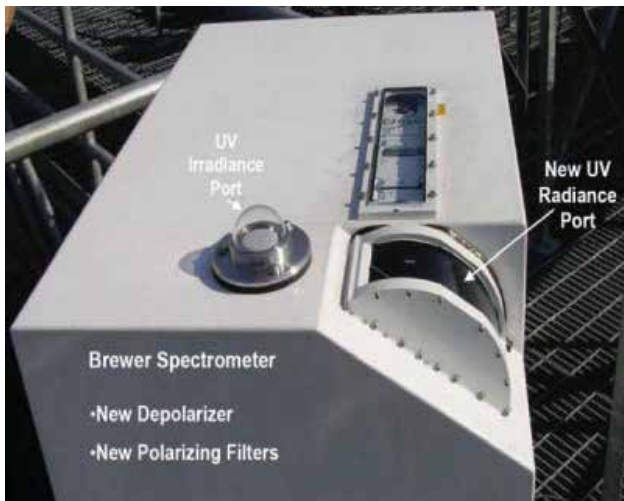
- What are the true scattering properties of generic aerosols (spherical and non-spherical) and cloud ice particles?
- How can a spaceborne imaging polarimeter improve our understanding between aerosols and clouds and help to narrow down the uncertainties in climate change?

## **Planned Campaigns**

Intended to become a HARP demonstration before launch and a calibration validation effort for HARP CubeSat amer launch.

# Brewer

## *Brewer Spectrophotometer*



*The GSFC modified Brewer spectrophotometer.*

### Key Brewer Facts

- A MK IV Brewer Spectrophotometer was purchased primarily for use in the validation of EP-TOMS ozone measurements, for research on new methods to retrieve ozone and SO<sub>2</sub>, and for the retrieval of aerosol properties in the ultraviolet range

### Description

The Brewer has the capability to measure the intensity of ultraviolet radiation but was modified to provide for sky radiance measurements by removing unneeded filters from the optical path. The TOMS team replaced them with a set of high quality polarization filters, added a curved quartz window to remove the Fresnel reflection effect, and incorporated a depolarizer. The TOMS team also developed new algorithms to measure the ultraviolet intensity and retrieve ozone and aerosols. The instrument has been well characterized and calibrated in laboratory at the Radiometric Calibration and Development Facility. A unique capability to measure ozone profiles in both the stratosphere and troposphere was developed. This measurement uses multiple angle observations of the sky radiances throughout the day to determine the ozone profiles every 20 minutes. The method is now being ported to the newly developed Pandora spectrometers.

In the spring of 2010, the Brewer was shipped to the University of Alaska Fairbanks, where it was being used to measure ozone at high latitudes. Zenith sky observations are being used to develop an accurate zenith sky ozone algorithm.

The Brewer was shipped back to Goddard in May 2017 to help validate the total column ozone measured by the Pandora instruments.

### Brewer Data Products

- Total column ozone from direct sun observations
- Ultraviolet radiation from 286 to 363 nm with a resolution of approximately 0.5 nm.
- Trace gases such as NO<sub>2</sub> in the 335–365 nm range; used to validate OMI NO<sub>2</sub> retrievals.
- Direct sun and zenith sky radiances at medium (327– 343 nm) and high (349–363 nm) wavelengths
- Polarized radiance and almucantar measurements
- Polarized Umkehr ozone profiles

### Co-Investigators:

Richard McPeters

NASA's Goddard Space Flight Center

Jay Herman

University of Maryland, Baltimore County

Joint Center for Earth Systems Technology

Alexander Cede

University of Maryland

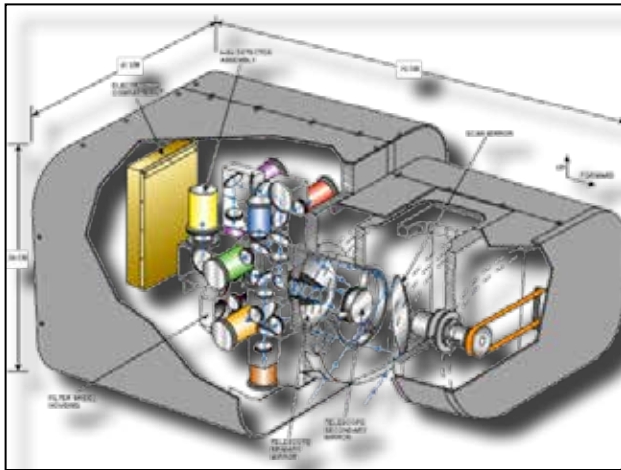
Earth System Science Interdisciplinary Center

### Future Plans

To send the Brewer to Table Mountain, California, in 2018 to compare with Dr. Sanders's FTUVS instrument to understand the interference between HCHO and BrO

# CAR

## Cloud Absorption Radiometer



Schematic illustration of NASA's Cloud Absorption Radiometer (CAR) mounted in the nose of the Naval Research Lab (NRL P-3C) aircraft during the SnowEx field experiment based out of Colorado Springs, Colorado, USA, in 2017 (picture credit: The Associated Press).

### Key CAR Facts

- Heritage: originally designed for cloud research in the diffusion domain defined by optically thick and horizontally extended cloud decks
- Provide unique angular measurements for characterizing surface bidirectional reflectance-distribution function
- Fly on P-3B
- Previously flown on Washington Aircraft Convair (CV-580, C-131A, Douglas B-23), Aerocommander 690A, Jetstream 31, Naval Research Lab (NRL P-3C) aircraft
- CAR URL: <https://car.gsfc.nasa.gov/>

### Description

The Cloud Absorption Radiometer (CAR) is an airborne multi-wavelength scanning radiometer that can perform several functions including: determining the single scattering albedo of clouds at selected wavelengths in the visible and near-infrared, measuring the angular distribution of scattered radiation of various surface types, and acquiring imagery of cloud and Earth surface features. The CAR was designed to operate from a position mounted on various aircraft. The CAR has been deployed on a regular basis in field campaigns around the world including deployments to Alaska, Brazil, Greenland, Kuwait, Portugal (Azores), southern Africa and many states in the continental United States.

### CAR Data Products

- Calibrated angular view data of the Earth surface features, including clouds and smoke on a pixel-by-pixel basis

- Measurements of spectral BRDF (bidirectional reflection distribution function)
- Level-1C data is available at the NASA Goddard Earth Science Data Information and Services Center

### CAR Parameters

- Total Field of View: 190 deg
- Instantaneous Field of View: 1 deg
- Scan Rate: 100 scans/minute (1.67 Hz)
- Spectral Channels: 14
- Spectral Range: 0.34-2.30  $\mu\text{m}$
- Spatial Resolution: 18 m at nadir and about 580 m at 80-deg viewing angle at a flight altitude of 1 km
- Spatial Coverage Cross-Track: zenith to nadir or horizon to horizon
- Environmental requirements: pressurized compartment
- Instrument Mass: 42 kg
- Dimensions: 72-cm long  $\times$  41-cm wide  $\times$  39-cm deep
- Power: 345 W max
- Data rate: between acquisition hardware and the flight computer is 12KHz for display and storage
- Data storage: all data stored on a flight computer

### Principal Investigator

- Charles Gatebe  
Universities Space Research Association  
[Charles.K.Gatebe@nasa.gov](mailto:Charles.K.Gatebe@nasa.gov)

## Team Members

Rajesh Poudyal  
Science Systems and Applications, Inc  
Kurt Rush  
Instrument Electronics Development Branch  
Charles Ichoku  
NASA's Goddard Space Flight Center

## Science Questions for Future Campaigns

- What is the distribution of the snow energy balance, in different canopy types and densities, and terrain?
- How does the average albedo of an area scale as we move from point to plot to hectare to stand and domain?
- How does the observed spatial heterogeneity in the aerosol and cloud field impact the spatial distribution of radiative heating rates in the atmosphere and the surface?
- To what extent does the heterogeneity of the atmosphere impede the use of satellite remotely sensed products for quantifying aerosol-induced changes to cloud and precipitation properties?

## Planned Campaigns

- 2018 – Cloud and Aerosol Monsoonal Processes-Philippines Experiment in the vicinity of the Philippines in August, 2018.
- 2019-2021 – NASA's SnowEx Years 3-5 Campaigns. Locations to be decided.

## References

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# eMAS

## Enhanced MODIS Airborne Simulator



Photograph of eMAS with its cover attached.

### Key eMAS Facts

- Heritage: MODIS Airborne Simulator (MAS)
- NASA ESD facility imager managed by the Ames Airborne Sensor Facility (ASF), and supported by EOS Project Science Office.
- ER-2 airborne scanning spectrometer. Provides measurements of reflected solar and emitted thermal radiation in 38 narrowband channels; used in satellite algorithm development/validation and science studies involving cloud, aerosol, water vapor, and surface properties.
- Participated in numerous major field campaigns around the world since 1991, including: ASTEX (1992), TOGA/COARE (1993), MAST (1994), SCAR-B (1995), FIRE-ACE (1998), SAFARI (2000), CRYSTAL-FACE (2002), CC-VEX (2006), TC4 (2007), SEAC4RS (2013), RADEX/OYMPEX (2015), and ORACLES (2016).
- Nominal Flight Characteristics: 65,000 ft (20 km), above 94 percent of Earth's atmosphere.
- eMAS URL: <https://mas.arc.nasa.gov>

### Description

The temporal and spatial distributions of clouds and aerosols are critical for understanding the Earth-atmosphere system processes and climate. Geophysical retrievals from high-quality multispectral imagery acquired from satellite platforms are an efficient and reliable means of fulfilling

global observational requirements, provided the retrievals are validated with known uncertainties. For over 25 years, eMAS/MAS has provided high spatial resolution multispectral imagery over many locations around the globe. Flying aboard the NASA ER-2 high altitude research aircraft, eMAS serves as a simulator for current and future satellite imagers, and provides essential imagery and science for field campaigns. Its frequent coincidence with *in situ* measurements and satellite underflights facilitates retrieval algorithm development and validation.

### eMAS Data Products

- True and false color imagery
- Cloud detection
- Cloud top temperature, pressure, thermodynamic phase
- Cloud optical thickness, effective particle size, and water/ice path
- Above cloud water vapor
- Aerosol optical depth
- Surface reflectance

### eMAS Instrument Characteristics

- Total Field of View: 85.92° across swath
- Swath Width: 37.25 km (at 20 km altitude)
- Instantaneous Field of View: 2.5 mrad
- Pixel Spatial Resolution: 50 m (at ground from 20 km)
- Pixels per Scan Line: 716
- Scan Rate: 6.25 scan lines per second
- Spectral Channels: 38
- Spectral Range: 0.47–14.0  $\mu\text{m}$

### Facility Lead

Jeffery Myers  
NASA's Ames Research Center  
[Jeffery.S.Myers@nasa.gov](mailto:Jeffery.S.Myers@nasa.gov)

### Science Principal Investigator

Steven Platnick  
NASA's Goddard Space Flight Center  
[Steven.E.Platnick@nasa.gov](mailto:Steven.E.Platnick@nasa.gov)

### Science Co-Investigator:

Kerry Meyer  
NASA's Goddard Space Flight Center

## Science Topics for Future Campaigns

- Cirrus cloud optical and microphysical properties
- Aerosol direct radiative effects
- Cloud-aerosol interactions
- Satellite algorithm development (Suomi NPP, VIIRS, PACE)

## Future Campaigns

- CAMP2Ex, 2018 (TBD)

## References

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## ISEM-FPS

### *International Space Station SpaceCube Experiment Mini (ISEM) Fabry-Perot Spectrometer for Methane*



*The ISEM-FPS instrument prior to deployment on the ISS.*

### Key ISEM-FPS Facts

- The NASA GSFC ISEM-FPS is a small, low-cost sensor for the measurement of atmospheric methane on board the ISS.
- Methane is 20-30 more effective than CO<sub>2</sub> at trapping outgoing long wave radiation on a per molecule basis. No decadal survey mission currently addresses methane.
- A major advantage of the Fabry Perot design is its high throughput which enables the instrument to operate at very short integration times to achieve a high spatial resolution.

### Description

The goals of this mission are to evaluate the FPS technology for measurement of greenhouse gases and to demonstrate the usefulness of on-board processing of the raw FPS images prior to ground-station transmission. It is currently hosted on the Space Test Program-Houston 5 (STP-H5) pallet on board the International Space Station (ISS), and has been operational since March 2017. The ISEM works in tandem with the FPS to process the raw FPS data and increase the level of information per down-loaded byte.

### ISEM-FPS Data Products

- Column-mean, dry-air mixing ratio of CH<sub>4</sub>
- Column-mean H<sub>2</sub>O mixing ratio
- Atmospheric absorption spectra near 1640 nm
- Surface and cloud/aerosol reflectances

### Science Questions to be Addressed in Future Campaigns

- What is the regional and temporal variability of methane in the tropics and mid-latitudes?
- What geophysical processes control the emissions and loss of methane to the atmosphere globally?

