



A Simulation Capability Developed for NASA GSFC's Spaceborne Backscatter Lidars: Overview and Projected Performance for the Upcoming AOS Mission

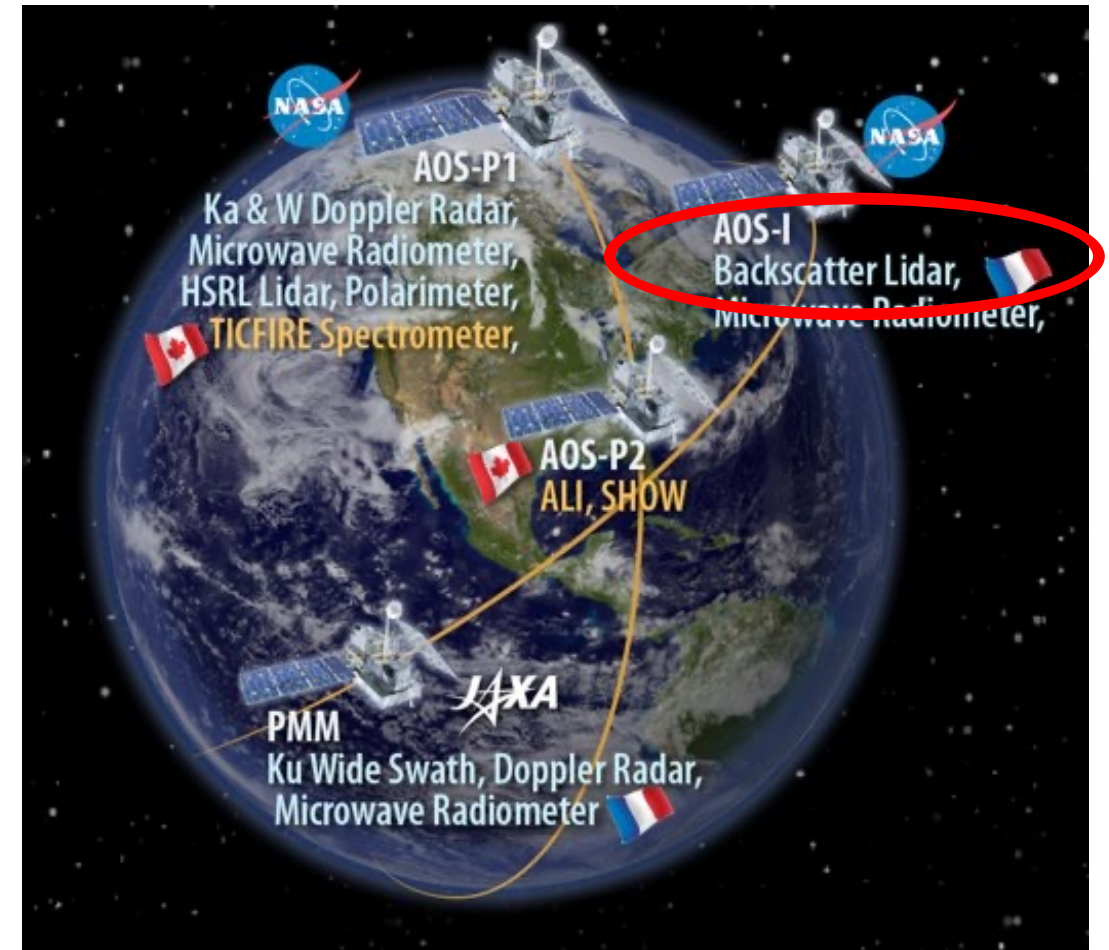
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NASA GSFC



