ATMOSPHERE Observing System

National Aeronautics and Space Administration

EARTH SYSTEM OBSERVATORY

# The ALICAT Lidar for the Atmospheric Observing System (AOS) Inclined Orbit: Instrument Overview and Projected Performance

ALICAT
Atmospheric Lidar Instrument for Clouds and Aerosol Transport


Ed Nowottnick[1], John Yorks[1], Matt McGill[2], Patrick Selmer[1], Kenny Christian[1], Melanie Follette-Cook[1]

[1]NASA GSFC

[2]University of Iowa

# ALICAT for AOS-Inclined Science

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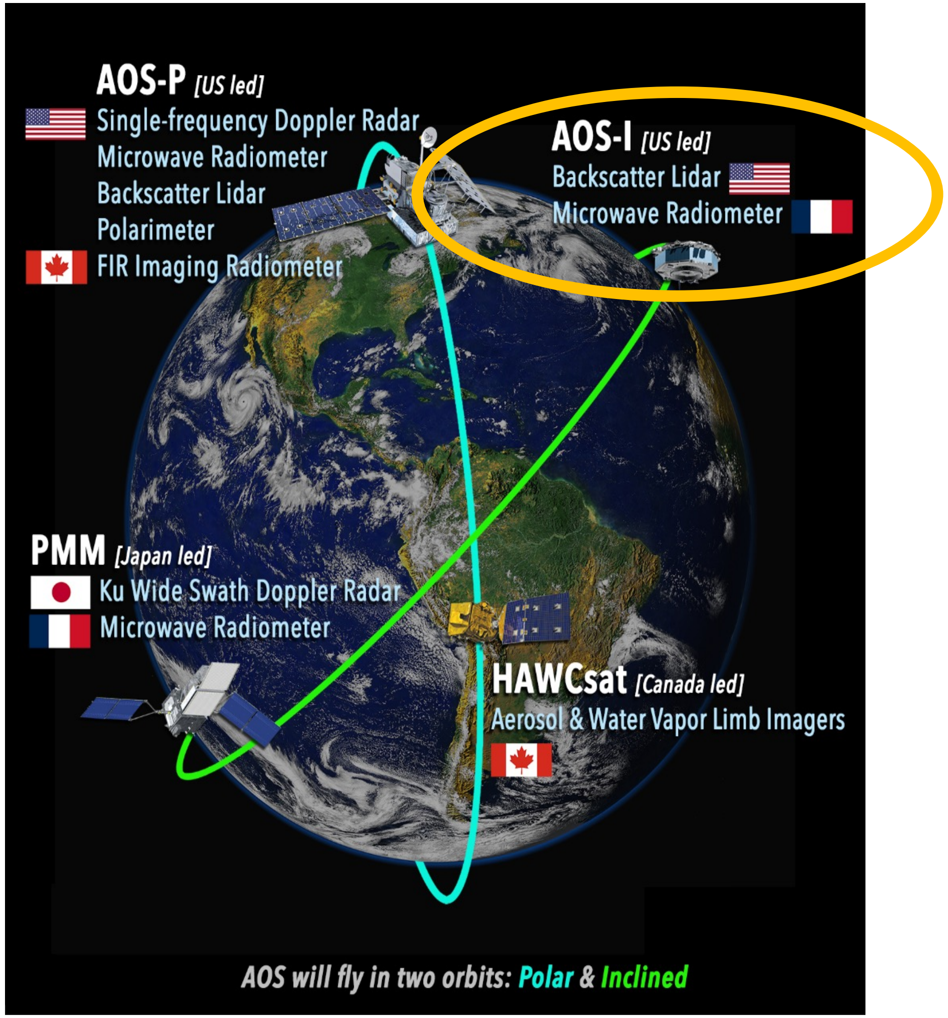
## ALICAT:

- Is an elastic backscatter lidar that provides measurements of attenuated backscatter and linear depolarization at 532 and 1064 nm for detection of clouds and aerosols
- Provides a new exciting opportunity for synergistic products in an inclined orbit (e.g. Ku radar+radiometer+lidar products) not possible with CALIPSO or CATS
- Will deliver near-real time (<6 hours) data products to the applications community
- Offers early science delivery for AOS by launching this decade – there will be a NASA spaceborne atmospheric lidar gap as CALIPSO enters Phase F in 2023

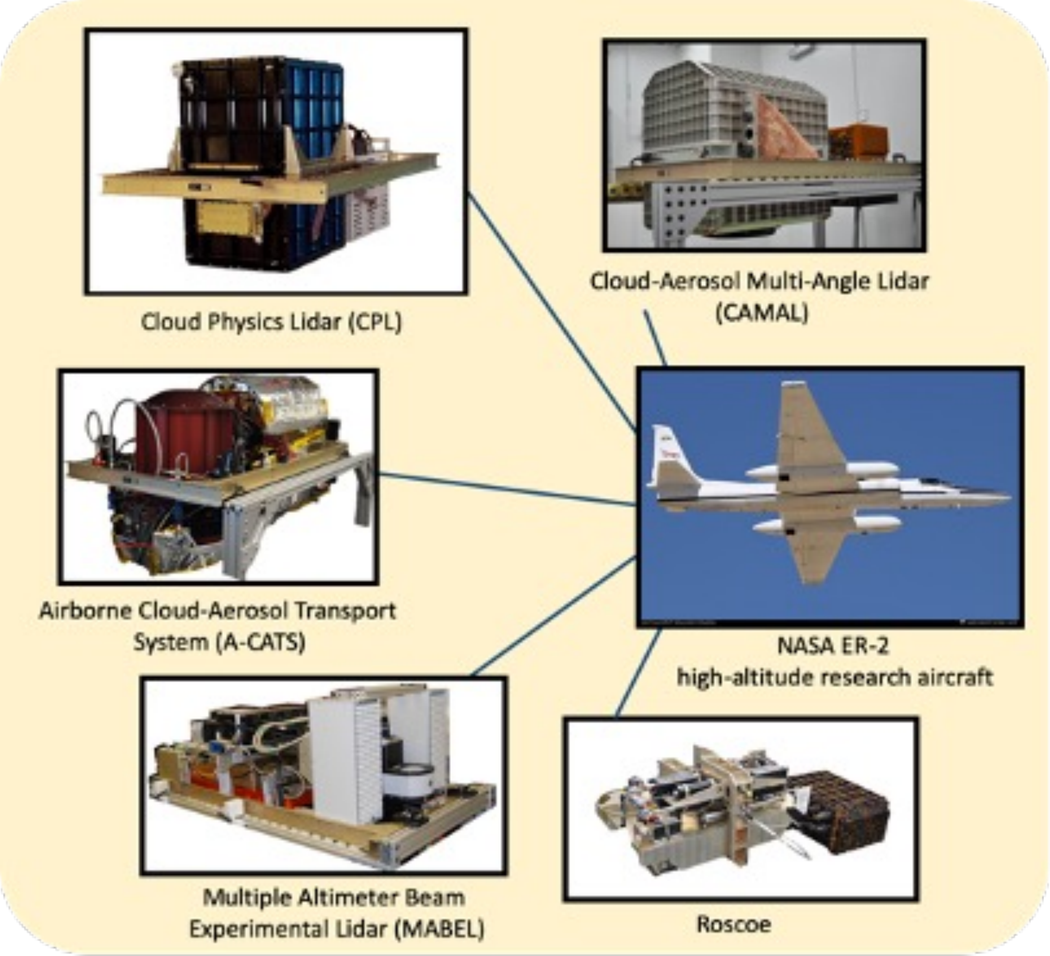
| Lidar Instrument | ALICAT | CALIPSO | CATS |
|---|---|---|---|
| Operational Period | 2028 – 2030+ | 2006 - Present | 2015-2017 |
| 532 nm Total Backscatter | • | • | |
| 1064 nm Total Backscatter | • | • | • |
| 532 nm Depolarization | • | • | |
| 1064 nm Depolarization | • | | • |
| Inclined Orbit | • | | • |
| < 6 Hr Data Latency | • | | • |



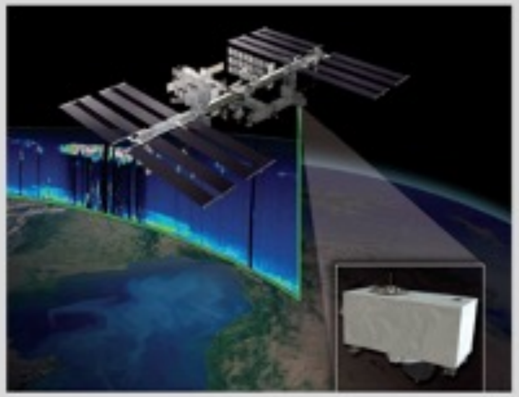
# 20 Years of Lidar Instrument Heritage



Since 1999 multiple high-altitude autonomous instruments have been built by our lidar group at GSFC. All are photon-counting/high rep-rate designs.