- How do the methane flux processes respond to changing composition and climate, and how well can they be predicted?

### Principal Investigators

William S. Heaps  
Johns Hopkins University Applied Physics Laboratory  
[William.Heaps@jhuapl.edu](mailto:William.Heaps@jhuapl.edu)

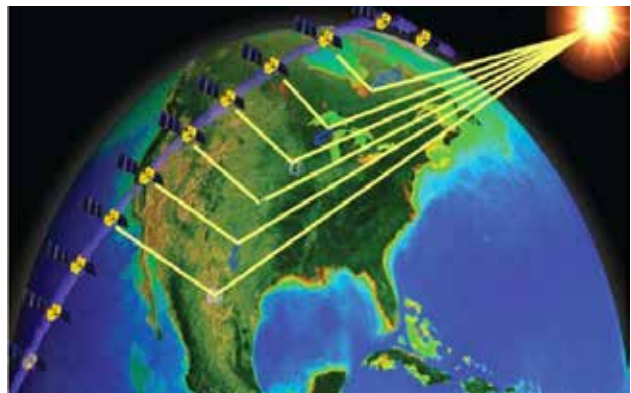
Thomas Flatley  
NASA's Goddard Space Flight Center  
[Thomas.P.Flatley@nasa.gov](mailto:Thomas.P.Flatley@nasa.gov)

### ISEM-FPS Science Team Members

S. Randolph Kawa  
NASA's Goddard Space Flight Center

Clark J. Weaver  
Earth System Science Interdisciplinary Center  
NASA's Goddard Space Flight Center

Compton J. Tucker  
NASA's Goddard Space Flight Center



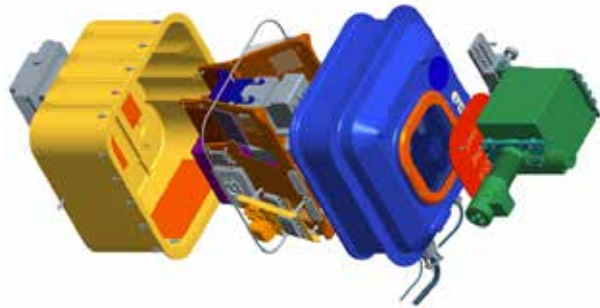
*The ISEM-FPS operates on the principal of detecting spectral absorption of reflected sunlight by greenhouse gases in the atmosphere.*

### References

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# GCAS

## GeoCAPE Airborne Simulator



Exploded view of GCAS components.

### Key GCAS Facts

- Broad wavelength coverage, hyperspectral radiance
- Compact; easily deployable on a variety of aircraft.
- Deployed during Discover-AQ (KingAir), NAAMES (C-130), GOES-R Validation (ER-2)

### Description

GCAS was developed in the IRAD program and is designed to provide high spatial resolution (< 1 km) remote-sensing observations of the tropospheric and boundary layer pollutants and aerosols in addition to providing coastal and open ocean color measurement capabilities. The system is designed to be low-cost and portable while still providing satellite instrument grade sensitivity in order to support future Air Quality/Ocean science decadal survey geostationary mission planning. This effort will also improve our capabilities to perform in-field absolute calibration of UV/VIS spectrographs and explore absolute radiance transfers with satellite instruments (e.g., OMI) under the 5-percent accuracy level.

### GCAS Geolocated Data Products

- Slant column abundances of NO<sub>2</sub>, O<sub>3</sub>, H<sub>2</sub>CO, and SO<sub>2</sub>
- Aerosol index

### GCAS Parameters

- NO<sub>2</sub> Sensitivity: 2x10<sup>-15</sup> molecules/cm<sup>2</sup>
- 2 Channel 300–480nm, 480–960nm
- Spatial Resolution: 250 m<sup>2</sup>
- Spatial Coverage Cross-Track: 15 km at flight altitude of 18 km
- Environmental requirements: Unpressurized compartment
- Instrument Mass: 40 kg
- Volume: 48 cm × 48 cm × 46 cm

- Power: 400 W max
- Data rate: Real-time status and swath averaged NO<sub>2</sub> at 1Hz = 4 Kbps
- Data storage: All data stored on instrument (50 GB/8 hour sortie)

### Principal Investigator

Scott Janz  
NASA's Goddard Space Flight Center  
[Scott.J.Janz@nasa.gov](mailto:Scott.J.Janz@nasa.gov)

### Team Members

Matt Kowalewski  
University Space Research Association  
Kent McCullough, Sam Xiong  
Science Systems and Applications, Inc.

### Science Questions for Future Observations

- What is the evolution of ozone and aerosol through chemical formation and loss, transport, and deposition processes?
- What are the influences of weather in transforming and dispersing emissions, ozone, and aerosol?
- What are the regional budgets for air quality criteria pollutants (O<sub>3</sub>, NO<sub>x</sub>, SO<sub>2</sub>, and aerosol)?
- What are the emission patterns of the precursor chemicals for tropospheric ozone and aerosols?

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# GeoTASO

## *Geostationary Trace Gas and Aerosol Sensor Optimization*



GeoTASO instrument integrated on the NASA LaRC Falcon for the Discover-AQ deployment in Denver (2014).

### Key GeoTASO Facts

- Heritage: Developed through the Instrument Incubator program, in collaboration with Ball Aerospace, and is designed to provide high spatial resolution ( $< 1$  km) remote-sensing observations of the tropospheric and boundary layer pollutants and aerosols.
- Imaging spectrometer in the UV-Visible band designed for atmospheric trace gas measurements.
- Airborne simulator for the NASA EV-I TEMPO and Korean GEMS instruments.
- Deployed during Discover-AQ (LaRC Falcon) and KORUS-AQ (LaRC King Air)

### Description

GeoTASO is a prototype of the geostationary air quality sensors being built for both the Tropospheric Emissions: Monitoring Pollution (TEMPO) and the Geostationary Environmental Monitoring Sensor (GEMS) platforms and is being used for field measurements to improve algorithm development and operational strategies for these missions. In the future, the instrument will be used in dedicated validation campaigns.

### GeoTASO Geolocated Data Products

- Slant and vertical column abundances of  $\text{NO}_2$ ,  $\text{O}_3$ ,  $\text{H}_2\text{CO}$ , and  $\text{SO}_2$

### GeoTASO Parameters

- $\text{NO}_2$  Sensitivity:  $2 \times 10^{-15}$  molecules/ $\text{cm}^2$
- HCHO Sensitivity:  $6.0 \times 10^{-15}$  molecules/ $\text{cm}^2$
- 2 Channel: 265-408 nm, 404-690 nm
- Spatial Resolution: 250  $\text{m}^2$
- Spatial Coverage Cross-Track: 7 km at flight altitude of 10 km

- Instrument and rack mass: 200 kg
- Volume: 100 cm  $\times$  75 cm  $\times$  50 cm
- Power: 700 W max
- Data rate: 1k  $\times$  1k pixels @4Hz
- Data storage: All data stored on instrument (50 GB per 4-hour sortie)

### Principal Investigator

Scott Janz  
NASA's Goddard Space Flight Center  
[Scott.Janz@nasa.gov](mailto:Scott.Janz@nasa.gov)

### Team Members

Matt Kowalewski  
University Space Research Association  
Kent McCullough, Sam Xiong  
Science Systems and Applications, Inc.  
James Leitch  
Ball Aerospace and Technology Corporation

### Science Questions for Future Observations

- What is the evolution of ozone and aerosol through chemical formation and loss, transport, and deposition processes?
- What are the influences of weather in transforming and dispersing emissions, ozone, and aerosol?
- What are the regional budgets for air quality criteria pollutants ( $\text{O}_3$ ,  $\text{NO}_x$ ,  $\text{SO}_2$ , and aerosol)?
- What are the emission patterns of the precursor chemicals for tropospheric ozone and aerosols?

### Planned Campaigns

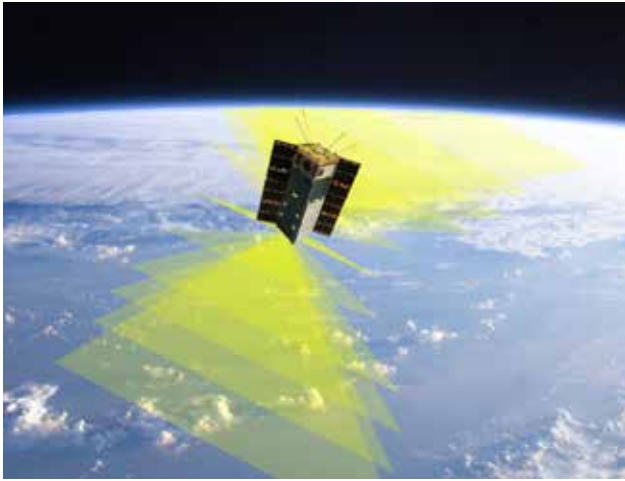
2017 – Lake Michigan Ozone Study (LMOS) in Madison, WI  
2018 – Long Island Ozone Study in Long Island, NY

### References

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J. W. Leitch; T. Delker; W. Good; L. Ruppert; F. Murcray; K. Chance; X. Liu; C. Nowlan; S. J. Janz; N. A. Krotkov; K. E. Pickering; M. Kowalewski; J. Wang: The GeoTASO Airborne Spectrometer Project, *Proc. SPIE*, 9218 (2014).

# HARP CubeSat

## *Hyper-Angular Rainbow Polarimeter*



*HARP CubeSat is a fully autonomous satellite that will be launched at the ISS orbit.*

### Key HARP CubeSat Facts:

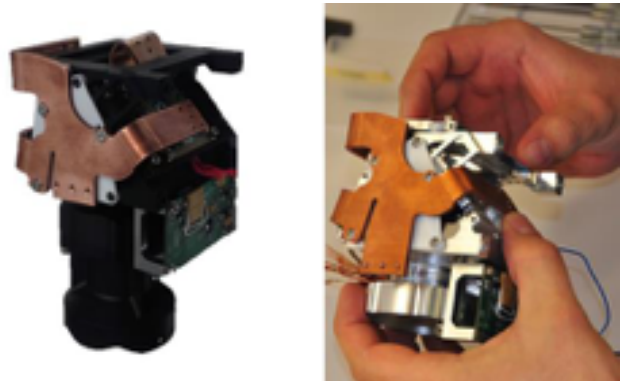
- Heritage: PACS (Passive Aerosol and Cloud Suite), Imaging polarimeter designed as a robust, accurate, multiwavelength, hyperangular polarimeter with no moving parts. Designed for the ER-2 aircraft but it can be easily adapted for other platforms.
- HARP is poised to be the first U.S. imaging polarimeter in space.
- HARP will ride on the CubeSat spacecraft; the launch date has not been established. Shortly thereafter, it will be released and become a fully autonomous, data-collecting satellite.
- HARP is designed to see how aerosols interact with the water droplets and ice particles that make up clouds. Aerosols and clouds are deeply connected in Earth's atmosphere – it's aerosol particles that seed cloud droplets and allow them to grow into clouds that eventually drop their precipitation.
- HARP will prove the on-flight capabilities of a highly-accurate, wide FOV hyper-angle imaging polarimeter for characterizing aerosol and cloud properties
- HARP is a potential precursor for the polarimeter in ACE (Aerosol-Clouds and Ecosystems) and other future NASA mission

### Description

The HARP payload is designed to observe interactions between clouds and aerosols – small particles such as pollution, dust, sea salt or pollen, suspended in Earth's atmosphere. HARP is poised to be the first U.S. imaging

polarimeter in space. It's an example of the kind of advanced scientific instrument it wouldn't have been possible to cram onto a tiny CubeSat in their early days. Shortly after launch, HARP will be released and become a fully autonomous, data-collecting satellite.

The HARP instrument is a wide field-of-view imager that splits three spatially identical images into three independent polarizers and detector arrays. This technique achieves simultaneous imagery of the same ground target in three polarization states and is the key innovation to achieve high polarimetric accuracy with no moving parts. The spacecraft consists of a 3U CubeSat with 3-axis stabilization designed to keep the image optics pointing nadir during data collection but maximizing solar panel sun pointing otherwise. The hyper-angular capability is achieved by acquiring overlapping images at very fast speeds.