ALICAT for AOS-Inclined Science

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

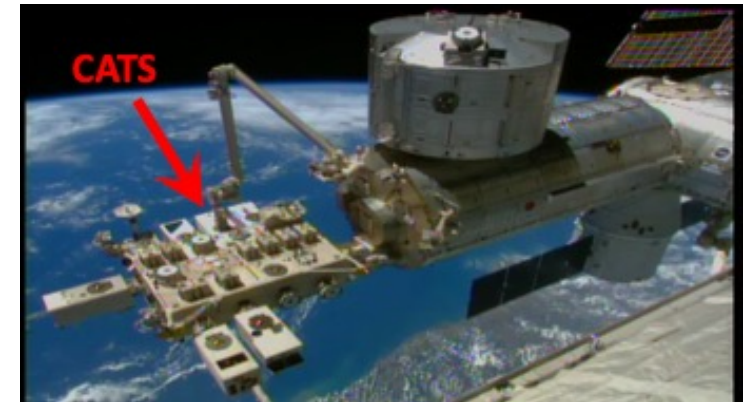
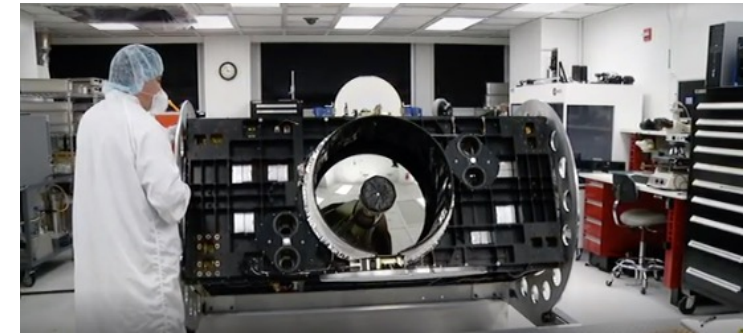


ALICAT Heritage from CATS

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

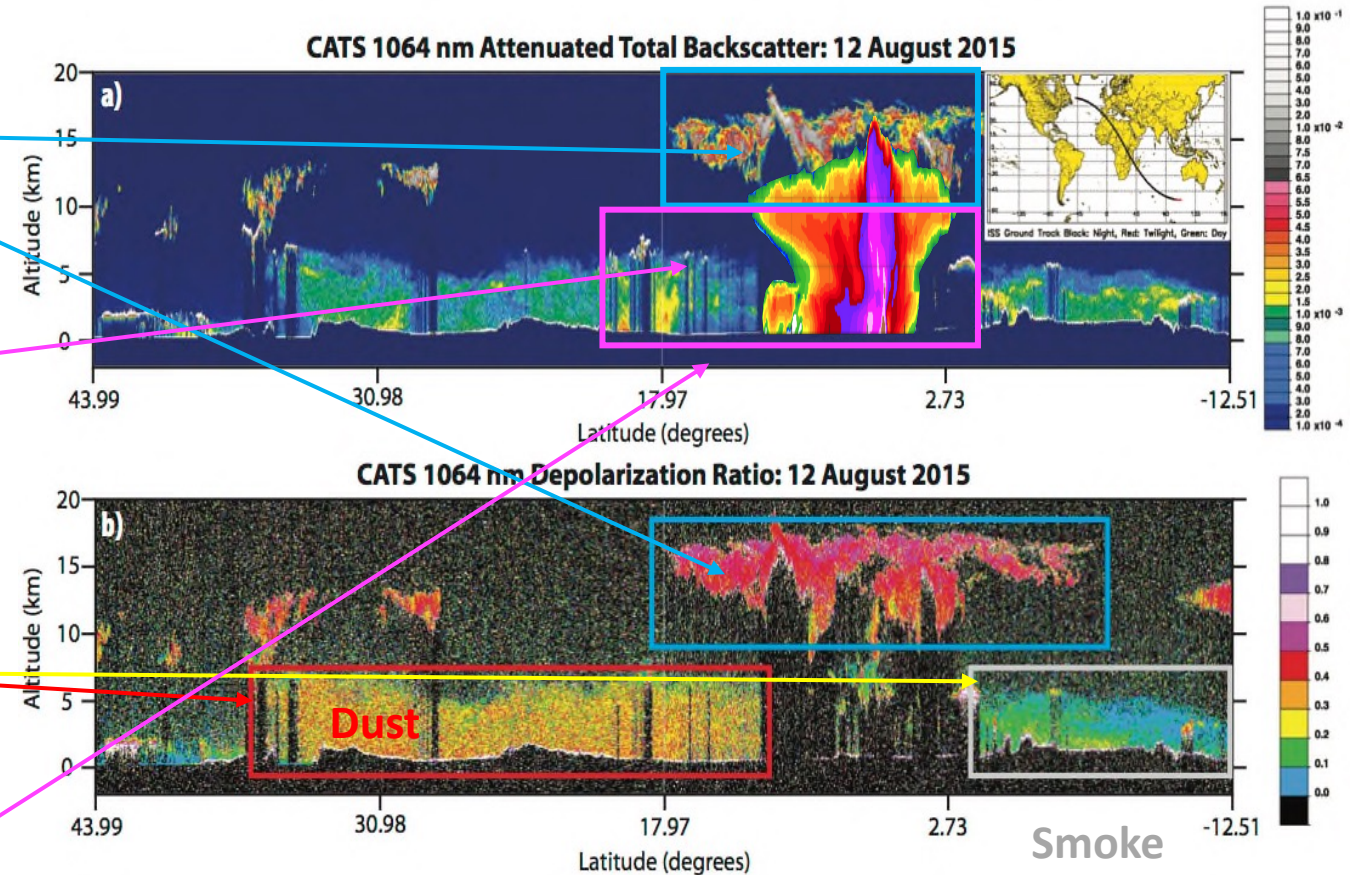
Detection of environmental aerosols in the presence of convection