UAV Cloud Physics Lidar (UAV-CPL) for Global Hawk



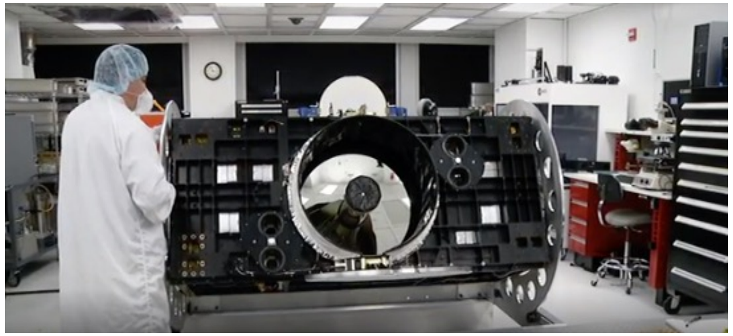
Cloud-Aerosol Transport System (CATS) on International Space Station

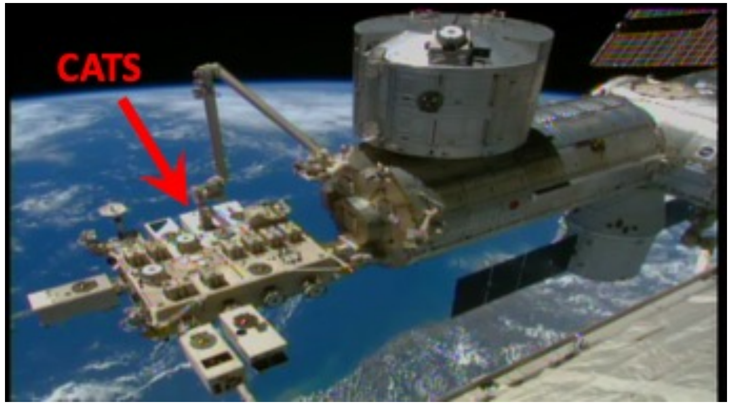
# ALICAT Heritage from CATS

The Cloud-Aerosol Transport System (CATS) was a cloud-aerosol lidar utilizing ISS as an affordable Earth Science observing platform.

- CATS was not a flight mission, was not driven by science requirements
- CATS provided in-space demonstration of measurement capability and technologies
- Designed to operate on-orbit for at least 6 months, CATS operated for 33 months
- CATS was limited in laser power due to ISS safety concerns
- Very low cost ($15 million), CATS was not limited by mass and power so functionality was the focus, not overly refined design for optimal mass/power/etc
- Much of the design and many of the CATS components are re-used for ALICAT, just repackaged to fit the SmallSat form factor
- Algorithms – will leverage proven algorithms from both CATS and CALIOP with additional optimization for AOS

ALICAT offers ***improved SNR*** compared to CATS and an opportunity to provide CALIPSO quality measurements with an added ***time dimension*** in an affordable package






**TIMELINE:**

Jan 10, 2015: CATS launched on SpaceX-5
Jan 22, 2015: installed to JEM-EF
Feb 5, 2015: "first light" with laser
Feb 10, 2015: first "science quality" data
Oct 30, 2017: end of science operations

>200 billion laser pulses on-orbit
14,000+ hours data collected

# Central AOS Science Addressed by ALICAT

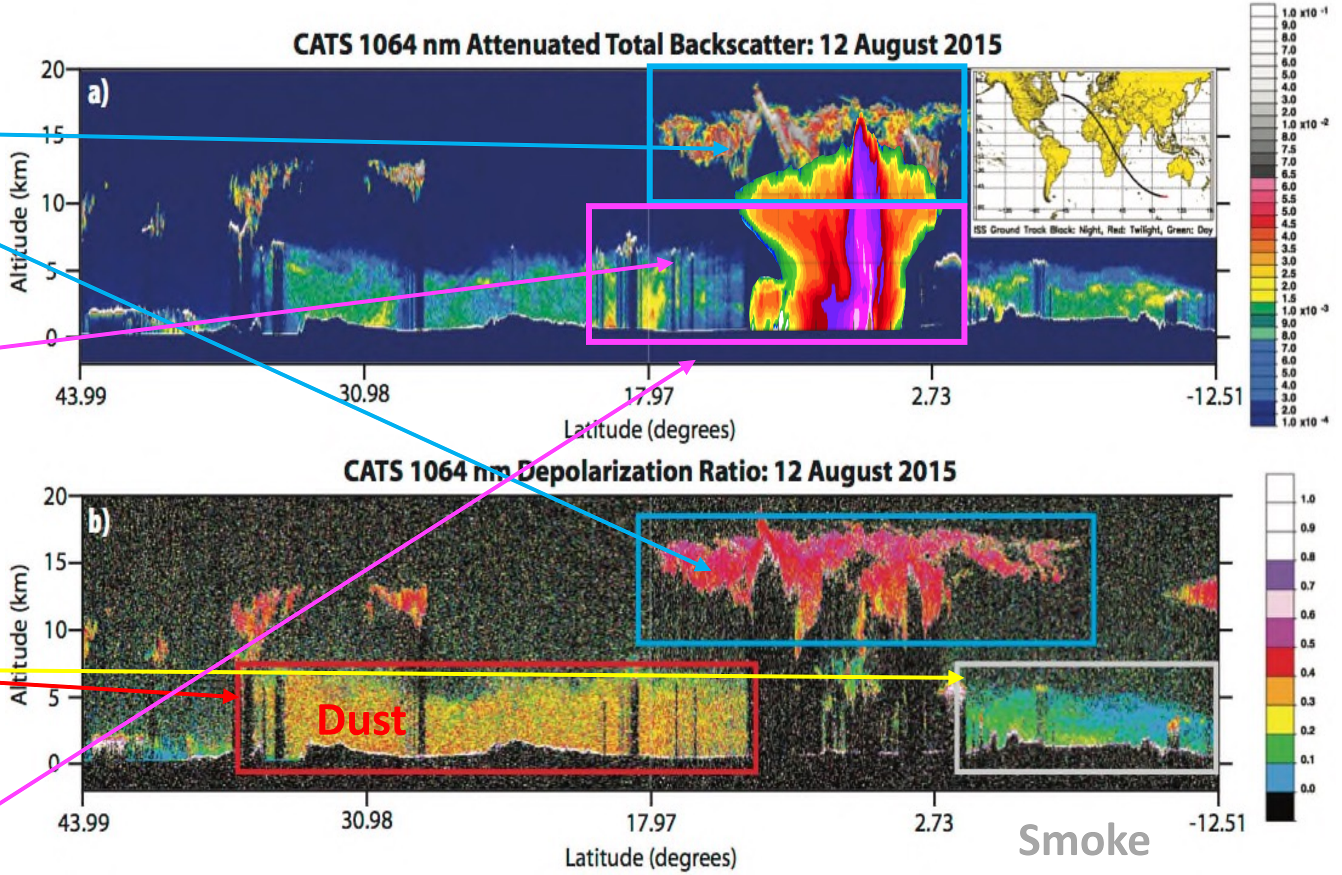
AOS is a process-focused mission with lidars and radars as centerpieces to provide critical vertical measurements of aerosols, clouds, and precipitation – ***and their diurnal variability***

**Objective 2: High Clouds**
Measurements of thin high clouds, especially in the presence of convection

**Objective 3: Convective Storms**
Detection of environmental aerosols in the presence of convection

**Objective 5: Aerosol Attribution/Air-Quality**
Measurements of optically thick dust, smoke, and anthropogenic aerosols in source regions above and within the PBL

**Objective 6: Aerosol Removal & Redistribution**
Synergistic observations of aerosols and convective precipitation/vertical motions




**ALICAT's strengths are detection and quantification of optically thin high clouds and dust/smoke aerosols, all features with diurnal variability**

# Algorithms Heritage



| Product | Parameter | Algorithm Description | References |
|---|---|---|---|
| Lidar Level 1 | Attenuated Backscatter | Night: Backscatter at both wavelengths is calibrated by normalizing to the atmospheric profile (Rayleigh + background aerosol) in the altitude region 31-34 km (1064 nm cirrus color ratio technique will also be used). Day: Calibration transfer from nighttime is used, similar to CALIOP, due to lower SNRs. | Pauly et al. (2019), Kar et al. (2018), Getzewich et al. (2018), Vaughan et al. (2019) |
| | Depolarization Ratio | The linear volume depolarization ratio is the ratio of perpendicular backscatter to parallel backscatter and is calibrated using the polarization gain ratio (PGR), defined as the relative gain between the perpendicular and parallel channels. | Yorks et al. (2016), Liu et al. (2004) |
| Lidar Level 2 | Cloud/Aerosol Layer Height | Layer Detection: A threshold-based method, similar to the CATS and CALIOP techniques, that uses multiple horizontal resolutions (350, 5, 60 km), the 1064 nm wavelength, and identifies clouds embedded within aerosol layers. Cloud-Aerosol Discrimination: A multidimensional PDF technique like the CATS and CALIOP methods using latitude, altitude, backscatter, color ratio, and depolarization ratio. | Yorks et al. (2020), Yorks et al. (2015), Vaughan et al. (2009), Liu et al. (2004, 2009) |
| | PBL Height | Automated algorithm that uses multiple horizontal resolutions and a 3-point binomial filter to the attenuated backscatter data below 7 km, similar to ICESat/GLAS. New machine learning techniques will also be explored. | Palm et al. (2012) |
| | Cloud Phase | Automated algorithm to determine 3 cloud phases based on depolarization ratio, attenuated backscatter, and cloud-top temperature. | Yorks et al. (2020), Yorks et al. (2015), Yorks et al. (2011), Hu et al (2009) |
| | Aerosol Type | Automated algorithm to determine 8 aerosol types based on surface type, altitude, backscatter, color ratio, and depolarization ratio. | Yorks et al. (2020), Yorks et al. (2015), Omar et al. (2009), Kim et al. (2018), Burton et al. (2012) |
| | Extinction Coefficient | Estimated as the product of the lidar ratio and particulate backscatter coefficient using the Fernald/Klett inversion. There are four basic categories of lidar ratio input sources: constrained, unconstrained default, modified default, and opaque. Constrained retrievals will be enabled by polarimeter measurements of clouds and aerosols. | Yorks et al. (2015), Hlavka et al. (2012), Yorks et al. (2011), Burton et al. (2010), Young et al. (2009) |
| | Ice Water Content | An estimate of ice water content is calculated based on its relationship with extinction and temperature, similar to CATS/CALIOP. | Yorks et al. (2015), Heymsfield et al. (2014) |
| NRT | Cloud/Aerosol Layer Height | Same method as L2 data product but using an expedited version that is only performed at a single horizontal resolution | Yorks et al. (2020), Hughes et al. (2016), Yorks et al. (2015) |
| | Attenuated Aerosol Backscatter | Cloud-screened L1 attenuated total backscatter averaged to 5 km horizontal resolution. | Yorks et al. (2020), Hughes et al. (2016), Yorks et al. (2015) |
| | Attenuated Cloud Backscatter | Aerosol-screened L1 attenuated total backscatter averaged to 5 km horizontal resolution. | Yorks et al. (2020), Nobis et al. (2019), Yorks et al. (2015) |

ALICAT has proven & space tested algorithms utilizing heritage from both CATS and CALIOP:

- The CATS algorithm team consisted entirely of early & mid-career scientists and will also support ALICAT.
- Early efforts to incorporate machine learning to improve CATS/ALICAT algorithms has shown promise.
- Algorithms are optimized to deliver NRT products from data acquisition to user's desktops within 3 hours

Retrieval algorithms are fully mature based on CATS-ISS and aircraft instruments and we estimate >90% reuse. The CATS-ISS ATBD is the primary source for retrieval algorithms, including near-real-time data product generation.