*Small size of the HARP instrument*

### HARP Future Data Products

- Aerosol optical thickness and microphysics
- Cloudbow phase function from water droplets
- Hyperangular phase function of ice clouds
- Cloud droplet effect radius and variance
- Surface BRDF

### HARP Visible and Near-Infrared Parameters

- Wavelengths: 440, 550, 670, 865 nm
- Pixel Resolution from ISS orbit: 400 m
- Binned Resolution from ISS orbit: 2500 to 4000 m
- Cross track swath: 94°
- 2048 pixels cross track (un-binned)
- Up to 20 along track angles at 440, 550, and 865 nm
- Up to 60 along track angles at 670 nm

## HARP Principal Investigator

J. Vanderlei Martins  
University of Maryland Baltimore County/JCET  
NASA's Goddard Space Flight Center  
[martins@umbc.edu](mailto:martins@umbc.edu)

## HARP Team Members

Roberto Fenandez-Borda, UMBC/JCET – NASA GSFC  
Lorraine Remer, JCET-UMBC  
Tim Nielsen, Utah State University/ Science Dynamics  
Laboratory (USU/SDL)  
Leroy Sparr, NASA/GSFC  
Mark Schoeberl, Science and Technology Corp (STC).

## Science Questions for Future Campaigns

- What are the true scattering properties of generic aerosols (spherical and non-spherical) and cloud ice particles?
- How can a spaceborne imaging polarimeter improve our understanding between aerosols and clouds and help to narrow down the uncertainties in climate change
- Can climate change estimates of uncertainties be narrowed through new observations and a better understanding of aerosol and cloud processes from a spacebourne polarimeter?

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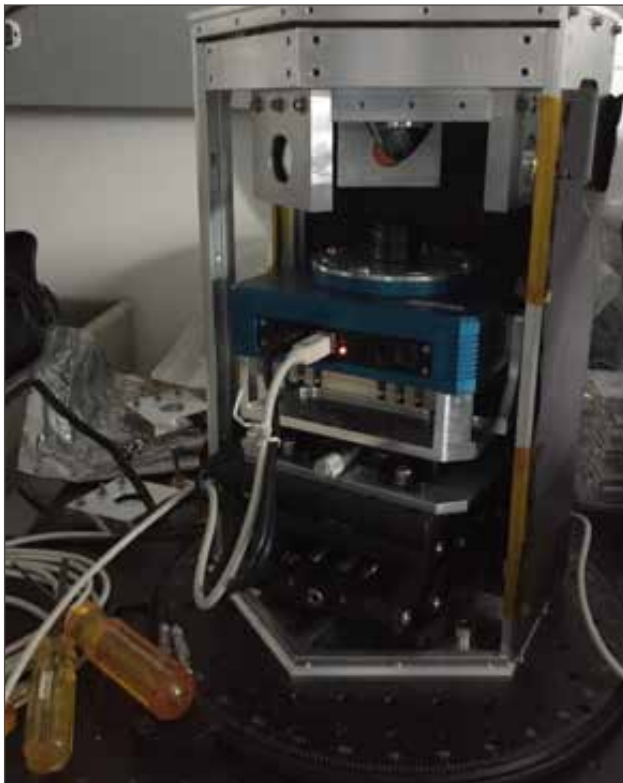
"HARP Hyper-Angular Rainbow Polarimeter," USU/SDL, URL: <http://www.sdl.usu.edu/downloads/harp.pdf>

"Hyper-Angular Rainbow Polarimeter (HARP) CubeSat," Feb. 2015, URL: <http://userpages.umbc.edu/~martins/laco/HARP%20QuadChart%20Feb%202015.pdf>

J. Vanderlei Martins, Tim Nielsen, Chad Fish, Leroy Sparr, Roberto Fernandez-Borda, Mark Schoeberl, Lorraine Remer, "HARP CubeSat—An innovative Hyperangular Imaging Polarimeter for Earth Science Applications," Small Sat Pre-Conference Workshop, Logan Utah, 3 Aug 2014, URL: <http://digitalcommons.usu.edu/cgi/viewcontent.cgi?filename=0&article=3154&context=smallsat&type=additional>

# MASTAR

## *Multi-Angle Stratospheric Aerosol Radiometer*



*Side view of the prototype MASTAR instrument in the laboratory, showing the primary components (viewing apertures, central mirror, focusing optics, CCD detector).*

### Key Facts

- Heritage: A new instrument currently under development under an Instrument Incubator Program (IIP) award from NASA HQ (“Advanced Development of a Multi-Angle Stratospheric Aerosol Radiometer (MASTAR)”)
- The goal for MASTAR is a multi-wavelength, multi-angle viewing capability

### Description

The contribution of atmospheric aerosols to the Earth’s energy budget is an important, yet relatively uncertain, component of the Earth system. Stratospheric aerosols represent a less well-studied, but nevertheless significant, element of this contribution through their impact on direct radiative forcing of the climate system. Comprehensive measurements of aerosol extinction vertical profiles with dense spatial sampling are needed to better constrain climate model simulations of aerosol extinction, composition, and particle size, in order to compute climate impacts. The most effective source of stratospheric aerosol extinction data

comes from satellite limb scattering measurements, which provide greater sensitivity than space-based lidar and much better spatial sampling than occultation measurements. The Ozone Mapping and Profiling Suite (OMPS) Limb Profiler (LP), currently flying on the Suomi National Polar-orbiting Partnership (S-NPP) satellite, has been providing daily aerosol extinction profile data from limb scattering measurements since April 2012. While the S-NPP OMPS LP instrument was designed for a 7- year operating lifetime, the next OMPS LP instrument is not scheduled to fly until 2022. This raises the possibility of a data gap in this crucial measurement. Furthermore, the present OMPS LP instrument provides only a narrow viewing swath on each orbit, and is subject to systematic uncertainties because of sampling biases related to the aerosol scattering angle sampling that its viewing geometry provides.

MASTAR follows from investment by Center and 610AT resources through the IRAD program that spearheaded initial concept development (“Global Aerosol Monitoring System (GAMS),” PI: Peter Colarco, 614). The concept for MASTAR is for a multi-directional, multi-spectral instrument suitable for a 3U-sized CubeSat that provides a low-cost, multi-view capability for observing stratospheric aerosols. This concept complements and extends the capabilities of the current OMPS LP, and future versions that will fly on JPSS 2 (launching in 2022) and beyond.

The MASTAR observation concept is illustrated in Figure 1. The multi-angle viewing capability is provided by employing multiple viewing apertures around the satellite bus. Each aperture projects onto a single, centrally located mirror, which reflects the incident beam through the optical chain and projects onto a CCD that records the observation. Figure 2 shows the MASTAR concept as viewed from the top down, laid out for six viewing apertures. As illustrated, each aperture contains filters to pass in one of several wavelengths of reflected light. Each aperture/filter combination projects a line onto the CCD, where the distance along the line is related to the altitude of the feature observed. A lab bench version of the MASTAR instrument based on the original GAMS IRAD project is shown in the top image, which shows the aperture arrangements, mirror assembly, and optics and detector array. This instrument is currently being tested with input from a lab light source.

The goal for MASTAR is a multi-wavelength, multi-angle viewing capability. Nominally we are designing for three wavelengths: 350 nm for altitude registration and 675 nm and 850 nm for aerosol detection. The use of two aerosol

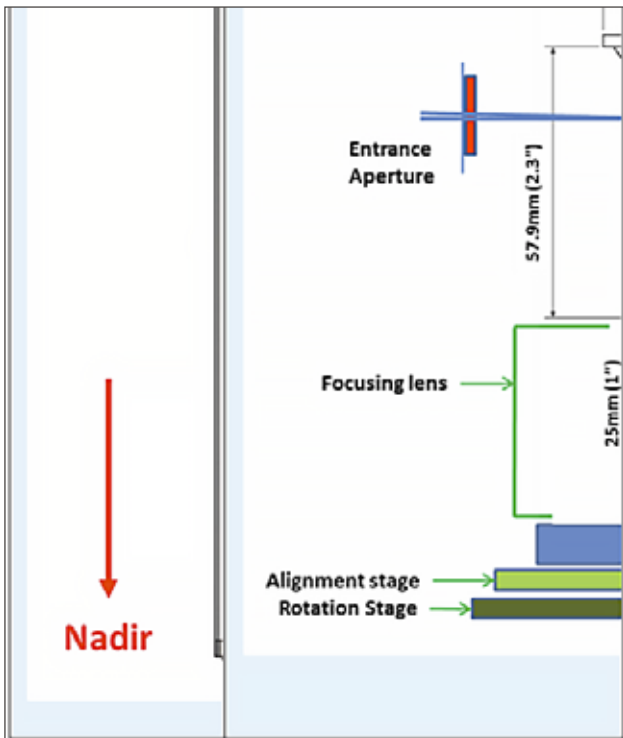


Figure 1. Left panel: Nominal view of the MASTAR instrument in a 3U Cubesat frame, showing viewing apertures in the top section and the CCD detector in the bottom section. Right panel: Cross-section view of the MASTAR optical design, showing incoming light (from left and right sides) being reflected down to the CCD detector.

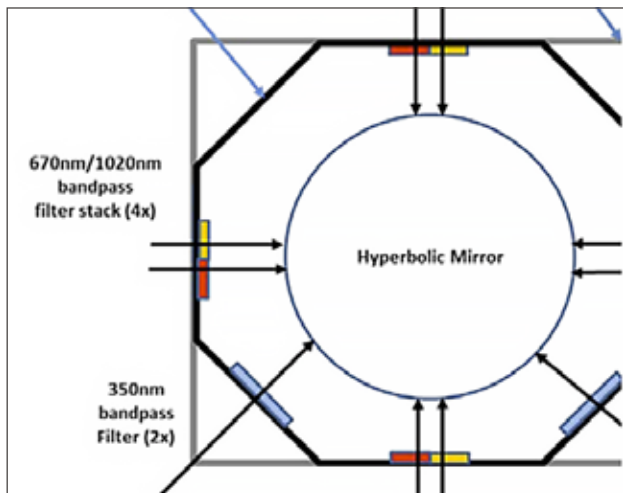


Figure 2. Top view of the MASTAR optical design, showing how incoming light from different directions intercepts the central mirror. This configuration shows four viewing directions for aerosol science and two viewing directions for altitude registration.

channels provides for different sensitivities to aerosol particle properties (i.e., size) and altitude, and also provides heritage with OMPS LP and SAGE measurements. Altitude registration requires 350 nm measurements in only two orthogonal directions, while aerosol detection can be made at multiple directions in order to increase both horizontal spatial coverage and sampling across the aerosol scattering phase function. Nominal altitude resolution requirement is sampling at 0.5 km per pixel along the CCD array.

The current status of the MASTAR instrument design is that we have recently acquired a Silicon Deep-Depleted detector suitable for measurement at all three channels, and we are performing optical modeling to improve on the initial hyperbolic mirror design.

### Principal Investigator

Matthew DeLand  
 Science Systems and Applications, Inc  
 NASA's Goddard Space Flight Center  
[Matthew.Deland@ssaihq.com](mailto:Matthew.Deland@ssaihq.com)

### Co-Investigators

Peter Colarco  
 NASA's Goddard Space Flight Center  
 Matthew Kowalewski  
 GESTAR/NASA GSFC  
 Luis Ramos-Izquierdo  
 NASA's Goddard Space Flight Center  
 Nick Gorkavyi  
 Science Systems and Applications, Inc

### Science Questions for Future Campaigns

- What is the contribution of stratospheric aerosols to direct radiative forcing of the Earth's climate system?
- How can we improve measurement sampling to better constrain the aerosol particle size distribution?
- How can we avoid a possible gap in stratospheric aerosol measurements?

# Mini-LHR

## *Miniaturized Laser Heterodyne Radiometer*



*The mini-LHR makes observations of CO<sub>2</sub> and CH<sub>4</sub> at 11,400 feet at Mauna Loa Observatory in Hawaii in tandem with an AERONET sun photometer.*

### Key Mini-LHR facts:

- Heritage: While laser heterodyne radiometers have been in common use at NASA for several decades, development of the miniaturized version began in July 2009 with regular measurements in the atmospheric column in April 2012. A patent was awarded to Emily Wilson and Matt McLinden in 2014 for this development which is the first LHR to use a distributive feedback laser and this optical arrangement.
- A low-cost, ground-based autonomous instrument that measures CO<sub>2</sub>, CH<sub>4</sub>, in the atmospheric column.
- Mini-LHR data products can be used for validation of satellite retrievals such as OCO-2, OCO-3, GeoCARB, and ASCENDS
- The mini-LHR can provide a continuous record of greenhouse gases that bridges gaps in data sets from flight missions
- The mini-LHR can provide coverage in key regions missed by satellite passes such as arctic regions (not covered by OCO-2) where accelerated warming due to the release of CO<sub>2</sub> and CH<sub>4</sub> from thawing tundra and permafrost is a concern.