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

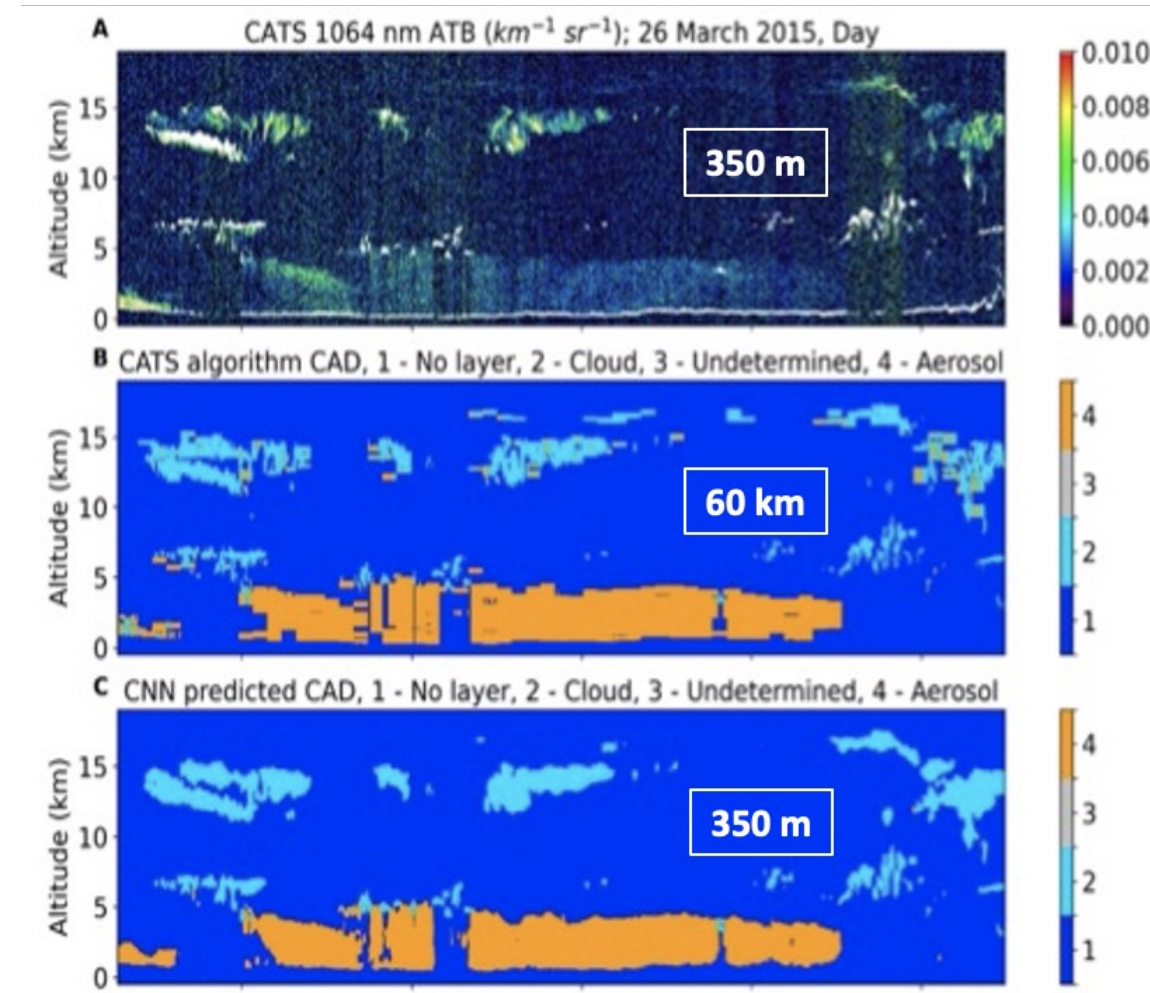
Synergistic observations of aerosols and convective precipitation/vertical motions