The CATS ATBD can be found at: [https://cats.nasa.gov/media/docs/CATS_ATBD_V1-02.pdf](https://cats.nasa.gov/media/docs/CATS_ATBD_V1-02.pdf)

Other information on CATS data processing algorithms can be found at https://cats.nasa.gov/publications

# Simulated Scenes Using Airborne Data

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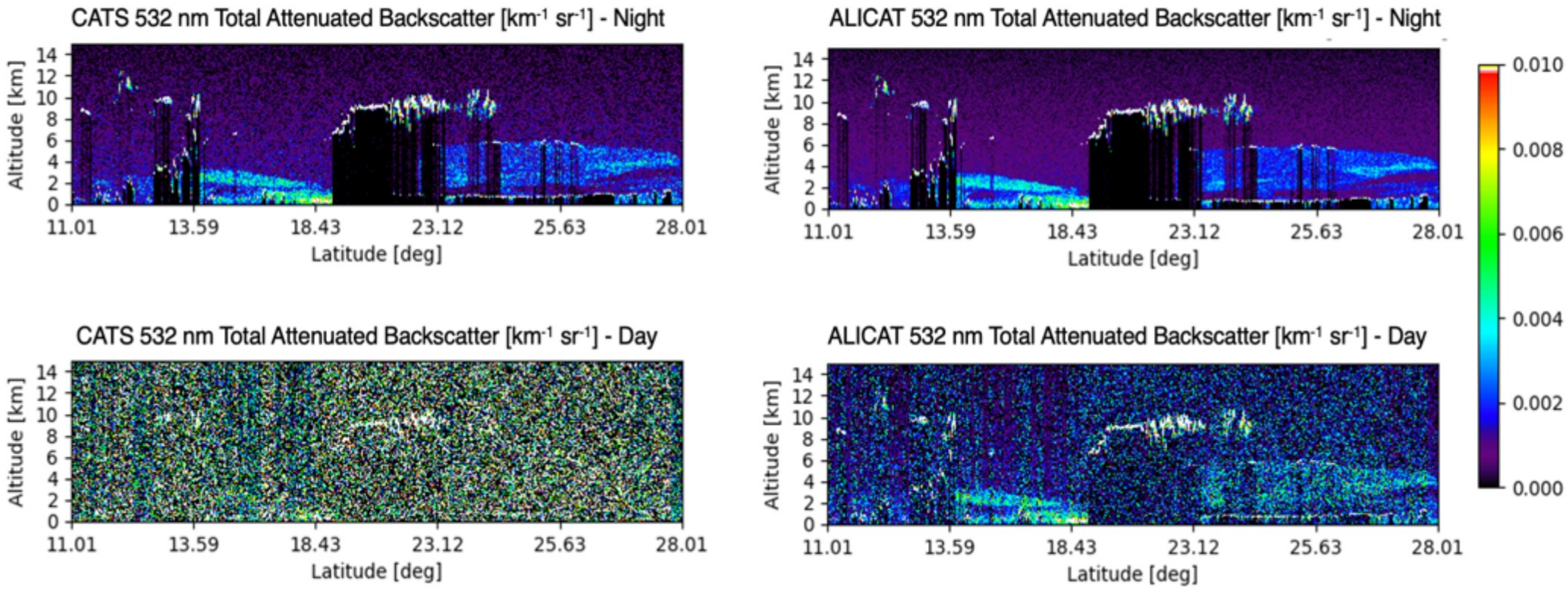
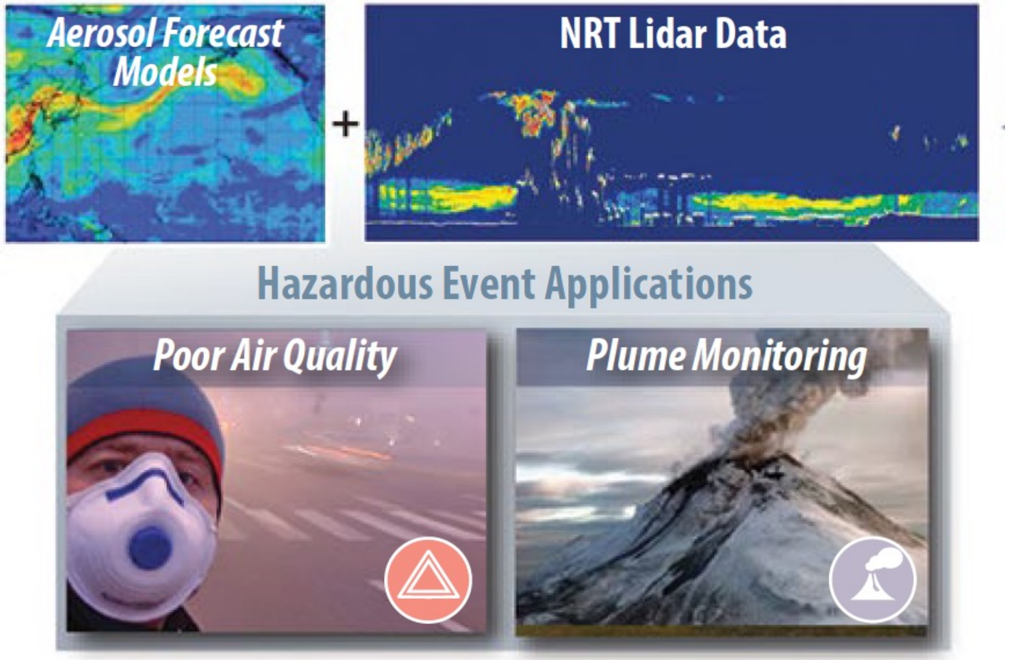



- Airborne and ground-based scenes provide scene realism and variability not captured in global aerosol transport models
- Will be used going forward to refine and test L2 algorithms for feature detection and classification

# Applications: A Progression from CATS

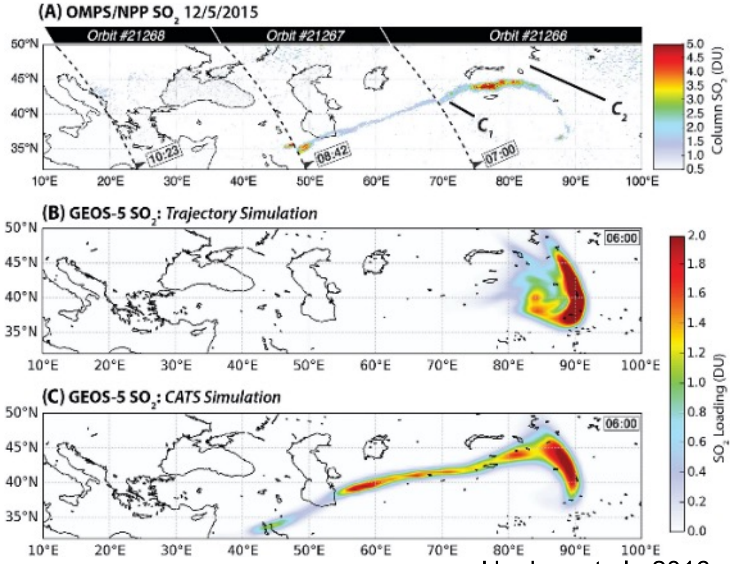
ISS provided real-time data downlink, allowing CATS to pioneer near-real time (<6 hours) data processing for the application community

Our algorithms and infrastructure are already in place to handle the more stringent latency requirements of AOS