### Description

The Mini-LHR is portable ground instrument that measures CO<sub>2</sub> and CH<sub>4</sub> in the atmospheric column. It has been field tested in locations such as Wisconsin (2012) to compare with TCCON observations, and California (2014) to measure methane over cattle-based agricultural areas. In early 2016 the Mini-LHR was redesigned to improve sensitivity and reduce its weight to fit on a backpack so it could be hiked into remote locations that do not have roads or electricity. Three complete instruments were built under the ROSES IDS Program, (HQ: Jared Entin) and successfully demonstrated at high latitudes (May 2016) measuring CH<sub>4</sub> and CO<sub>2</sub> emitted from thawing permafrost. In 2017, mini-LHRs were deployed to notable locations including Hi-SEAS - the long-term Mars simulation experiment on Mauna Loa, Hawaii as well as the University of Edinburgh in Scotland.

**Operation:** The mini-LHR operates in tandem with an AERONET sun photometer and uses its sun tracker as a platform for the mini-LHR light collection optics. This partnership offers a simultaneous measure of aerosols, known to be important modulators in regional carbon cycles as well as an established global framework for the deployment of mini-LHR instruments.

In the operation of the mini-LHR, infrared sunlight that has undergone absorption by the gas is collected and mixed with laser light that scans across the wavelength of the absorption feature of interest. Lines for both methane and carbon dioxide have been selected in wavelength regions that contain minimal interferences from other species such as water vapor, but also that are within the C-L bands for commercially available distributive feedback (DFB) lasers.

### Mini-LHR Data Products

- Half-hour, and hourly column CH<sub>4</sub> and CO<sub>2</sub> retrievals

### Mini-LHR Parameters

- High resolution spectra of CH<sub>4</sub> and CO<sub>2</sub> measured at 1640 nm and 1610 nm
- Scanning resolution: 0.0015 nm
- Field of view: 0.2 degrees
- Portion of the atmosphere: entire column
- Sensitivities: 1 ppm for carbon dioxide and 10 ppb for methane

## Mini-LHR Principal Investigator

Emily L. Wilson  
NASA's Goddard Space Flight Center  
[Emily.L.Wilson@nasa.gov](mailto:Emily.L.Wilson@nasa.gov)

## Team Members/Co-Investigators

Melissa Floyd  
AJ DiGregorio  
Lesley Ott  
Bryan Duncan  
Matt McLinden  
Geronimo Villanueva  
Giuliano Liuzzi  
Paul Palmer  
Jake Bleacher  
Bryan Caldwell  
Jianping Mao  
Liang Feng  
Karla Miletti  
Mischa Grünberg  
Arsenio Menendez  
Christopher Grünberg  
Lauren Cutlip  
Dodd Fleming

## Science Questions for Future Campaigns

- How will increasing anthropogenic emissions impact the Earth's climate?
- Our Observing System Simulation Experiments (OSSE) study results show that carbon flux uncertainty could be reduced by up to 70% if mini-LHR instruments were deployed in 50 selected AERONET sites globally.

## Planned Campaigns

- Hi-SEAS (Hawai'i Space Exploration Analog and Simulation) is a Habitat on an isolated Mars-like site on the Mauna Loa side of the saddle area on the Big Island of Hawaii at approximately 8200 feet above sea level. Crewmembers from Hi-SEAS V operated the mini-LHR from March 2017-September 2017 and crewmembers from the upcoming Hi-SEAS VI will run similar operations.
- Royal Observatory in Edinburgh Scotland. As of October 2017, the mini-LHR is making regular observations.

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# Pandora Spectrometer Instrument



Three Pandora instruments tracking the Sun on the roof of the Chesapeake Bay Bridge Tunnel during the 2017 Ozone Water-Land Environmental Transition Study (OWLETS).

## Key Pandora Facts:

- The Pandora instrument prototype was conceived and deployed in 2006 with the goal of designing of a small, low cost instrument capable of providing high precision, high spatial and high temporal resolution of total columns based on direct sun measurements. It has since evolved into an instrument used for the validation of Earth observing satellites as well as a valuable addition to ground-based air quality monitoring efforts such as those of the EPA and MDE.
- The NASA Pandora Project and its ESA counterpart, Pandonia, are moving towards a synergistic, global network of instruments known as the Pandonia Global Network.
- The UV-Vis spectroscopy based instrument gathers information about trace gases such as ozone, nitrogen dioxide, formaldehyde and sulfur dioxide.
- Pandora instruments are small, mobile and can be controlled remotely through the use of software.
- Pandora instruments have participated in many field campaigns, including the 2015 KORUS-AQ campaign, the 2017 Lake Michigan Ozone Study, 2017 SARP and most recently in the 2017 OWLETS campaign.
- Pandora URL: <https://acd-ext.gsfc.nasa.gov/Projects/Pandora.Test/index.html>

## Description

- The trace gases that Pandora instruments study are important for both climate and air quality, and the high spatial and temporal resolution of the instrument makes it a great tool for studying these emerging issues. Because of this, Pandora instruments have been sited during NASA field campaigns to provide context of trace gases for the

additional instruments being used during the campaign. Further, total column measurements of trace gases are important for calibration and validation of satellites, which is a major component of the overall Pandonia Global Network.

- The Pandora instrument consists of two main components: the sensor head and the instrument box. The sensor head acts to collect sunlight as it passes through the atmosphere and filters out certain wavelengths so that only the wavelengths where the signals of trace gases of interest lie pass through. The light passes from the sensor head into an optical fiber, which carries the light to a spectrometer inside the instrument box. The data output of the spectrometer is read by the mini-pc also housed in the instrument box and synced over the internet to be processed. Near real-time data processing is utilized during intensive field campaigns and is invaluable in coordinating the movements and measurements of ancillary instrumentation.

## Pandora Data Products

- Quality-assured total column ozone, nitrogen dioxide and formaldehyde
- Atmospheric profiles are a work in progress, along with spectral fitting for sulfur dioxide

## Pandora Specifications

- Wavelength range: 270–530 nm
- Spectral resolution: 0.6 nm
- Field of view: 1.5°
- Azimuth range: 360°/0.01°
- Zenith range: +100°/0.01°

## Improvements to the Pandora

- New optics to reduce noise from straylight have been incorporated. Addition of a new, more robust industrial grade PC has also improved performance and durability of the system. Addition of a miniature camera system for better sun tracking as well as new capability for installation on moving platforms (e.g. boat, truck). The delivery of an improved tracker system is anticipated by the spring of 2018.

## Principal Investigator

Robert J. Swap  
 NASA's Goddard Space Flight Center  
[Robert.J.Swap@nasa.gov](mailto:Robert.J.Swap@nasa.gov)

## Pandora Team Members

- Jay Herman, NASA GSFC/JCET
- Nader Abuhassan, NASA GSFC/JCET
- Joe Robinson, NASA GSFC/JCET
- Lena Shalaby, NASA GSFC/JCET
- Mischa Grunberg, NASA GSFC/CRESST
- Alexander Dimov, NASA GSFC/SSAI
- Alexander Cede, NASA GSFC/GESTAR/ Luftblick
- Elena Spinei, NASA GSFC/ESSIC/VT

## Science Questions for Future Endeavors

- What is the intra-pixel variation of trace gases measurements from polar orbiting and geostationary satellites?
- How do urban centers and the pollution they produce behave at the land-water interface?
- How do vertical column densities of trace gases observed by Pandora vary temporally and spatially over the long term and how do they relate to satellite measurements, both polar-orbiting and geostationary?

## Planned Campaigns

- Pandora will continue to support planned and future satellite validation campaigns such as 2018 – OWLETS II (Baltimore/Long Island Sound), CAMPEX (SE Asia), and TROPOMI, TEMPO and GEMS validation activities.

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# SDS

## *Solar Disk Sextant*



SDS preparing for launch from Fort Sumner, New Mexico.

### Key SDS Facts

- Heritage: Designed at GSFC for climate/solar physics studies by means of ultra precise measurements of the solar diameter and shape.
- The SDS uses a custom fused silica wedge to insure a long term, stable calibration reference.
- The SDS is a balloon-borne payload that is launched by CSBF at its facility in Fort Sumner, New Mexico.

### Description

The Solar Disk Sextant (SDS) is a balloon-borne experiment whose objective is to measure the diameter of the Sun with a precision of several milli-arc-seconds, maintained over a time frame of decades. It has flown twelve times starting in 1992, and the latest flight was in October 2011. It is scheduled to fly again in the fall of 2018, with the primary objective of continuing inter-calibration with the SODISM experiment onboard the CNES PICARD satellite, and obtaining long-term secular solar diameter data.

In general the SDS diameter measurements are to be used along with simultaneous solar luminosity measurements to determine the relationship between radius and luminosity changes in the Sun. The team can then use historical solar radius change data (obtained from solar eclipse timings) to determine the amplitude of solar luminosity changes in the past. This is to help in validating climate models. In addition, as a byproduct of this research, the team plans to obtain a value for the solar oblateness, which is of great interest to those working in relativity and fluid dynamics and several areas of solar physics.

### SDS Data Products

- Solar diameter
- Solar shape

### SDS Instrument Parameters

- Main telescope is a ruggedized 7-in Questar
- Reference wedge is 1/50 wave, optically bonded fused silica, detector package = 7 linear CCDs

### Principal Investigator

U. J. Sofia  
American University  
[Sofia@american.edu](mailto:Sofia@american.edu)

### GSFC Principal Investigator

Emily L. Wilson  
NASA's Goddard Space Flight Center  
[Emily.L.Wilson@nasa.gov](mailto:Emily.L.Wilson@nasa.gov)

### Co-Investigators

Gerard Thuillier CNES/LATMOS/SSAI

### SDS Team Members

Terry Girard, Yale University  
Laurence Twigg, Science Systems and Applications, Inc.

### Science Questions for Future Campaigns

- How do the solar diameter and shape change with time?
- How do the SDS and SODISM (an instrument currently flying on the ESA PICARD satellite) solar diameter measurements compare?
- How does the solar diameter change effect climate?

### Planned Campaigns

SDS is scheduled to fly again in the fall of 2018, with the primary objective of continuing inter-calibration with the SODISM experiment onboard the CNES PICARD satellite, and obtaining long-term secular solar diameter data.

### References

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# *In situ* Measurement Systems



## 2DVD

### *Two-dimensional Video Disdrometer*



A 2DVD as commonly deployed. The unit is elevated on cinder blocks to help mitigate splashing of rain drops by the ground. The drops fall through the center of the instrument and are simultaneously imaged by two orthogonal cameras.

### Key 2DVD Facts

- The two-dimensional video disdrometer (2DVD) is manufactured by Joanneum Research (<https://www.joanneum.at>) in Graz, Austria.
- The instrument measures individual precipitation particle (rain drops, hailstones and/or snowflakes) simultaneously with two orthogonally positioned cameras.
- 2DVDs have been in use by NASA since 1999.
- Wallops Flight Facility currently owns six units, and they have been deployed for numerous field campaigns in Finland, Canada, Oklahoma, Iowa, South Carolina, Washington and NASA's Wallops Flight Facility.
- 2DVD URL: <https://wallopsprf.gsfc.nasa.gov/Disdrometer>

### Description

The two-dimensional video disdrometer (2DVD) is manufactured by Joanneum Research (<https://www.joanneum.at>) at the Institute for Applied Systems Technology in Graz, Austria. The Outdoor Unit measures every single precipitation particle—i. e. rain drops, hailstones or snowflakes—from front and side with two high-speed cameras in real-time. The Indoor Unit's analysis PC gives detailed information about size, shape, state of aggregation, orientation and fall speed of each precipitation particle. Taking into account rain rate and accumulated amount of rain, these measurement data are the basis for a thorough understanding of atmospheric processes and precise prediction of the precipitation types, impact on radio links and free-space optics. These are surface-deployed instruments

and have been deployed in multiple field campaigns by NASA and other organizations.