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

New Capability for ALICAT: Real Time Data

- 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

Simulation Capability

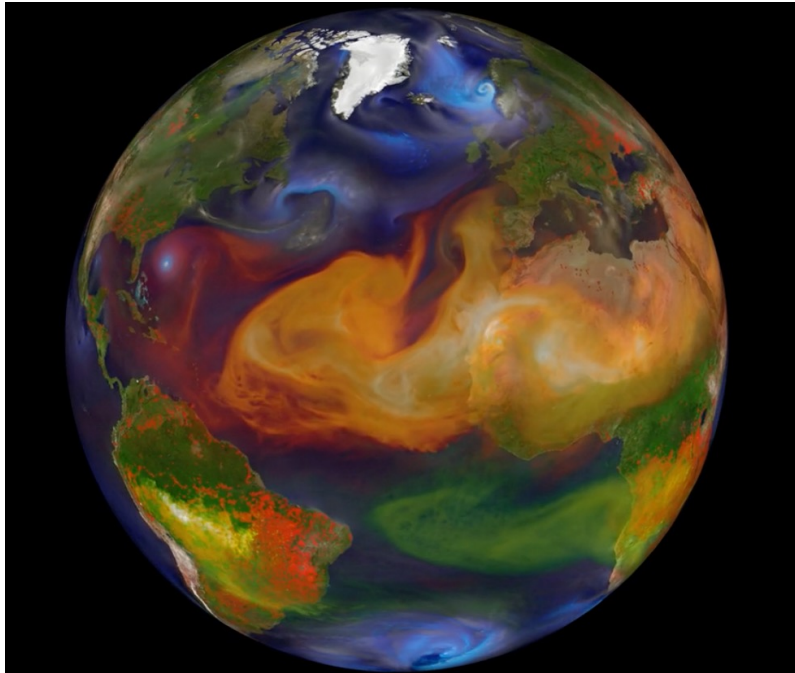
- We developed a lidar simulation capability for the Cloud Aerosol Transport System (CATS) technology demonstration that flew on the ISS for 2015-2017

$$N(r) = \frac{C_{bks}}{r^2} \times (P_P(\pi, r)B_P(r)) + P_M(\pi, r)B_M(r))e^{-2 \int_0^r \sigma(r')dr'} + B_S + B_D$$