Application End Users

Use of CATS to Monitor Volcanic Plumes




Hughes et al., 2016

# New Capability for ALICAT: Real Time Data

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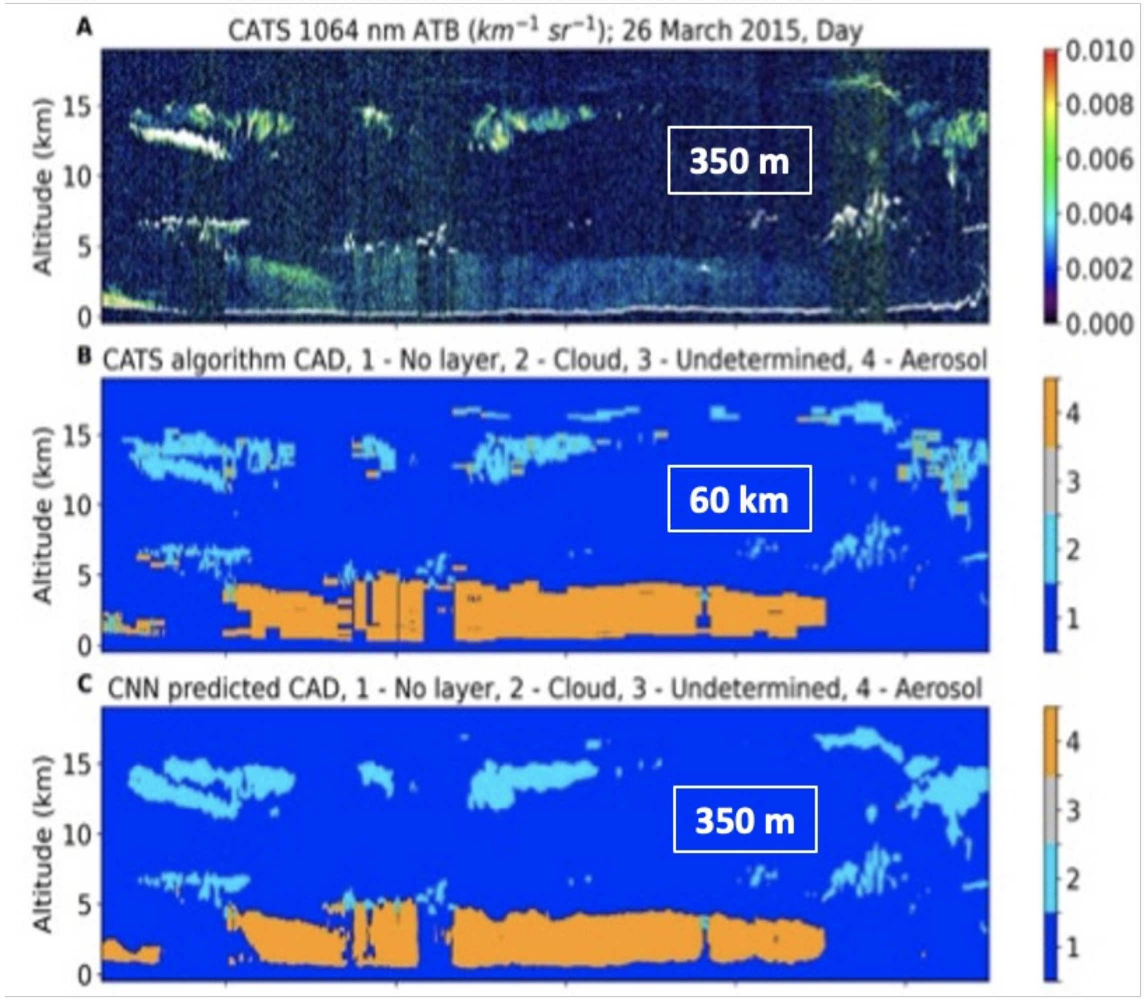
- A key success of CATS was the ability to provide real time data and near-real time data products
- ALICAT builds on this capability to provide data products to users ***in real time***
- ALICAT will include a Jetson TX2 GPU to deliver real-time data
- Signal de-noising and convolutional neural network (CNN) machine learning techniques have been developed and tested on CATS daytime data, which has lower SNR than ALICAT
- Machine techniques show promise for enabling L2 products such as feature detection at L1 resolution




Yorks et al., 2021

# ALICAT Trace Matrix



| Science Objectives | Geophysical Variables: Geophysical Variable | Geophysical Variables: Requirements | Observables | Measurement: Requirements | | Measurement: Projected Performance |
|---|---|---|---|---|---|---|
| **O2. Relate the vertical structure, horizontal extent, ice water path, and microphysical properties of convectively generated high clouds to convective vertical transport and large-scale high clouds to environmental factors.** | **Aerosol-cloud feature mask**<br>**O2, O3, O5, 06** | **Range: .1-20 km**<br>**Res: ≤350 m horiz ≤60 m vertical** | Vertical Profiles of Attenuated Total Backscatter | Vertical Resolution | <= 60 m | 30 m (*60m*) |
| | | | | Horizontal Resolution | <=350 m | 100 m (*350m*) |
| | | | | 532 nm SNR in Aerosol Layer (Dust AOD = 0.3 over ocean) | > 6.3 | 20.7 (night)<br>11.0 (day) |
| **O3. Relate vertical motion within convective storms to their a) cloud and precipitation structures, b) microphysical properties, c) latent heating, d) local environment thermodynamic and kinematic factors such as temperature, humidity, and large-scale vertical motion, e) ambient aerosol loading, and f) diurnal variability. Place these observations into the context of storm life cycle, ambient aerosol profiles, and surface properties** | | | | 1064 nm SNR in Aerosol Layer (Dust AOD = 0.3 over ocean) | > 1.4 | 5.2 (night)<br>2.6 (day) |
| | | | | 532 nm Min Detectable Backscatter at 5 km | <8.0E-4 | 4.1E-4 (night)<br>5.3E-4 (day) |
| **O5. Quantify optical and microphysical aerosol properties in the PBL and free troposphere to improve process understanding, estimates of aerosol emission (including diurnal variability), and speciation.** | **Aerosol Extinction (VIS, NIR)**<br>**O3, O5, O6** | **Unc: maximum of 0.03 $km^{-1}$ or 80% (VIS/NIR)**<br>**Res: ≤5 km (*10 km*) horiz ≤60 m (*120 m*) vert** | | Calibration Uncertainty | <=10% | 3-8% (532)<br>5-10% (1064) |
| | | | | Calibration Resolutions (SNR > 75) | <1500 km (hori)<br><5 km (vert.) | 750 km (hori)<br>2.5 km (vert.) |
| **O6. Relate the vertical structure of aerosol properties to cloud and precipitation properties to improve understanding of processes impacting aerosol vertical transport, removal, and overall lifecycle.** | **Volume depolarization ratio (VIS, NIR)**<br>**O3, O5, O6** | **Range: 0.05-1.0**<br>**Unc: 100% (VIS/NIR)**<br>**Res: ≤5 km (*≤50 km*) horiz, ≤60 m (*≤500 m*) vertical** | Vertical Profiles of Attenuated Perpendicular Backscatter | Polarization Gain Ratio Uncertainty | < 8% | 3-5% |
| | | | | Perpendicular Attn. Backscatter SNR (Dust AOD = 0.3 over ocean) | > 1.5 (532nm)<br>> 0.4 (1064nm) | 2.7/8.8 (532nm, D/N) 1.0/2.6 (1064nm, D/N) |

* additional range provided by Program of Record (Geostationary Sensors)

*Threshold Resolution Requirement (TBD)*

# Measurement Requirements Mapped to GVs

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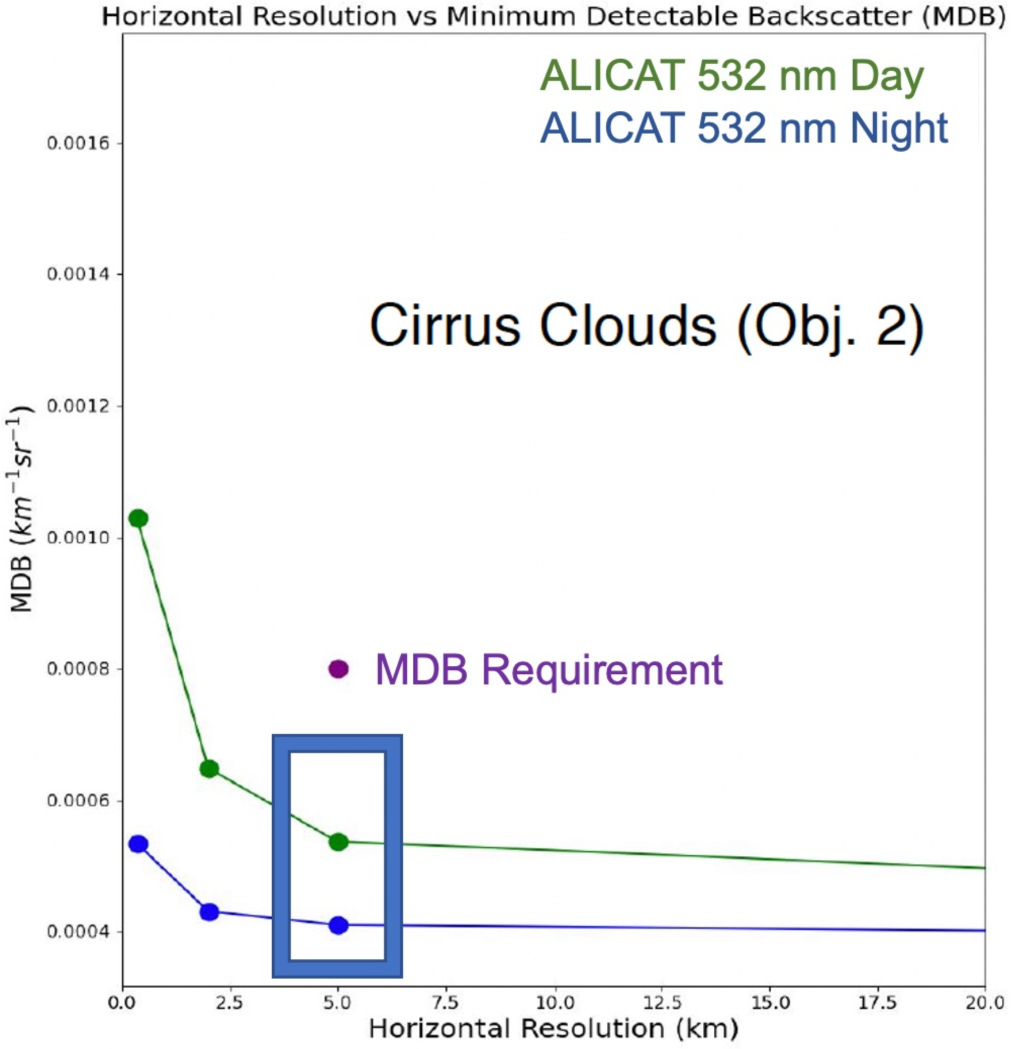
| VFM Geophysical Variable Requirement |
|---|
| Determine the aerosol-cloud vertical feature mask profile at nadir over various times of day, including the aerosol mixing layer height, layer top height of other detectable layers, and base height of non-opaque layers, with an along-track horizontal resolution ≤ 350 m and a vertical resolution ≤60 m for altitudes up to 20 km. |

| # | VFM Measurement Requirements | Projected Performance | B/T |
|---|---|---|---|
| **2A** | ALICAT shall provide continuous vertical profiles of attenuated total backscatter and attenuated perpendicular backscatter at 2 wavelengths and at resolutions of <=60 m (vertical) and <=350 m (horizontal). | 30 m (*60 m*) vertical 100 m (*350 m*) horiz. | T |
| **2B** | ALICAT shall detect the height of aerosol and cloud layers at nadir with resolutions of <=60 m (vertical) and 350 m or less (horizontal) with a minimum detectable backscatter (MDB) of 8.0E-4 km-1 sr-1 at 5 km | 4.1e-4 (night) 5.3e-4 (day) | B |