### 2DVD Data Products

- Canting angle
- Drop size and shape (3D reconstruction)
- Precipitation type assessment
- Open interface for user-defined models

### 2DVD Parameters

- Fall velocity, front and side view of individual precipitation particles
- Virtual top view of measurement area
- Optical resolution:  $\sim 0.17$  mm, no upper limit of particle size
- Time stamp with high resolution of  $\sim 18$   $\mu$ s
- Vertical resolution better than 0.17 mm for velocity  $< 10$  m/s
- Vertical velocity accuracy: better than 4% for velocity  $< 10$  m/s
- Sampling area: approximately  $100 \times 100$  mm<sup>2</sup>
- Rain rate: compared to tipping bucket differences, typically less than 10%
- Integration time: 15 s to 12 h
- Sampling area: approximately  $100 \times 100$  mm<sup>2</sup>
- Rain Rate: typically less than 10% compared to tipping bucket differences
- Integration Time: 15 sec to 12 h

### Science Team Members

David B. Wolff

NASA's Wallops Flight Facility

[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

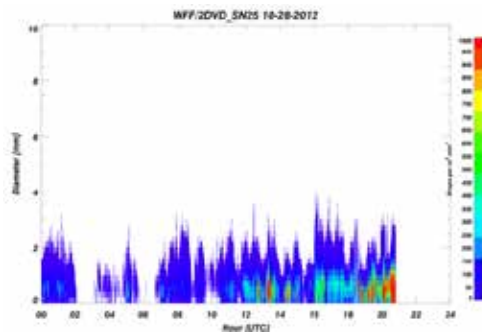
Walter A. Petersen

NASA's Marshall Space Flight Center

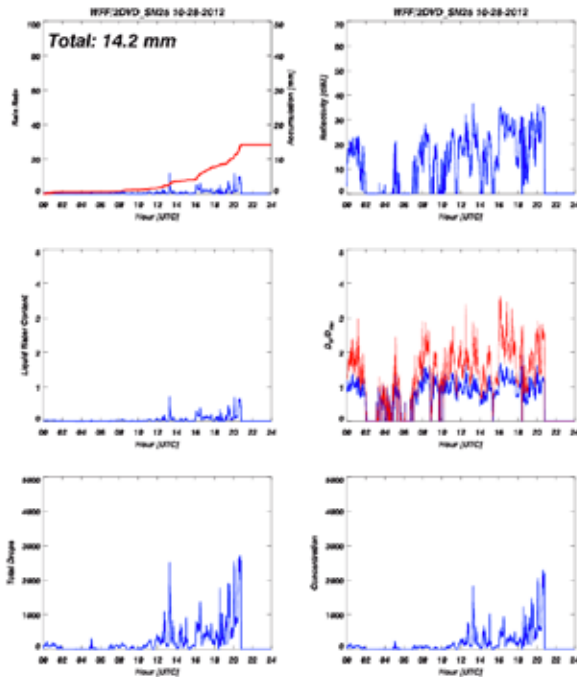
[Walt.Petersen@nasa.gov](mailto:Walt.Petersen@nasa.gov)

### Science Questions

- What is the particle size and velocity distribution of particles in different precipitation types and regimes?
- What is the rain or snow rate?
- What is the liquid water content?
- What are the concentrations and total number of particles observed?



Drop size distribution of precipitation observed by 2DVD SN25 on 10/28/2012. The ordinate is drop size, the abscissa is time of day. The colors represent the number of drops of a given size.



Integrated parameters from 2DVD SN25 on 10/28/2012. The abscissa is time of day. The plots from left to right and top to bottom are: rain rate; reflectivity; liquid water content; drop size; total number of drops per minute; and drop concentration, respectively.

## Future Campaigns

- Although the 2DVD was deployed in numerous GPM field campaigns, they are currently deployed at NASA's Wallops Flight Facility supporting the GPM Precipitation Research Facility (David B. Wolff, Manager). However, from time to time GPM collaborates with and loans the instruments to other members of the GPM community, e.g. NASA's Marshall Flight Facility.

## References

<http://www.distrometer.at>

# CAFE

## Compact Airborne Formaldehyde Experiment



The CAFE instrument installed on the NASA ER-2 at the Armstrong flight research facility in Palmdale, CA. CAFE is easily adapted to fly almost any aircraft.

### Key CAFE Facts

- Heritage: Designed to fly on high-altitude aircraft in unpressurized bays, but it can fly on any aircraft with enough payload capacity (60 lbs/27.2 kg). CAFE measures HCHO *in situ* with laser-induced fluorescence (LIF)
- CAFE can fly on high altitude aircraft in unpressurized bays
- CAFE uses an industrial laser to ensure long-term hands-off operation

### Description

Formaldehyde is produced in the atmosphere from the oxidation of volatile organic compounds (VOCs). These species can be transported to the upper troposphere where they can produce ozone and organic aerosol. Formaldehyde is an excellent tracer of these gases and a sensitive indicator of recent transport by deep convection.

The NASA Compact Airborne Formaldehyde Experiment (CAFE) instrument is a high-performance, laser-based detector for gas-phase formaldehyde. It is designed to fly on high altitude aircraft in unpressurized bays, but it can fly on any aircraft with enough payload capacity (60 lbs). The instrument samples ambient air through an inlet mounted to the exterior of the aircraft and detects the HCHO in the sample with non-resonant laser excitation at 353 nm. The laser-induced fluorescence is detected with photon counting photomultipliers, giving CAFE uniquely sensitive and fast detection capabilities. .

### CAFE Data Products

- Cloud ice water path (IWP)
- Cloud bulk particle size (Deff) and shape (Aspect Ratio)

### CAFE Parameters

- Size: 38 × 43 × 60 cm<sup>3</sup>
- Weight: 25 kg
- Power: 600 W
- Precision: 50 pptv/s
- Accuracy: ±10%
- Time response: < 0.2 s
- Data rate: 1 s (100 ms on request).

### Principal Investigator

PI Thomas F. Hanisco  
 NASA's Goddard Space Flight Center  
[Thomas.Hanisco@nasa.gov](mailto:Thomas.Hanisco@nasa.gov)

### Co-Investigators

Glenn M. Wolfe  
 Joint Center for Earth Systems Technology  
 Jin Liao  
 United Space Research Association  
 Jason M. St. Clair  
 Joint Center for Earth Systems Technology

### Science Goals for Future Campaigns

- Measure the transport of HCHO and the volatile organic compounds (VOCs) to the upper troposphere/lower stratosphere (UT/LS)
- Quantify oxidation sources in the UT/LS
- Quantify vertical profiles for remote-sensing validation

### Planned Campaigns

- 2017–2018: Atmospheric Tomography (Atom) Earth Venture
- 2019: Fire Impacts on Regional Emissions and Chemistry (FIREChem), Salina, Kansas

### References

- J. M. St. Clair, A. K. Swanson, S. A. Bailey, G. M. Wolfe, J. E. Marrero, L. T. Iraci, J. G. Hagopian, and T. F. Hanisco, A new non-resonant laser-induced fluorescence instrument for the airborne *in situ* measurement of formaldehyde, *Atmos. Meas. Tech.*, <https://doi.org/10.5194/amt-2017-282>.

# CARAFE

## CARbon Airborne Flux Experiment



The CARAFE is installed on the Sherpa aircraft (left). Payload includes gas analyzers (center), nose radome modified for the 3-D wind system; pressure ports highlighted for clarity (upper right), and fuselage plate holding angle-of-attack and true air temperature probes (lower right).

### Key CARAFE Facts

- Heritage: The instrument system used in CARAFE was developed for flies on the NASA C-23 Sherpa which is an ideal platform for airborne eddy covariance. The instrument system used in CARAFE currently flies on the NASA C-23 Sherpa which is an ideal platform for airborne eddy covariance.
- Typical minimum flight speeds of 75 m/s provide extended sampling time and thus better turbulent statistics over a target area.
- The greenhouse gas (GHG) package consists of two Los Gatos Research (LGR) analyzers ( $\text{CH}_4/\text{H}_2\text{O}$  and  $\text{CO}_2$ ), a Picarro analyzer ( $\text{CH}_4/\text{CO}_2/\text{H}_2\text{O}$ ) and a custom-built data acquisition and fast pumping system. Laboratory tests and boundary layer spectra confirm a time response of  $\sim 10$  Hz for the LGRs, sufficient to resolve  $> 95\%$  of concentration fluctuations in the mixed layer. The Picarro serves as a stable accuracy standard. Fast water vapor measurements are also provided by the NASA LaRC Diode Laser Hygrometer (DLH, Diskin et al., 2002).

### Description

Eddy covariance is the only experimental method that directly quantifies surface-atmosphere exchange. The technique relies on acquiring fast, simultaneous measurements of concentration fluctuations and vertical wind speed, driven by atmospheric turbulence. The time-averaged product of vertical wind and concentration (their covariance) yields a direct measurement of the surface flux.

The advantage offered by airborne measurements, especially when combined with the wavelet transform technique, is the ability to characterize a wide range of ecosystems at model-relevant scales (1–100 km) with a single measurement package. Airborne eddy covariance has elucidated surface-atmosphere exchange processes for more than three decades (Lenschow et al., 1981; Kawa and Pearson, 1989; Wolfe et al., 2015).

### CARAFE Data Products

- Surface-atmosphere exchange (flux) of  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{H}_2\text{O}$  and sensible heat
- Atmospheric chemical composition of  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{H}_2\text{O}$
- Atmospheric mean and turbulent wind components
- Atmospheric meteorological state
- Incoming photosynthetically active radiation
- Spectral surface state imagery
- Surface flux footprint probabilities

### CARAFE Parameters

- Dry air-gas mixing ratios of  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{H}_2\text{O}$  at 10 Hz and 0.3 Hz, calibrated to NOAA/NIST standards
- Concentration of  $\text{H}_2\text{O}$  vapor at 20 Hz
- 3-D winds, temperature, and pressure with respect to Earth at 20 Hz
- Aircraft position and attitude at 20 Hz
- Visible, infrared, and 4-band vegetation health imagery along track at 1 Hz
- Downward photosynthetic photon flux density at 1 Hz

## Principal Investigators

S. Randolph Kawa  
NASA's Goddard Space Flight Center  
[Stephan.R.Kawa@nasa.gov](mailto:Stephan.R.Kawa@nasa.gov)

Glenn M. Wolfe  
University of Maryland, Baltimore County  
[Glenn.M.Wolfe@nasa.gov](mailto:Glenn.M.Wolfe@nasa.gov)

Thomas F. Hanisco  
NASA's Goddard Space Flight Center  
[Thomas.Hanisco@nasa.gov](mailto:Thomas.Hanisco@nasa.gov)

Paul A. Newman  
NASA's Goddard Space Flight Center  
[Paul.A.Newman@nasa.gov](mailto:Paul.A.Newman@nasa.gov)

Lenschow, D. H., Pearson, R., and Stankov, B. B.: Estimating the ozone budget in the boundary-layer by use of aircraft measurements of ozone eddy flux and mean concentration, *J. Geophys. Res. Oceans Atmos.*, 86, 7291–7297, 1981.

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## Instrument Science Team Members

Glenn S. Diskin  
NASA's Langley Research Center

John D. Barrick, K. Lee Thornhill  
NASA's Langley Research Center

Geoffrey L Bland  
NASA's Wallops Flight Facility

## Science Questions

- How do we validate greenhouse gas surface flux estimates from top-down, satellite data inversions and bottom-up biogeochemical process models?
- What is the response of the geophysical processes that control GHG fluxes to changing composition and climate?
- How well can we predict future carbon-climate interactions?

## Planned Campaigns

- Contributions to Earth Venture-Suborbital 3
- Possible ABoVE deployment

## References

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Kawa, S. R., and R. Pearson, Jr., Ozone budgets from the Dynamics and Chemistry of Marine Stratocumulus Experiment, *J. Geophys. Res.*, 94, 9809–9817, 1989.

# COMMIT

*Chemical, Optical, and Microphysical Measurements of In situ Troposphere*



The COMMIT mobile laboratory was established in 2006.

## Key COMMIT Facts

- Nominal field configuration: comprehensive and rack-mounted *in situ* instruments (shown) for aerosol and trace gas measurements, serving as a supersite in Ground-based Formation Flight operations.
- COMMIT URL: <https://labs.gsfc.nasa.gov/>

## Description

COMMIT is equipped with four inlet stacks to ingest sample air from ~6–10 meters above the ground and to split it into groups of instruments: five trace gas analyzers for carbon monoxide/dioxide, nitrogen monoxide/dioxide, sulfur dioxide and ozone concentrations, and aerosol optical (light scattering, absorption, and extinction) and microphysical (mass concentration and size distribution at different size cuts) properties. Also, two identical sets of nephelometers and scanning mobility particle sizers are used to probe aerosol hygroscopicity between ambient and adjustable relative humidities

## COMMIT Data Products

- Aerosol mass concentration and size distribution
- Aerosol light extinction/scattering/absorption coefficient
- Aerosol hygroscopicity and activation
- Trace gas concentration

## COMMIT Parameters

- Gas concentration:  $\text{NO}_x/\text{NO}_y$ ,  $\text{SO}_2$ , CO,  $\text{CO}_2$ , and  $\text{O}_3$
- Mass concentrations:  $\text{PM}_{10}$   $\mu\text{m}$ ,  $\text{PM}_{2.5}$   $\mu\text{m}$  and  $\text{PM}_1$   $\mu\text{m}$
- Aerosol size distribution: 5 nm ~ 20  $\mu\text{m}$  in diameter
- Extinction/scattering/absorption coefficient: At nominal wavelengths of 0.45 (blue), 0.55 (green), 0.65 (red)  $\mu\text{m}$ , with additional absorption at 0.37, 0.59, 0.88, 0.95  $\mu\text{m}$

## Science Questions to be Addressed

- How are the chemical and microphysical properties of aerosol particles linked to their optical properties?
- How are the aerosol properties near the surface related to those in the boundary layer and aloft?
- Can we better quantify the aerosol indirect effect?