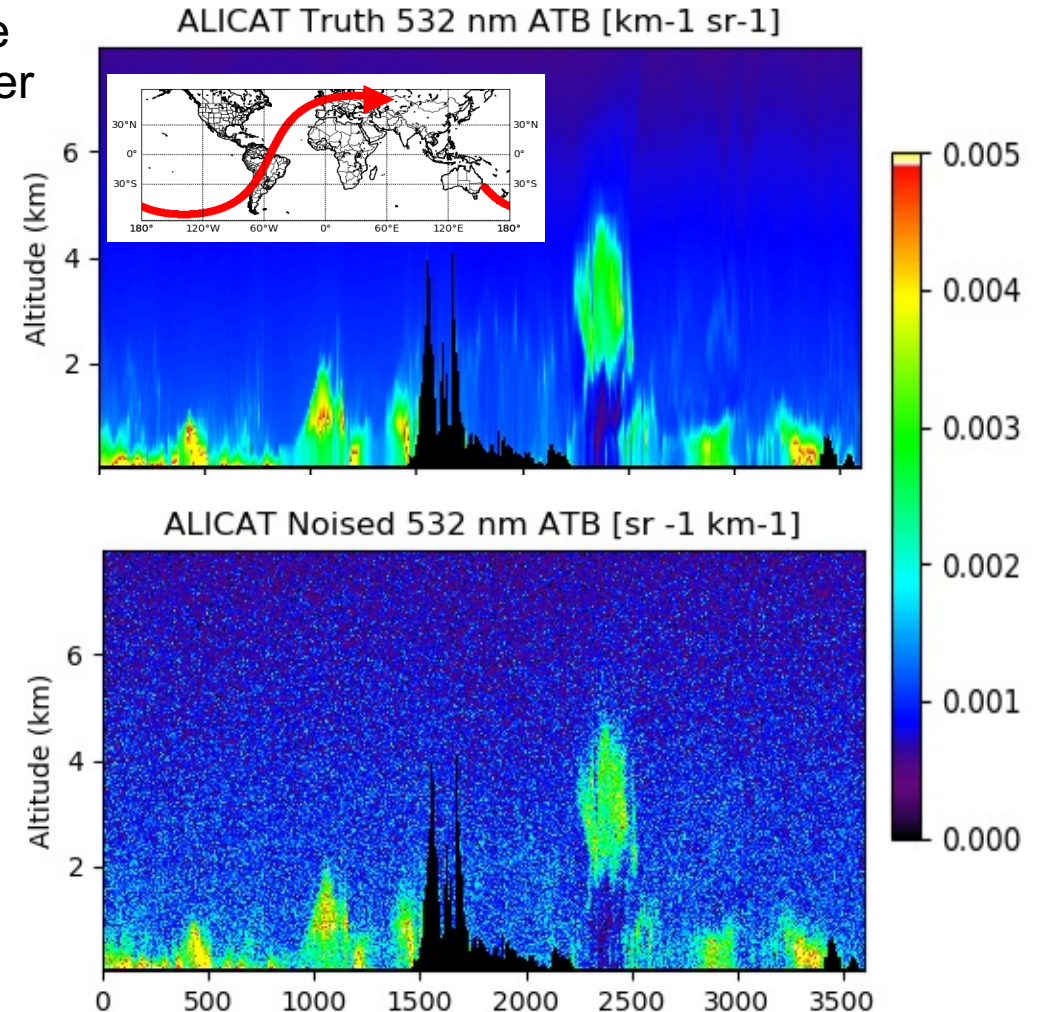
- Our simulator capability was improved during the ACCP study phase to simulate additional scene complexity using inputs from the NASA GEOS model and airborne/ground-based data, along with canonical cases
- Configurable for various instrument parameters and horizontal/vertical resolutions
- Instrument specs are used to simulate scenes under various viewing conditions over different surface types:
 - Raw photon counts with random Poisson noise
 - L1B products: total attenuated backscatter and volume depolarization ratio with systematic uncertainty
 - L2 products such as particulate extinction can be retrieved by invoking several methods used by CATS, CALIPSO, and CPL