# Measurement Requirements Mapped to GVs

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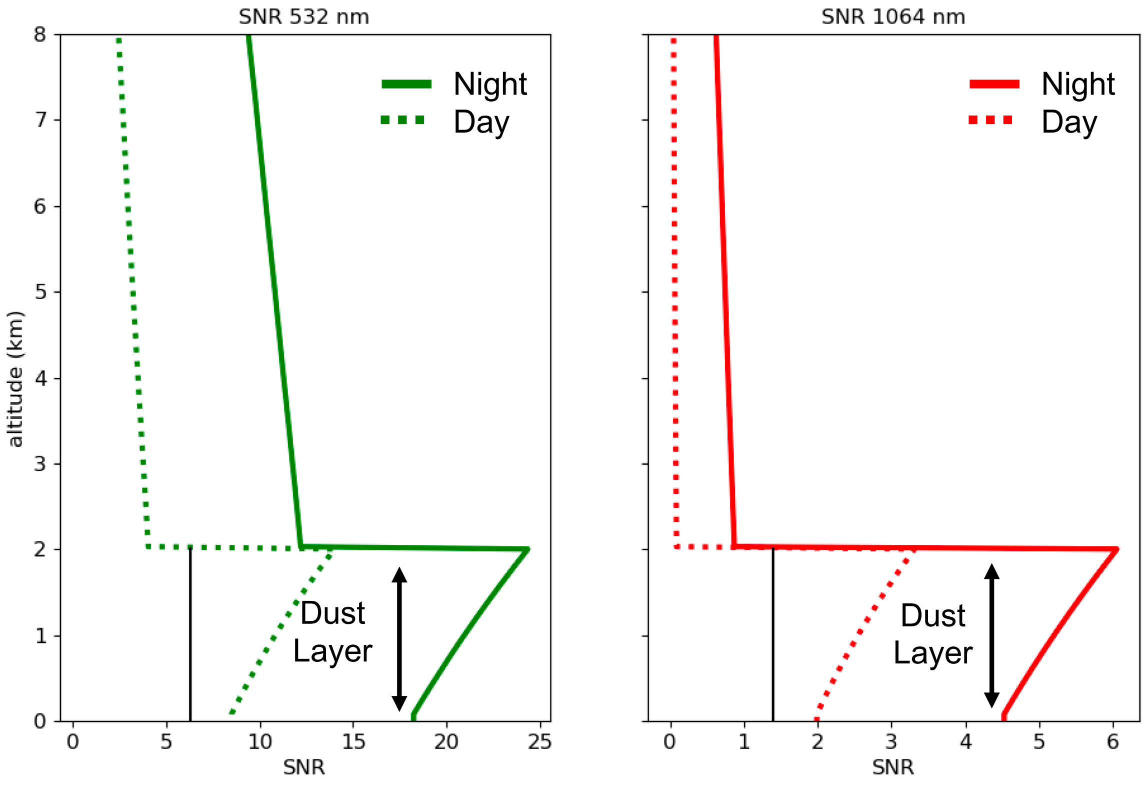
| Aerosol Extinction Geophysical Variable Requirement |
|---|
| Quantify vertical profiles of aerosol extinction at nadir in the visible (VIS) and near-infrared (NIR) over various times of day to within uncertainties of the maximum of 0.03 $km^{-1}$ or 80 percent (VIS and NIR) at an along-track horizontal resolution of ≤5 km and a vertical resolution of ≤60 m for aerosol backscatter > $6x10^{-4}$ $km^{-1}$ $sr^{-1}$ under clear sky conditions. |

| # | Aerosol Extinction Measurement Requirements | Projected Performance | B/T |
|---|---|---|---|
| 2C | ALICAT shall produce and distribute >80% of calibrated attenuated backscatter profiles, depolarization ratio profiles, and feature heights within 6 hours of collection to applications end users. | < 6 hours | B |
| 2D | ALICAT shall calibrate attenuated total backscatter profiles with a relative calibration uncertainty of <= 8% at 532 nm and <= 10% at 1064 nm. | 3-8% (532)<br>5-10% (1064) | T |
| 2E | ALICAT shall measure 532 nm backscatter at resolutions of >5 km (vertical) and >1500 km (horizontal) within the calibration altitude region (32.5-35 km) with SNR of >75. | 750 km (hori)<br>2.5 km (vert.) | T |
| 2F | ALICAT shall measure 532 nm backscatter at resolutions of <=60 m (vertical) and <=5 km (horizontal) within a dust aerosol layer (dust AOD over ocean = 0.3) with SNR of >6.3 | 20.7 (night)<br>11.0 (day) | B |
| 2G | ALICAT shall measure 1064 nm backscatter at resolutions of <=60 m (vertical) and <=5 km (horizontal) within a dust aerosol layer (dust AOD over ocean = 0.3) with SNR of >1.4 | 5.2 (night)<br>2.6 (day) | B |

## ALICAT SNR for Dust AOD=0.3 Over Ocean



# Measurement Requirements Mapped to GVs

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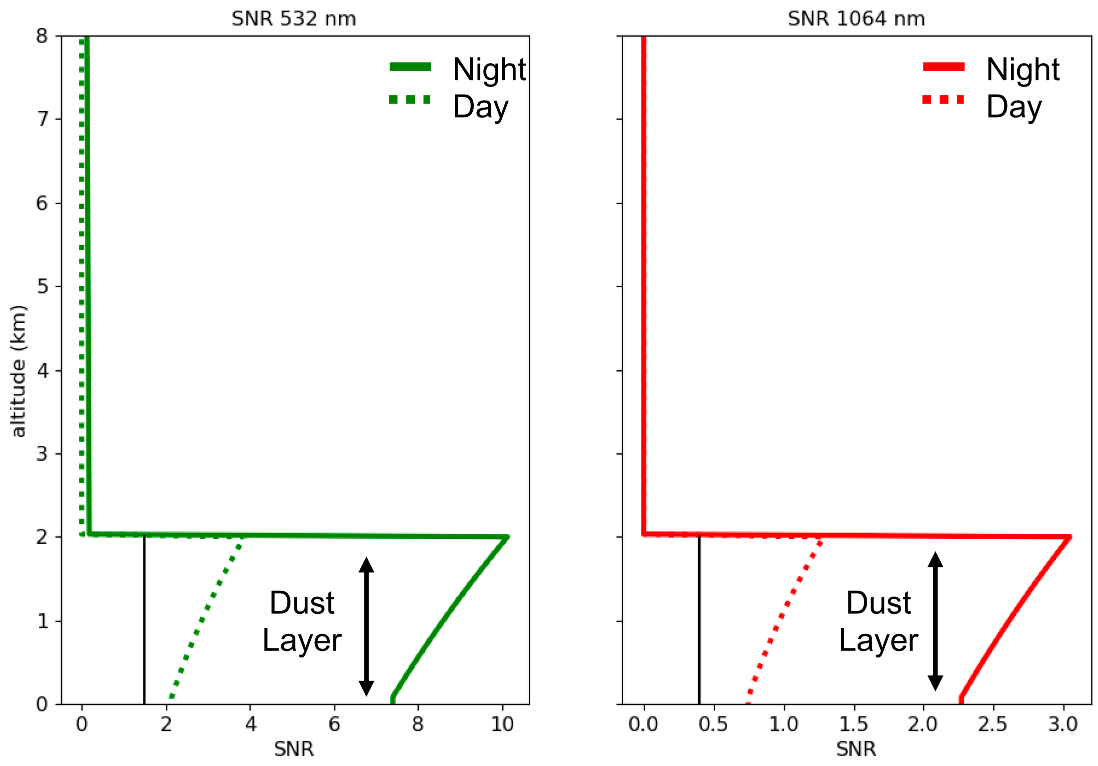
| Volume Depolarization Ratio Geophysical Variable Requirement |
|---|
| Quantify vertical profiles of volume depolarization ratio at nadir within detectable aerosol layers in the VIS, NIR over various times of day to within uncertainties of 100 percent (VIS and NIR) at an along-track horizontal resolution of ≤5 km and a vertical resolution of ≤60 m for aerosol backscatter > $6x10^{-4}$ $km^{-1}$ $sr^{-1}$ under clear sky conditions. |

| # | Volume Depolarization Ratio Measurement Requirements | Projected Performance | B/T |
|---|---|---|---|
| **2A** | ALICAT shall provide continuous vertical profiles of attenuated total backscatter and attenuated perpendicular backscatter at 2 wavelengths and at resolutions of <=60 m (vertical) and <=350 m (horizontal). | 30 m (*60 m*) vertical<br>100 m (*350 m*) horiz. | T |
| **2H** | ALICAT shall measure 532 nm and 1064 nm perpendicular backscatter at resolutions of <=60 m (vertical) and <=5 km (horizontal) within a dust layer (dust AOD over ocean = 0.3) with SNR > 1.5 at 532 nm and SNR > 0.4 at 1064 nm | 2.7/8.8 (532nm, D/N)<br>1.0/2.6 (1064nm, D/N) | B |