## Principal Investigator

Si-Chee Tsay  
[Si-Chee.Tsay@nasa.gov](mailto:Si-Chee.Tsay@nasa.gov)  
NASA's Goddard Space Flight Center

## Instrument Team Members

Ukkyo Jeong  
University of Maryland  
Adrian M. Loftus  
University of Maryland  
Peter Pantina  
Science Systems and Applications, Inc.

## Key References

Tsay, et al., *AAQR*, 2016, doi:10.4209/aaqr.2016.08.0350  
Pantina, Tsay, et al., *AAQR*, 2016, doi:10.4209/aaqr.2015.011.0630



The COMMIT Laboratory trailer, 2006.

# RAIN GAUGES

## Tipping Bucket Rain Gauges



. Dual-Tipping Bucket Rain Gauges

### Key Rain Gauge Facts

- NASA has used tipping bucket rain gauges for a very long time and their deployment has been a critical part of ground validation for the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) Ground Validation (GV) programs.

### Description

The current inventory of gauges is approximately a total of 200 separate instruments. The setup illustrated in the image above shows a dual-tipping bucket system that was designed by the University of Iowa. This system provides two independent estimates of rain rate, but has built in cell modems that communicate with NASA servers every 15 minutes to provide the number of tips that have occurred, as well as soil moisture info (if soil moisture probes are attached), the GPS location of the gauge and other “health” or metadata that is used to determine whether a gauge and/or battery needs maintenance. These 15-minute packets are then interpreted and used to maintain a near-real-time web site showing the rain rate and health info. (<http://wallops-prf.gsfc.nasa.gov/Gauge>)

### Rain Gauge Observables

- Rain rate, soil moisture, system health, GPS location

### Rain Gauge Parameters

- Bucket size: 8 in and 12 in
- Mechanism: Tipping bucket
- Tip resolution: 0.254 or 0.200 mm
- Time resolution: Based on time to tip
- Communications: Cell modem
- Power: Solar and battery

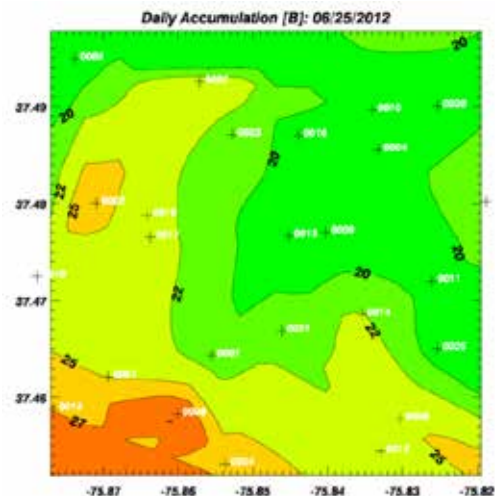
### Instrument Team Members

David B. Wolff  
NASA's Wallops Space Flight Center  
[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

Walter A. Petersen  
NASA's Marshall Space Flight Center  
[Walt.Petersen@nasa.gov](mailto:Walt.Petersen@nasa.gov)

### Rain Gauge Support and Future Plans

NASA has deployed these gauges in multiple GPM field campaigns and also has approximately forty currently deployed in the regions near Wallops Flight Facility. Of these forty gauges, approximately 25 are located in an approximately 5 km x 5 km high-density network in the Pocomoke City, MD area.



This figure shows a contour of rainfall over the Pocomoke grid from June 25, 2012. It well illustrates the variability of rainfall over the 25 km<sup>2</sup> area: namely, 27 mm in the southwest corner versus 20 mm in the northeast corner. This represents approximately a 35% difference.

## ISAF

### In situ Airborne Formaldehyde



The ISAF instrument operated on the NASA DC-8 by University of Maryland graduate student Heather Arkinson.

### Key ISAF Facts

- Heritage: ISAF was designed to fly on any number of NASA and non-NASA aircraft.
- It measures HCHO with laser-induced fluorescence (LIF).
- It is small and simple enough to fly on most aircraft.
- ISAF has flown on different aircraft (DC-8, P3, C-130, and G-V) for different agencies (NASA, NOAA, and NSF).

### Description

Formaldehyde is a reactive trace gas produced from the oxidation of hydrocarbons. It usually has a very low abundance ranging from a few parts per trillion in the upper troposphere to a few parts per billion in the boundary layer. Despite its low abundance it plays an important role in the photochemistry that determines the composition of the atmosphere.

The NASA *In situ* Airborne Formaldehyde (ISAF) instrument is a high-performance laser-based detector for gas phase formaldehyde. It is designed to fly on any number of NASA and non-NASA aircraft. The ISAF instrument samples ambient air through an inlet mounted to the exterior of the aircraft and detects the HCHO in the sample with rotational-state specific laser excitation at 353 nm. The laser-induced fluorescence is detected with photon counting photomultipliers, giving ISAF uniquely sensitive and fast detection capabilities.

### ISAF Parameters

- Size: 38 × 43 × 60 cm<sup>3</sup>
- Weight: 25 kg
- Power: 200 W
- Precision: 20 pptv/s

- Accuracy: ±10%
- Time response: < 0.2 s
- Data rate: 1 s (100 ms on request)

### Principal Investigator

Thomas F. Hanisco  
NASA's Goddard Space Flight Center  
[Thomas.Hanisco@nasa.gov](mailto:Thomas.Hanisco@nasa.gov)

### Co-Investigators

Glenn M. Wolfe, Joint Center for Earth Systems Technology  
Jin Liao, United Space Research Association  
Jason M. St. Clair, Joint Center for Earth Systems Technology

### Science Goals for Future Campaigns

- Measure the transport of HCHO and the volatile organic compounds that produce HCHO
- Contribute to the understanding of atmospheric photochemistry and oxidation processes
- Determine the role of HCHO and its precursors in the formation of organic aerosols
- Provide *in situ* validation for satellite remote sensing of HCHO columns

### Planned Campaigns

- 2017–2018: Atmospheric Tomography (Atom) Earth Venture
- 2019: Fire Impacts on Regional Emissions and Chemistry (FIREChem), Salina, Kansas.

### References

- Cazorla, M.; Wolfe, G. M.; Bailey, S. A.; Swanson, A.K.; Hanisco, T. F., A new airborne laser-induced fluorescence instrument for *in situ* detection of formaldehyde throughout the troposphere and lower stratosphere, *Atmos. Meas. Tech.*, 8(2), 2015.
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# PARSIVEL<sup>2</sup> DISDROMETER



Automated Parsivel Unit (APU) deployed at NASA's Wallops Flight Facility. The Parsivel disdrometer itself is shown atop the computer and electronics container. The small antenna is a GPS. The APUs were designed at NASA's Marshall Flight Facility for remote operations of the Parsivel instruments.

## Key Parsivel<sup>2</sup> Facts

- The Parsivel<sup>2</sup> is the second version of Parsivel instrument developed by OTT Inc. <http://www.ott.com/en-us/products/meteorological-sensors-26/ott-parsivel2-laser-weather-sensor-1536>
- The Global Precipitation Measurement (GPM) Ground Validation (GV) currently owns 24 separate units.
- The APU unit shown above allows for specialized processing of the Parsivel<sup>2</sup> data and can allow operations with commercial or solar power.
- APUs have been deployed during all GPM Field Campaigns and at NASA's Wallops Flight Facility.
- Parsivel URL: <https://wallops-prf.gsfc.nasa.gov/Disdrometer>

## Description

The OTT Parsivel<sup>2</sup> is a modern laser disdrometer for comprehensive measurement of all precipitation types. The Parsivel<sup>2</sup> captures both the size and speed of falling particles, classifying them into one of 32 separate size and velocity

classes. The raw data are used to calculate the type, amount, intensity, and kinetic energy of the precipitation, the visibility in the precipitation, and the equivalent radar reflectivity.

## Parsivel<sup>2</sup> Observables

- Rain rate, present weather, particle size distributions
- Precipitation types: drizzle, rain, mixed rain/snow, snow, snow grains, sleet, hail

## Parsivel<sup>2</sup> Parameters

- Optical sensor: laser diode
- Wavelength: 650 nm
- Peak output power: 0.2 mW
- Laser Class: 1 (IEC/EN 60825-1:2014)
- Measuring surface: 180 × 30 mm
- Particle size range (liquid): 0.2 – 8.0 mm
- Particle size range (ice): 0.2 – 25.0 mm
- Particle velocity: 0.2 – 20.0 m/s
- Size and velocity classes: 32

## Parsivel<sup>2</sup> Team Members

Patrick Gatlin  
NASA's Marshall Space Flight Center  
[Patrick.Gatlin@nasa.gov](mailto:Patrick.Gatlin@nasa.gov)

Walter A. Petersen  
NASA's Marshall Space Flight Center  
[Walt.Petersen@nasa.gov](mailto:Walt.Petersen@nasa.gov)

Matt Wingo  
NASA's Marshall Space Flight Center  
[Matthew.T.Wingo@nasa.gov](mailto:Matthew.T.Wingo@nasa.gov)

David B. Wolff  
NASA's Wallops Flight Facility  
[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

## Science Questions

- What is the particle size and velocity distribution of particles in different precipitation types and regimes?
- What is the rain or snow rate?
- What is the liquid water content?
- What are the concentrations and total number of particles observed?

## Previous and Future Campaigns

GPM currently owns and operates 24 separate Parsivel<sup>2</sup> instruments. Many of these have been deployed in the GPM field campaigns and others are deployed at the Wallops

Precipitation Research Facility at NASA's Wallops Flight Facility. In the image, the actual Parsivel<sup>2</sup> instrument is located on the top, while the encasement was designed at NASA's Marshall Space Flight Center and contains the processing computer, GPS, communications and power. When the Parsivel<sup>2</sup> is paired with this NASA unit, it is referred to as the Autonomous Parsivel Unit (APU) and can use DC, AC, or solar power for operations. Currently, Parsivels are being used primarily at NASA's Wallops Flight Facility, but some will be deployed as requested by other GPM collaborators.

## References

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# PIP

## Precipitation Imaging Package



A Precipitation Imaging Package disdrometer shown deployed near Marquette, MI. The PIP was designed by Dr. Larry Bliven at Wallops Flight Facility. It consists of a halogen light and a high-speed camera that are used to image precipitation particles.

### Key PIP Facts

- The Precipitation Imaging Package (PIP) was designed in-house at the NASA's Wallops Flight Facility Field Support Office by Larry Bliven.
- It consists of hardware and software that record and process images of falling particles near ground level.
- The main hardware components are a high-frame-rate (380 fps), fast-shutter-speed (28 s) video camera with a lamp, and at least a six core PC with two-disc drives.
- The PIP instrument has proven very popular among Global Precipitation Measurement (GPM) partners and have been deployed worldwide, including at NASA's Wallops Flight Facility, Colorado, Michigan, Alaska, Finland, Canada, and Korea.
- 2DVD URL: <https://wallopsprf.gsfc.nasa.gov/Disdrometer>

### Description

The instrument/package consists of hardware and software that record and process images of falling particles near ground level. The main hardware components are a high-frame-rate (380 fps), fast-shutter-speed (28 s) video camera with a lamp, and at least a six-core PC with two-disc drives. Each 8-bit grey-scale image is  $240 \times 640$  pixels that

correspond to  $48 \times 64$  mm. Precipitation events produce many images with particles, so PIP software uses parallel processing to hasten product delivery, which is near real-time.

Software challenges were numerous because storage and near real-time analysis of one billion images per month seems overwhelming for a PC. Challenges were solved by ~15,000 lines of Matlab code and a similar amount of graphical Labview code that were written for this project. Using both Matlab and Labview enabled optimization for hardware/software interfacing, for parallel processing techniques, and for code development. Special modules were written for (a) image compression and storage (~1.8 PB/yr reduced to ~100 GB/yr), (b) conversion to a widely used visualization format (~5 GB per minute of precipitation), (c) quick particle identification, (d) speedy particle-tracking, even with multiple particles per image, (e) reliable particle fall-velocity that compensates for outliers that here-to-fore had no logically way to remove, (f) logic controls for parallel processing, optimization of two disc utilization, and looping for continuous analysis.

### PIP Attributes

For each minute of precipitation, the basic data products are (a) a visualization of falling particles, (b) a particle size distribution and (c) a fall speed distribution. Raindrops (water) fall at close to terminal velocity, whereas non-raindrops (particles that contain ice, such as sleet and snow) fall at slower speeds. This distinguishing trait is used to assign rain and non-rain classification to each size within a particle size distribution.