## ALICAT Perpendicular Channel SNR for Dust AOD=0.3 Over Ocean



# Key Takeaways for ALICAT



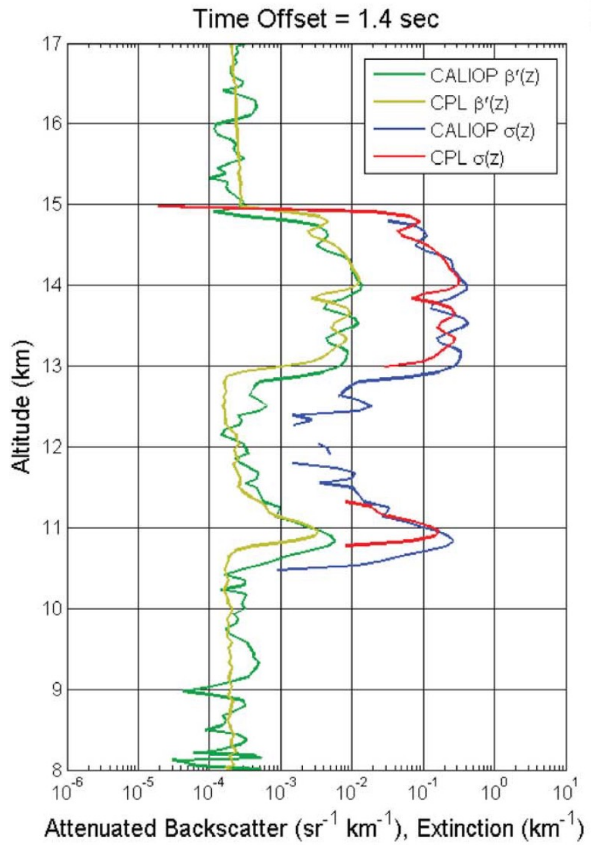
## ALICAT:

- Provides critical measurements of aerosol and cloud diurnal variability for AOS and a first-ever opportunity to pair a lidar with a radar and microwave radiometers in an inclined orbit
- Provides a low-cost opportunity for early science return for AOS this decade
- Compact design enables placement options on AOS spacecraft
- Has high heritage in all key areas: hardware and design, measurements, applications, and personnel
- Led to the development of a more comprehensive simulation capability for requirement verification and future algorithm development/tesing

# ALICAT Science for AOS: Cirrus Clouds

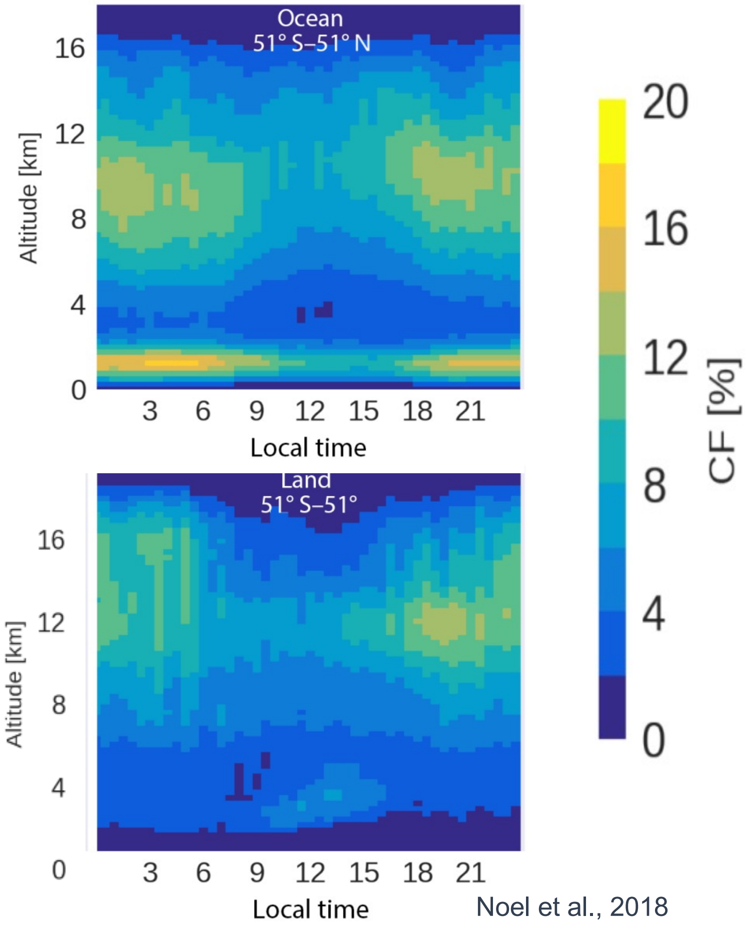
- CALIPSO has provided cloud measurements for 16 years in a sun-sync orbit
- CATS provided diurnal measurements of clouds with a single wavelength, but was a tech demo without science requirements
- ALICAT offers ***improved SNR*** compared to CATS and an opportunity to provide CALIPSO quality measurements with an added ***time dimension*** in an affordable package
- AOS-I matches ALICAT with microwave radiometers and a Ku radar for diurnal sampling of convective processes

**CALIPSO Cirrus Validation of Cloud Measurements using Airborne CPL**




Hlavka et al., 2012

**Diurnal Cycle of Clouds Observed by CATS Tech Demo (2015-2017)**




Noel et al., 2018

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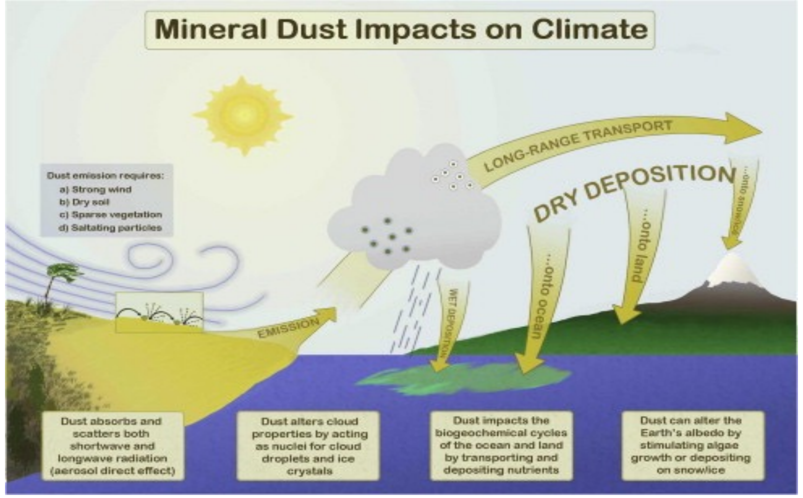
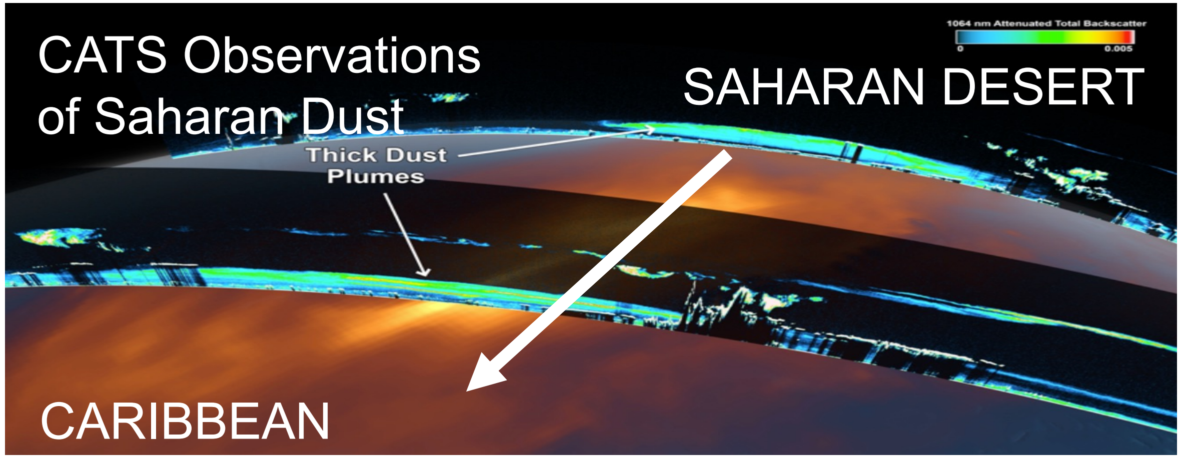
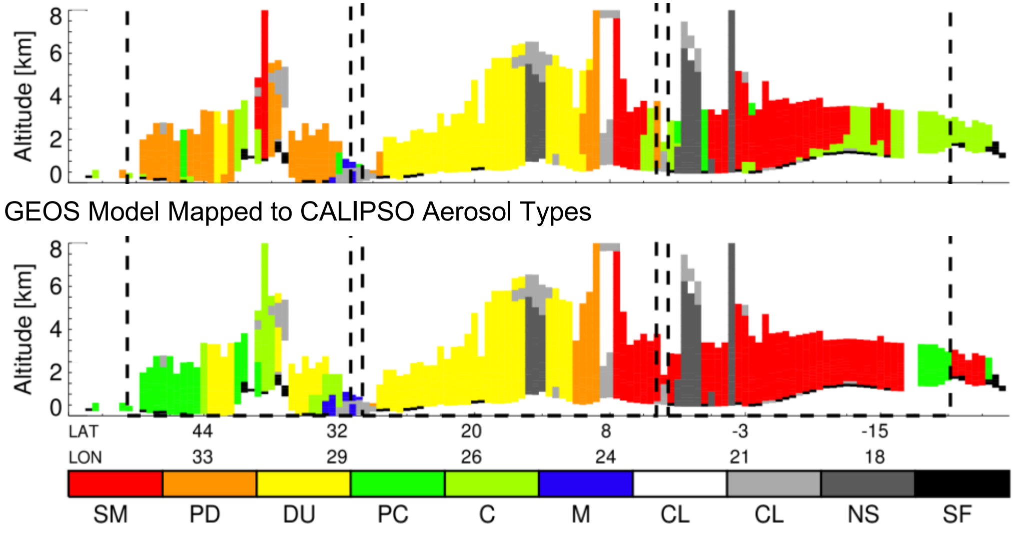
# ALICAT Science for AOS: Dust Aerosols

Dust emissions have a diurnal cycle and interact with convective processes that impact cloud properties which in turn influence dust removal processes

Depolarization measurements provided by ALICAT are used to discern dust from other aerosol types and have been shown to type best for dust/dust mixtures



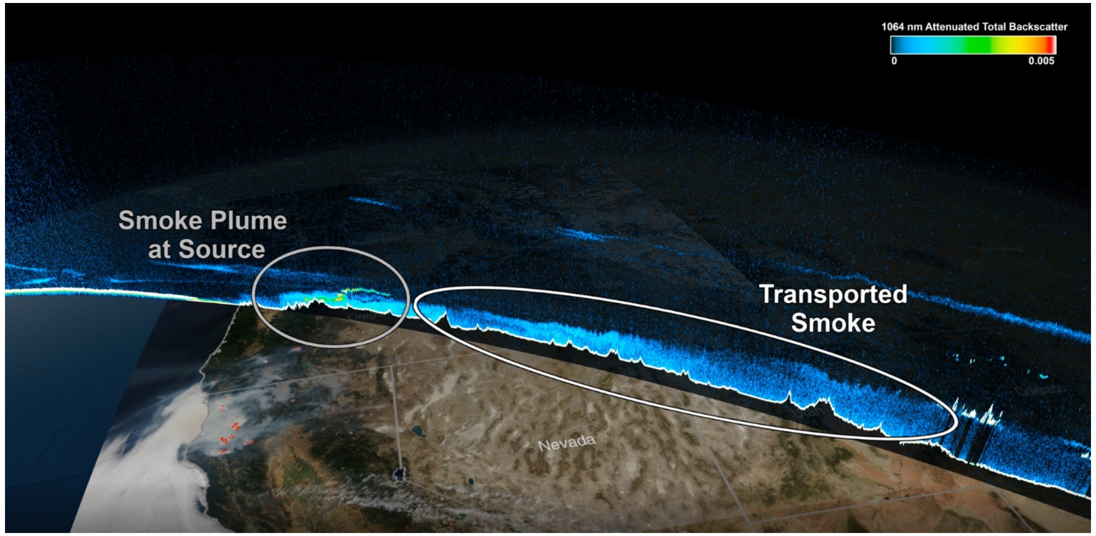

Nowottnick et al., 2015

# ALICAT Science for AOS: Smoke Aerosols



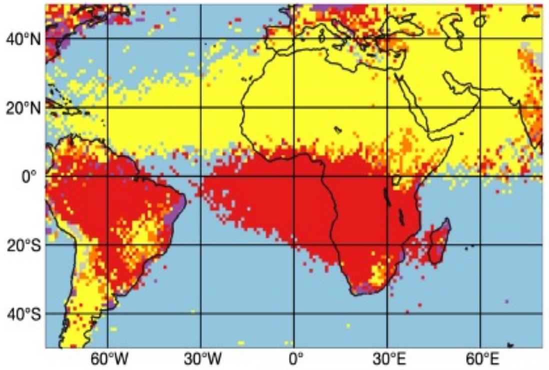
- Smoke aerosols exhibit strong diurnal cycles that typically correspond to enhanced burning during daytime hours*
- Smoke interacts with the evolution of the planetary boundary layer and has implications for the diurnal cycle of convection** - important for smoke transport forecasting in current models***

**Smoke from Oregon: Implications for Transport and Air Quality Observed by CATS**

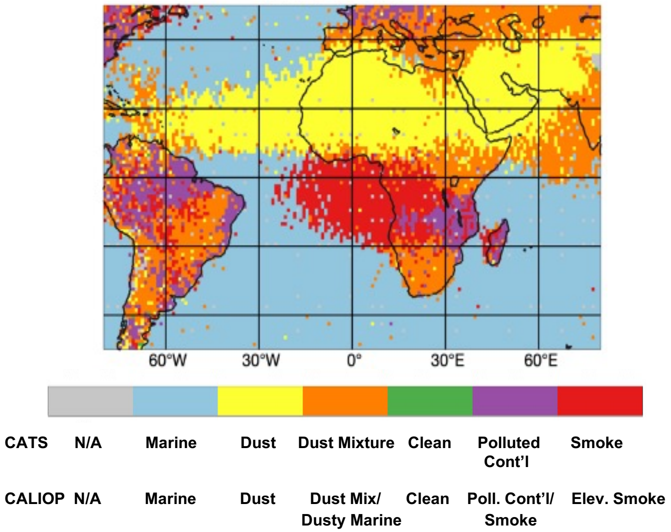



* Hyer et al., 2013
** Zhang and Zuidema, 2019; Hodzik and Duvell, 2017
*** Ye et al., 2021

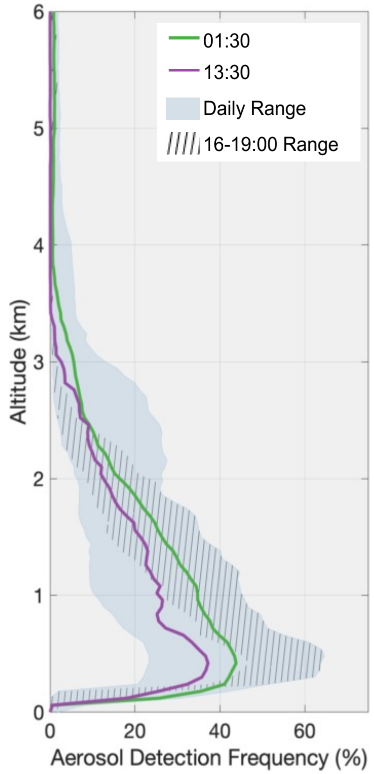
**CATS V3 2015-2017**




**CALIPSO V4.20 2015-2017**




**Diurnal Variability of Smoke Aerosols Observed by CATS over Borneo**



# Instrument Specs



| Parameter | Value |
|---|---|
| Laser Type | Nd:$YVO_4$ |
| Laser Wavelengths | 1064 and 532 nm |
| Depolarization | 1064 and 532 nm |
| Laser Repetition Rate | 4 kHz |
| Laser Pulse Energy | 3 mJ at 1064 nm; 2 mJ at 532 nm |
| Laser Pulse Length | ~10 ns |
| Transmitted Beam Divergence | 70 µrad (1064 nm)/35 µrad (532 nm) |
| Telescope Diameter | 60 cm |
| Telescope Field of View | 115 µrad (1064 nm)/85 µrad (532 nm) |
| Vertical Resolution | 30 m or 60 m |
| Horizontal Resolution | 70 Hz or 100 m along-track |

# ALICAT: Vertical Measurements of Aerosols and Clouds for AOS-I

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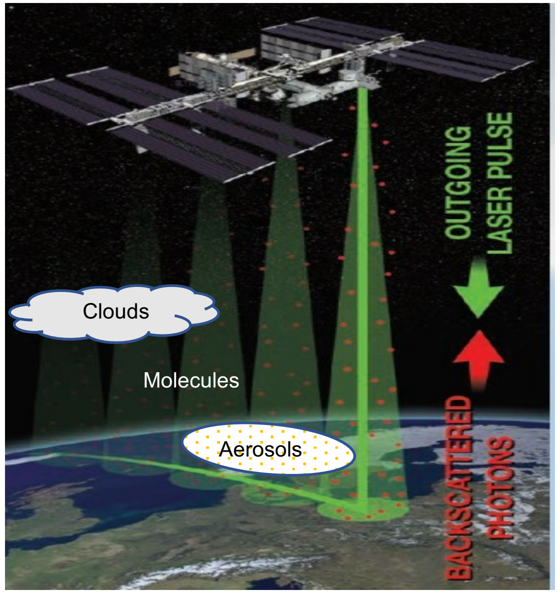
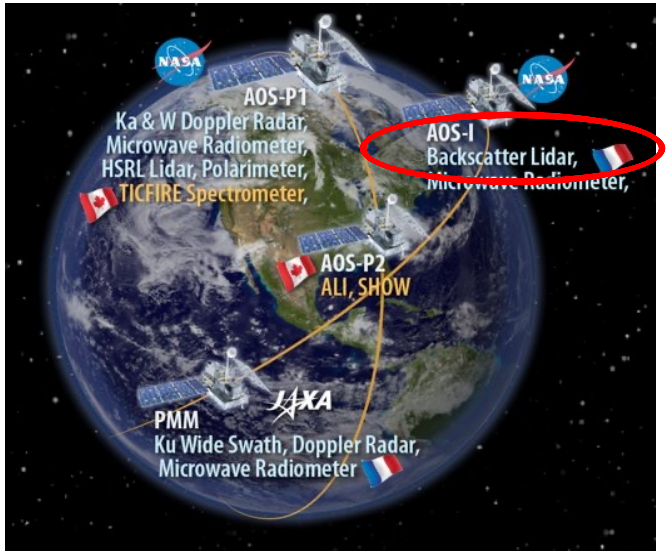
ALICAT:

- Provides vertical profiles of total and perpendicular attenuated backscatter at 532 and 1064 nm to identify clouds, aerosols, as well as their phase and type
- Provides a new exciting opportunity for synergistic products in an inclined orbit (e.g. Ku radar+radiometer+lidar products) not possible with CALIPSO or CATS
- Will deliver near-real time (<6 hours) data products to the applications community
- Offers early science delivery for AOS by launching this decade – there will be a NASA spaceborne atmospheric lidar gap as CALIPSO enters Phase F in 2023

| Lidar Instrument | ALICAT | CALIPSO | CATS |
|---|---|---|---|
| Operational Period | 2028 – 2030+ | 2006 - Present | 2015-2017 |
| 532 nm Total Backscatter | ● | ● | |
| 1064 nm Total Backscatter | ● | ● | ● |
| 532 nm Depolarization | ● | ● | |
| 1064 nm Depolarization | ● | | ● |
| Inclined Orbit | ● | | ● |
| < 6 Hr Data Latency | ● | | ● |



# CATS as Pathfinder

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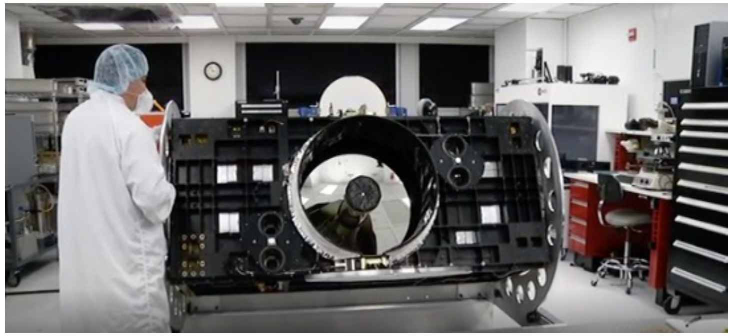
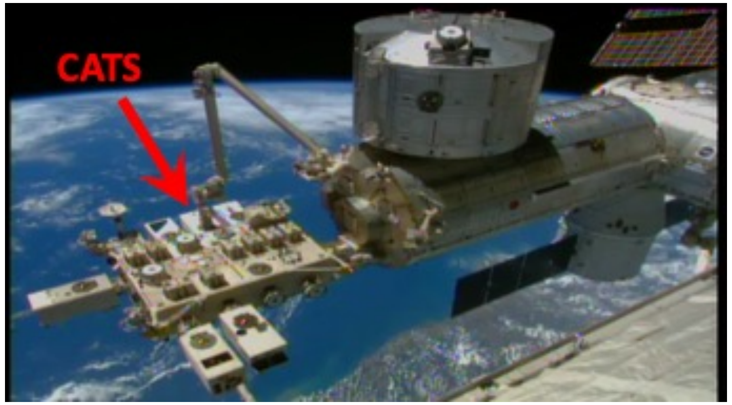
The Cloud-Aerosol Transport System (CATS) was a cloud-aerosol lidar utilizing ISS as an affordable Earth Science observing platform.

- CATS was not a flight mission, was not driven by science requirements
- CATS provided in-space demonstration of measurement capability and technologies
- Designed to operate on-orbit for at least 6 months, CATS operated for 33 months
- CATS was limited in laser power due to ISS safety concerns
- Very low cost ($15 million), CATS was not limited by mass and power so functionality was the focus, not overly refined design for optimal mass/power/etc
- **Much of the design and many of the CATS components are re-used for ALICAT, just repackaged to fit the SmallSat form factor**

**CATS data provided science and algorithm advancements, near-real time data for hazard detection and tracking, and near-real time data for assimilation to aerosol models.**






TIMELINE:

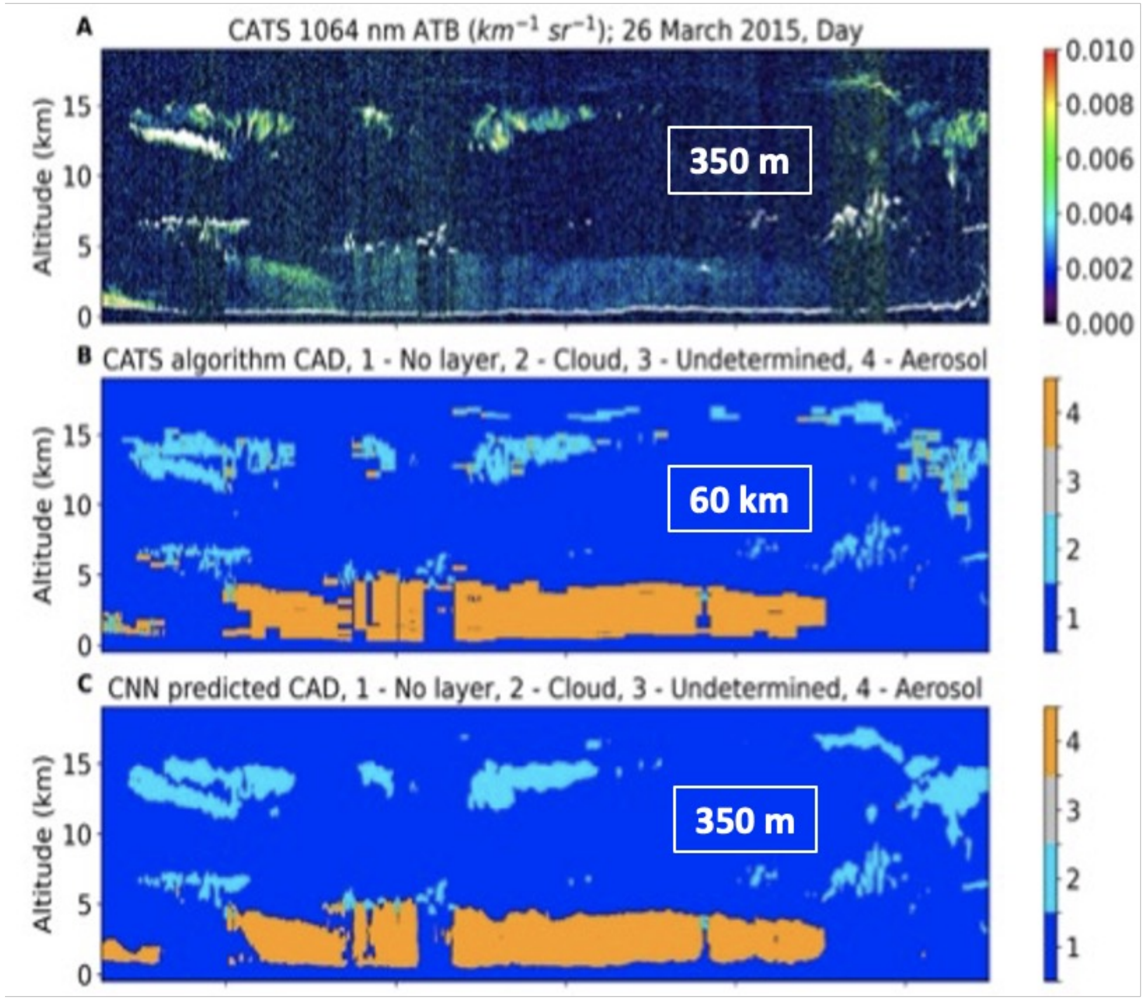
Jan 10, 2015: CATS launched on SpaceX-5
Jan 22, 2015: installed to JEM-EF
Feb 5, 2015: "first light" with laser
Feb 10, 2015: first "science quality" data
Oct 30, 2017: end of science operations

>200 billion laser pulses on-orbit
14,000+ hours data collected

# ALICAT: Providing Real Time Data Products

EARTH SYSTEM OBSERVATORY

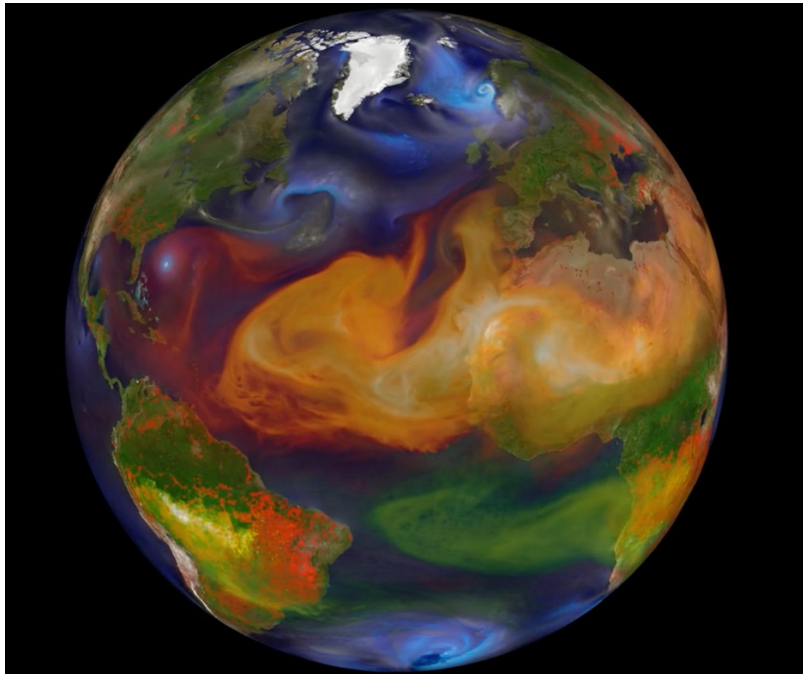
- A key success of CATS was the ability to provide real time data and near-real time data products
- ALICAT builds on this capability to provide data products to users ***in real time***
- Jetson TX2 GPU mounted adjacent to ALICAT Data System Card
- Separate interfaces, locally switched power
- Fault tolerant
  - ALICAT Data System operates with or without Jetson
    - Monitors Jetson "heartbeat" function, cycles power if fault detected.




Yorks et al., 2021

# Simulated Scenes Using Model Inputs

- Global aerosol transport model simulation such as the NASA GEOS nature run paired with a radiative transfer model such as VLIDORT provide opportunities to simulate performance and test algorithms for various viewing and solar background conditions beyond simple canonical cases



GEOS Nature Run Image courtesy of NASA GSFC SVS