### PIP Products

- Canting angle
- Drop size and shape (3D reconstruction)
- Hydrometeor ID
- Precipitation type assessment
- Effective snow density

### PIP Team Members

F. L. Bliven  
NASA's Wallops Flight Facility  
[Francis.L.Bliven@nasa.gov](mailto:Francis.L.Bliven@nasa.gov)

David B. Wolff  
NASA's Wallops Flight Facility  
[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

## Science Questions

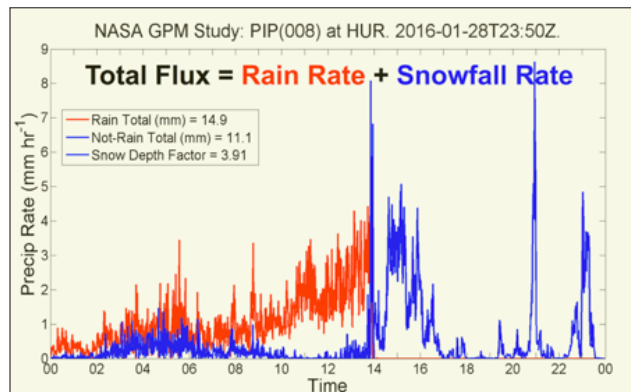
- What is the particle size and velocity distribution of particles in different precipitation types and regimes?
- What is the rain or snow rate?
- What is the liquid water content?
- What are the concentrations and total number of particles observed?
- What is the effective density of observed mixed-phase or frozen precipitation?
- How can this information be used to help validate space-borne snow rate estimates from GPM?

## Future Campaigns

The PIP is undergoing a patent application process with the hope that the instrument will eventually be developed commercially by a third party. Nonetheless, the PIP is currently deployed worldwide (NASA's Wallops Flight Facility, Colorado, Michigan, Alaska, Finland, Canada, and South Korea).

## References

<http://www.distrometer.at>



*PIP observations of precipitation rate for 01/28/2016. The blue curve represents observed snow and the red curve represents liquid rain. The total precipitation flux is the sum of these two fall amounts. The snow is identified by measuring the reduced fall speed of frozen particles.*

# PLUVIO<sup>2</sup> Precipitation Gauges



A Pluvio weighing gauge deployed at NASA's Wallops Flight Facility. The instrument is in the center and catches precipitation that falls through the center orifice into a solution that melts frozen particles and stores liquid particles so that they can be weighed. This provides a measurement of the liquid water equivalent necessary for approximating the density of frozen particles. The instrument is surrounded by two fences, one next to the gauge, the other a few meters away. These fences help shelter the gauge from wind and turbulence that adversely affects the motion of frozen particles.

## Key PLUVIO<sup>2</sup> Facts

- Pluvios are unique gauges in that they measure the weight of precipitation rather than the volume.
- Pluvios can be used to get the liquid water equivalent of snow, thus allowing researchers to calculate the density of the falling snow.
- Pluvios can be used to measure liquid (rain), mixed-phase (e.g. ice pellets) and frozen (e.g. hail or snow).
- Pluvios have been used in several GPM field campaigns.
- Pluvio URL: <http://www.ott.com/en-us>

## Description

The OTT Pluvio<sup>2</sup> is an all-weather precipitation gauge that uses superior weight-based technology to measure the amount and intensity of rain, snow, and hail. Developed in conjunction with industry-leading meteorological services, the OTT Pluvio<sup>2</sup> employs a high-precision load cell and algorithms that compensate for wind, temperature, and evaporation, ensuring the highest accuracy precipitation measurements over time.

## PLUVIO<sup>2</sup> Products

- Rain rate, snow water equivalent

## PLUVIO<sup>2</sup> Parameters

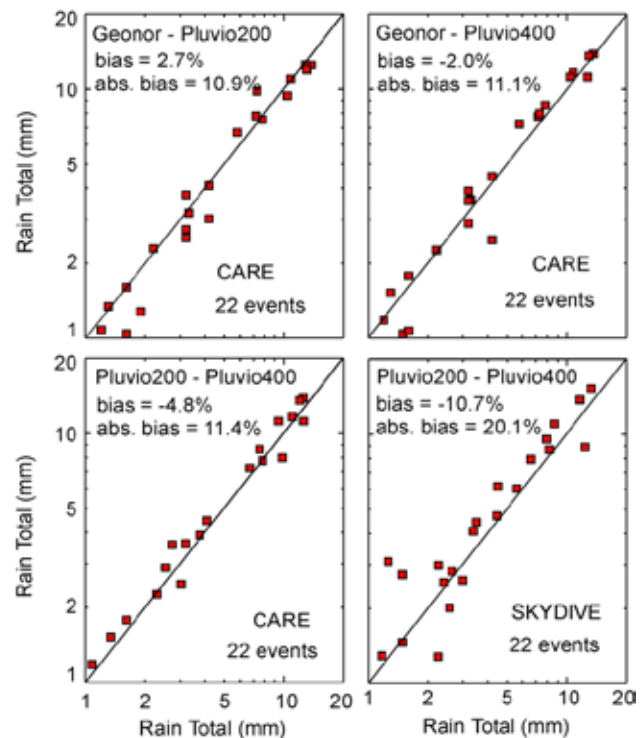
- Types of precipitation: liquid, solid, and mixed
- Collecting area: 200 and 400 cm<sup>2</sup>
- Collection volume: 1500 and 750 mm/m<sup>2</sup>
- Serial interface, SDI-12 or RS 485
- Temperature (operations): -40°C to +60°C

## Principal Investigator

David B. Wolff  
NASA's Wallops Flight Facility  
[David.B.Wolff@nasa.gov](mailto:David.B.Wolff@nasa.gov)

## Co-Investigators

Ali Tokay  
Joint Center for Earth Systems Technology  
University of Maryland, Baltimore County  
[Ali.Tokay-1@nasa.gov](mailto:Ali.Tokay-1@nasa.gov)



A comparison of Pluvio<sup>2</sup> estimates to those of previous community standard Geonor weighing-gauge shows excellent agreement.

Walter A. Petersen  
NASA's Marshall Space Flight Center  
[Walt.Petersen@nasa.gov](mailto:Walt.Petersen@nasa.gov)

### **Support and Future Plans**

- GPM has deployed four of its Pluvio systems in several cold-weather field campaigns. A recent purchase of an additional 12 instruments is being prepared for deployment in the Marquette, MI, area to help validate snow totals for GPM. This deployment will occur during the 2017–2018 winter.

### **Science Questions**

- What is the density of falling snow?
- How much liquid water content was contained in a given snow event?

### **References**

Hydromet/OTT: <http://www.ott.com/en-us>

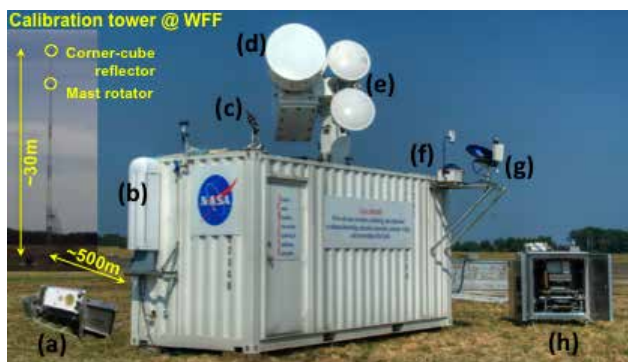
Download PDF: <http://www.ott.com/en-us/products//ott-pluvio2-1-weighing-rain-gauge-1521/productAction/outputAsPdf/>

Mobile Laboratories  
Integrated Active/Passive



# ACHIEVE

## *Aerosol-Cloud-Humidity Interactions Exploring and Validating Enterprise*



The ACHIEVE mobile laboratory was established in 2011.

### Key ACHIEVE Facts

- Heritage: In support of the NASA Earth Observing System (EOS) endeavor, GSFC's SMART, COMMIT, and ACHIEVE ground-based mobile laboratories were conceptualized, built, and have participated in numerous field campaigns.
- Nominal field configuration: integrated passive and active instruments for cloud, aerosol and atmospheric state parameter measurements, serving as a supersite in "Ground-based Formation Flight" operations.
- Radar calibration: Using corner-cube reflectors atop a ~30 m telescoping tower with remotely controlled rotator for precise alignment with radar beam, a unified and robust statistical procedure is used for pre- & post-mission calibration of multi-frequency radars at NASA's Wallops Flight Facility (WFF).
- ACHIEVE URL: <https://smartlabs.gsfc.nasa.gov/>

### Description

Accurate retrievals of aerosol and cloud properties from spaceborne sensors have been achieved with certain degrees of confidence. One of the most difficult tasks remaining to be resolved is the interaction between aerosols and clouds, co-existing in the planetary boundary layer. Ground-based measurements of aerosol, cloud and radiation properties are critical to provide independent assessment of satellite retrievals and diagnostic/prognostic modeling studies.

ACHIEVE, extending the success of SMART-COMMIT mobile facility, is being built to provide urgently needed test-bed data with high temporal and spectral resolutions. ACHIEVE (see above image) contains active remote-sensing instruments of scanning 94/9.6 GHz radars (c & d), vertical-pointing 24 GHz radar (e), a ceilometer (b), and passive instruments of a scanning microwave radiometer (a), an all-sky imager (f) and an interferometer (g).

### ACHIEVE Data Products

- Temperature, pressure and humidity profiles, boundary layer depth
- Cloud cover imagery, cloud base/top heights, cloud thermodynamic phase
- Cloud water content and effective particle size profiles, cloud optical thickness
- Doppler mean velocity
- Precipitation occurrence and rain rate

### Achieve Parameters

- Multi-frequency (94, 24, and 9.6 [in progress] GHz) radars: Range-dependent Doppler spectral width and equivalent radar reflectivity, linear depolarization ratio
- Ceilometer (910 nm lidar): Range-dependent total attenuated backscatter intensity
- Interferometer (3–20  $\mu\text{m}$ ): downwelling spectral intensity or sky brightness temperature
- Microwave radiometer (22–24, 36.5, and 89 GHz): spectral brightness temperature (H-/V-polarization at 89 GHz)

### Principal Investigator

Si-Chee Tsay  
NASA's Goddard Space Flight Center  
[Si-Chee.Tsay@nasa.gov](mailto:Si-Chee.Tsay@nasa.gov)

### Team Members

Ukkyo Jeong  
University of Maryland  
Adrian M. Loftus  
University of Maryland  
Peter Pantina  
Science Systems and Applications, Inc.

### Science Questions to be Addressed

- How do clouds respond to perturbations in aerosols, in terms of cloud condensation nuclei and ice nuclei activation?
- What is the sensitivity of the climate system to low-level cloud macro-/micro-structure in the planetary boundary layer (PBL)?
- What is the role of drizzle evaporation play in sub-cloud layer impacting the PBL moisture and energy budgets? And how quantitatively the lifecycle of drizzle can be measured?

## Future Campaigns

ACHIEVE is being prepared to deploy in late December 2017 to northern Vietnam to serve at the supersite located in the aerosol-cloud confluence region, together with various regional contributing UAVs and IMPACT in profiling and *in situ*, respectively, the atmospheric state parameters and aerosol distribution. All of these remotely-sensed and *in situ* measurements will provide essential input/initialization data to the regional chemistry-transport and cloud-resolving models in simulating aerosol-cloud interaction processes and cloud lifecycle studies. These activities represent an important milestone for the 7-SEAS/BASELInE (Seven SouthEast Asian Studies/Biomass-burning Aerosols & Stratocumulus Environment: Lifecycles & Interactions Experiments 2013–2018).

## Key References

Tsay, et al., *AAQR*, 2016, doi:[10.4209/aaqr.2016.08.0350](https://doi.org/10.4209/aaqr.2016.08.0350)

Loftus, Tsay, et al., *AAQR*, 2016, doi:[10.4209/aaqr.2015.011.0630](https://doi.org/10.4209/aaqr.2015.011.0630)

# SMART

## Surface-sensing Measurements for Atmospheric Radiative Transfer



The first mobile laboratory, SMART trailer established in 2001, which hosted an array of remote-sensing instruments, has been transformed into network operations (Figs. A & B)..

### Key SMART Facts

- Heritage: The original SMART instruments cover a wide spectral range, from ultraviolet to microwave, and were integrated into a 20-ft weather-sealed trailer with a thermostatic temperature control to facilitate the shipping to, and operation in, the field.
- SMART: is currently transformed into six satellite units, serving as the ground-based formation measurements, with COMMIT-ACHIEVE (-Other contributing instruments) supersite operations.
- Nominal field configuration: unified sets, currently up to six of ground-based solar spectrometers (Fig. A), short-wave (with thermal-dome-effect corrected) and longwave irradiance radiometers (Fig. B), serving as the satellite units in “Ground-based Formation Flight” operations.
- SMART URL: <https://smartlabs.gsfc.nasa.gov/>

### Description

As the suite evolved over time, SMART was transformed into six unified units (Figs. A&B), distributed around the core supersite of COMMIT-ACHIEVE mobile laboratories in 2011. Collectively, it became SMARTLabs (Surface-based Mobile Atmospheric Research & Testbed Laboratories) and has been deployed in many national and international field experiments. Many unique data sets have been generated for ground-based remote sensing and *in situ* studies in atmospheric sciences. The overarching goal of the SMARTLabs mobile facility is to enrich NASA Earth Sciences by (1) contributing to NASA satellite missions in providing

calibration/validation of data products, (2) piloting innovative science research through the mobility, flexibility and rich suite of complementary instruments offered in these test-bed platforms, and (3) promoting NASA Earth Sciences through educational and public outreach activities.

### SMART Data Products

- Sun and sky solar spectral radiance at 1 nm resolution for retrieving trace gas, aerosol and cloud properties
- Surface spectral bi-directional reflectance and albedo at 1 nm resolution
- Hemispheric/direct-beam shortwave and longwave irradiance with various bands of energy partitioning

### SMART Parameters

- Solar spectra: 280~800 nm and 0.35~2.5  $\mu\text{m}$
- Broadband wavelengths: 0.3~3, 0.4~3, 0.7~3, and 4~50  $\mu\text{m}$  (global, diffuse and direct component)



Complementary setup: an additional spectroradiometer (Fig. a) in sun-tracking mode; or in surface bi-directional reflectance mode (Fig. b); and broadband radiometers on tracking station for diffuse and direct components (Fig. c) at various selected wavelength ranges.

## Principal Investigator

Si-Chee Tsay  
NASA's Goddard Space Flight Center  
[Si-Chee.Tsay@nasa.gov](mailto:Si-Chee.Tsay@nasa.gov)

## Team Members

Ukkyo Jeong  
University of Maryland  
Adrian M. Loftus  
University of Maryland  
Peter Pantina  
Science Systems and Applications, Inc.

## Science Questions To Be Addressed

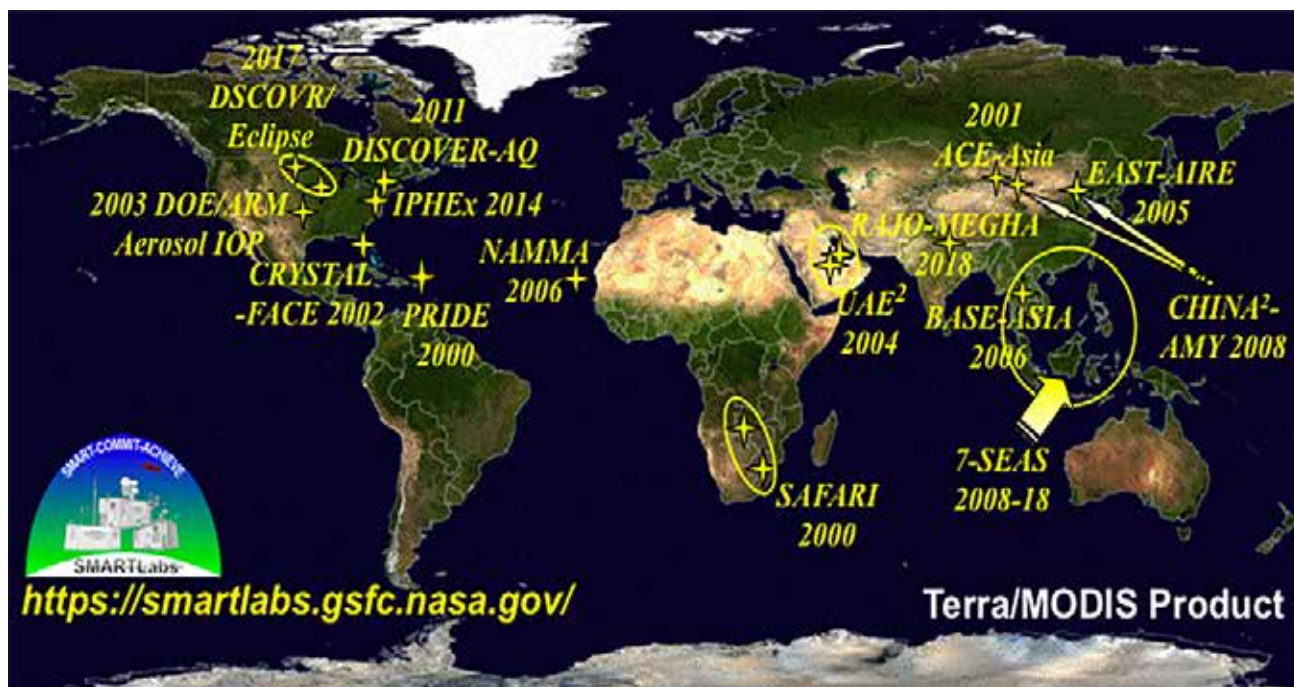
- How is atmospheric composition changing?
- What are the effects of atmospheric composition changes on air quality and radiative energetics?

## Planned and Participated Campaigns

In 2017, various satellite units of SMART have participated domestic OWLETS (Ozone, Water-Land Environmental Transition Study) and Eclipse and will be in the 7-SEAS/BASELInE and HMA deployments.

## References

Ji and Tsay, *JGR*, 2010, doi:[10.1029/2009JD013483](https://doi.org/10.1029/2009JD013483)  
Ji, Tsay, et al., *JGR*, 2011, doi:[10.1029/2011JD016466](https://doi.org/10.1029/2011JD016466)  
Hansell, Tsay, et al., *JGR*, 2014, doi:[10.1002/2013JD021423](https://doi.org/10.1002/2013JD021423)



**PRIDE** (Puerto Rico Dust Experiment), Puerto Rico, June–July 2000

**SAFARI** (Southern Africa Fire-Atmosphere Research Initiative), southern Africa, August–September 2000

**ACE-Asia** (Aerosol Characterization Experiment – Asia), eastern Asia, March–May 2001

**CRYSTAL-FACE** (Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment), Florida, July 2002

**UAE2** (United Arab Emirates United Aerosol Experiment), Arabian Gulf, August–September 2004

**EAST-AIRE** (East Asian Study of Tropospheric Aerosols: an International Regional Experiment), China, February–July 2005

**BASE-ASIA** (Biomass-burning Aerosols in South East-Asia: Smoke Impact Assessment), Thailand, February–May 2006

**NAMMA** (NASA African Monsoon Multidisciplinary Activities), Cape Verde, August–September 2006

**CHINA2-AMY08** (Cloud, Humidity Interacting Natural/Anthropogenic Aerosols in Asian Monsoon Year-2008), China, April–October 2008

**7-SEAS/Dongsha** (7-South East Asian Studies/Dongsha), Dongsha Island, Taiwan, March–June 2010

**DISCOVER-AQ** (Deriving Information on Surface conditions from COlumn and VERTically resolved observations relevant to Air Quality), Greater Washington-Baltimore area, July 2011

**7-SEAS/Son La** (7-South East Asian Studies), Son La, Vietnam, March–April 2012–2013

**IPHEX** (Integrated Precipitation and Hydrology Experiment), eastern United States, May–June 2014

**7-SEAS/BASELInE** (Biomass-burning Aerosols & Stratocumulus Environment: Lifecycles & Interactions Experiment), northern Southeast Asia, March–April 2013–2015

**DSCOVR/Eclipse** (Deep Space Climate Observatory – Solar Eclipse), mid-Western U.S., August 2017

**7-SEAS/Yen Bai** (7-South East Asian Studies), Yen Bai, Vietnam, March–April 2018

**RAJO-MEGHA** (Radiation, Aerosol Joint Observation Modeling Exploration over Glaciers in Himalayan Area), Nepal and India, April–June 2018

**7-SEAS** (7-South East Asian Studies), Maritime Continent, August–September 2018



# Acronyms



7-SEAS	Seven South East Asian Studies
ACAM	Airborne Compact Atmospheric Mapper
ACE	Advanced Composition Explorer
ACHIEVE	Aerosol-Cloud-Humidity Interactions Exploring and Validating Enterprise
AERONET	Aerosol Robotic Network
ALVICE	Atmospheric Lidar for Validation, Interagency Collaboration and Education
ARM IOP-2000	Atmospheric Radiation Measurement program – cloud Intensive Operational Period – March 2000
AROTAL	Airborne Raman Ozone, Temperature, and Aerosol Lidar
ASCENDS	Active Sensing of CO <sub>2</sub> Emissions over Nights, Days, and Seasons
AT Lidar	Aerosol and Temperature Lidar
BASE-ASIA	Biomass-burning Aerosols in South-East Asia: Smoke Impact Assessment
CalVal	Calibration and Validation
CATS	Cloud-Aerosol Transport Lidar
CCD	Charge Coupled Device
CLS	Cloud Lidar System
CMOS	Complementary Metal-Oxide Semiconductor
CNES	Centre National d'Etudes Spatiales
COMMIT	Chemical, Optical, and Microphysical Measurements of <i>In situ</i> Troposphere
CoSMIR	Conical Scanning Millimeter-wave Imaging Radiometer
CoSSIR	Compact Scanning Submillimeter-wave Imaging Radiometer
CPL	Cloud Physics Lidar
CRS	Cloud Radar System
CRYSTAL-FACE	Cirrus Regional Study of Tropical Anvils and Cirrus Layers —Florida Area Cirrus Experiment
DDF	Director's Discretionary Fund
DIAL	Differential Absorption Lidar
DSCOVR	Deep Space Climate Observatory
EDOP	ER-2 Doppler Radar
EPIC	Earth Polychromatic Imaging Camera
EP-TOMS	Earth Probe–Total Ozone Mapping Spectrometer
ER-2	Earth Science Technology Office
ESTO	Earth Sciences Technology Office
EXRAD	ER-2 X-band Radar
FOV	Field of View
FPGA	Field Programmable Gate Array
GACM	Global Atmospheric Composition Mission
GCOS	Global Climate Observing System
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GOES	Geostationary Operational Environmental Satellite
GeoSpec	Geostationary Spectrograph for Earth and Atmospheric Science Applications

GEST	Goddard Earth Sciences and Technology Center
GloPac	Global Hawk Pacific campaign
GLOW	Goddard Lidar Observatory for Winds
GPM	Global Precipitation Measurement
GRUAN	GCOS Reference Upper Air Network
HARGLO	Intercomparison of Wind Profile Systems experiment involving the HARLIE and GLOW instruments
HARLIE	Holographic Airborne Lidar Instrument Experiment
HIWRAP	High-Altitude Imaging and Wind and Rain Airborne Profiler
HOE	Holographic Optical Element
HOPEX	Houston Precipitation Experiment
HSRL	High Spectral Resolution Lidar
ICESat-2	Ice, Cloud, and land Elevation Satellite-2
IHOP	International H <sub>2</sub> O Project
IIP	Instrument Incubator Program
IRAD	Internal Research and Development
ISO	International Standards Organization
JCET	Joint Center for Earth Systems Technology
JPL	Jet Propulsion Laboratory
KILT	Kiritimati Island Lidar Trailer
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LIF	Laser Induced Florescence
MABEL	Multiple Altimeter Beam Experimental Lidar
MOHAVE	Measurements of Humidity in the Atmosphere and Validation Experiments
MPLNET	Micro Pulse Lidar Network
NAAMES	North Atlantic Aerosols and Marine Ecosystems
NAMMA	NASA African Monsoon Multidisciplinary Analyses
NASA	National Aeronautics and Space Administration
NDACC	Network for the Detection of Atmospheric Composition Change
NDSC	Network for the Detection of Stratospheric Change
NIR	Near Infrared
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
OMI	Ozone Monitoring Instrument
PACS	Passive Aerosol and Cloud Suite
PSC	Polar Stratospheric Cloud
RASL	Raman Airborne Spectroscopic Lidar
SAFARI-2000	Southern African Regional Science Initiative 2000
SAGE III	Stratospheric Aerosol and Gas Experiment III

SLED	Storage Latency Estimation Descriptor
SMART	Surface-sensing Measurements for Atmospheric Radiative Transfer
SODISM	SOLar Diameter Imager and Surface Mapper
SOLVE	SAGE III Ozone Loss and Validation Experiment
STROZ LITE	Stratospheric Ozone Lidar Trailer Experiment
SWIR	Short-Wave InfraRed
TC4	Tropical Composition, Cloud, and Climate Coupling
TCSP	Tropical Cloud Systems and Processes
TEFLUN	Texas and Florida Underflight Experiment
THOR	Thickness from Offbeam Returns
TIMS	Technical Information and Management Services
TRL	Technical Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TWILITE	Tropospheric Wind Lidar Technology Experiment
TWT	Traveling Wave Tube
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UV	Ultraviolet
UV/VIS	Ultraviolet and Visible
UV-MFRSR	UV Multifilter Rotating Shadowband Radiometer
VIS	Visible Light
VNIR	Visible and Near InfraRed