Simulated Scenes Using Model Inputs

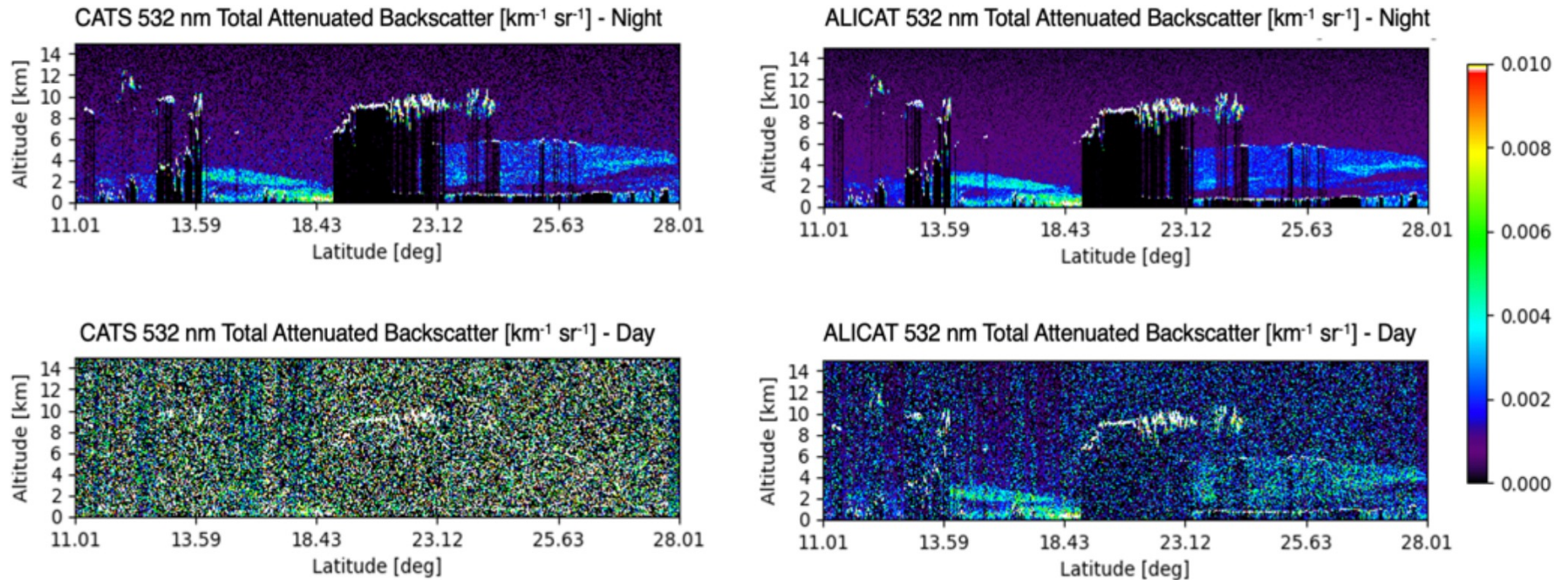
- Global aerosol transport model simulation such as the NASA GEOS nature run paired with a radiative transfer model such as VLIDORT provide opportunities to simulate performance and test algorithms for various viewing and solar background conditions beyond simple canonical cases



GEOS Nature Run Image courtesy of NASA GSFC SVS



Simulated Scenes Using Airborne Data



- 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

ALICAT Trace Matrix

Science Objectives	Geophysical Variables		Observables	Measurement		
	Geophysical Variable	Requirements		Requirements		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 O2, O3, O5, O6	Range: .1-20 km 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) 11.0 (day)
				1064 nm SNR in Aerosol Layer (Dust AOD = 0.3 over ocean)	> 1.4	5.2 (night) 2.6 (day)
				532 nm Min Detectable Backscatter at 5 km	<8.0E-4	4.1E-4 (night) 5.3E-4 (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	Aerosol Extinction (VIS, NIR) O3, O5, O6	Unc: maximum of 0.03 km ⁻¹ or 80% (VIS/NIR) Res: ≤5 km (10 km) horiz ≤60 m (120 m) vert		Calibration Uncertainty	≤10%	3-8% (532) 5-10% (1064)
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.				Calibration Resolutions (SNR > 75)	<1500 km (hori) <5 km (vert.)	750 km (hori) 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) O3, O5, O6	Range: 0.05-1.0 Unc: 100% (VIS/NIR) 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) > 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)

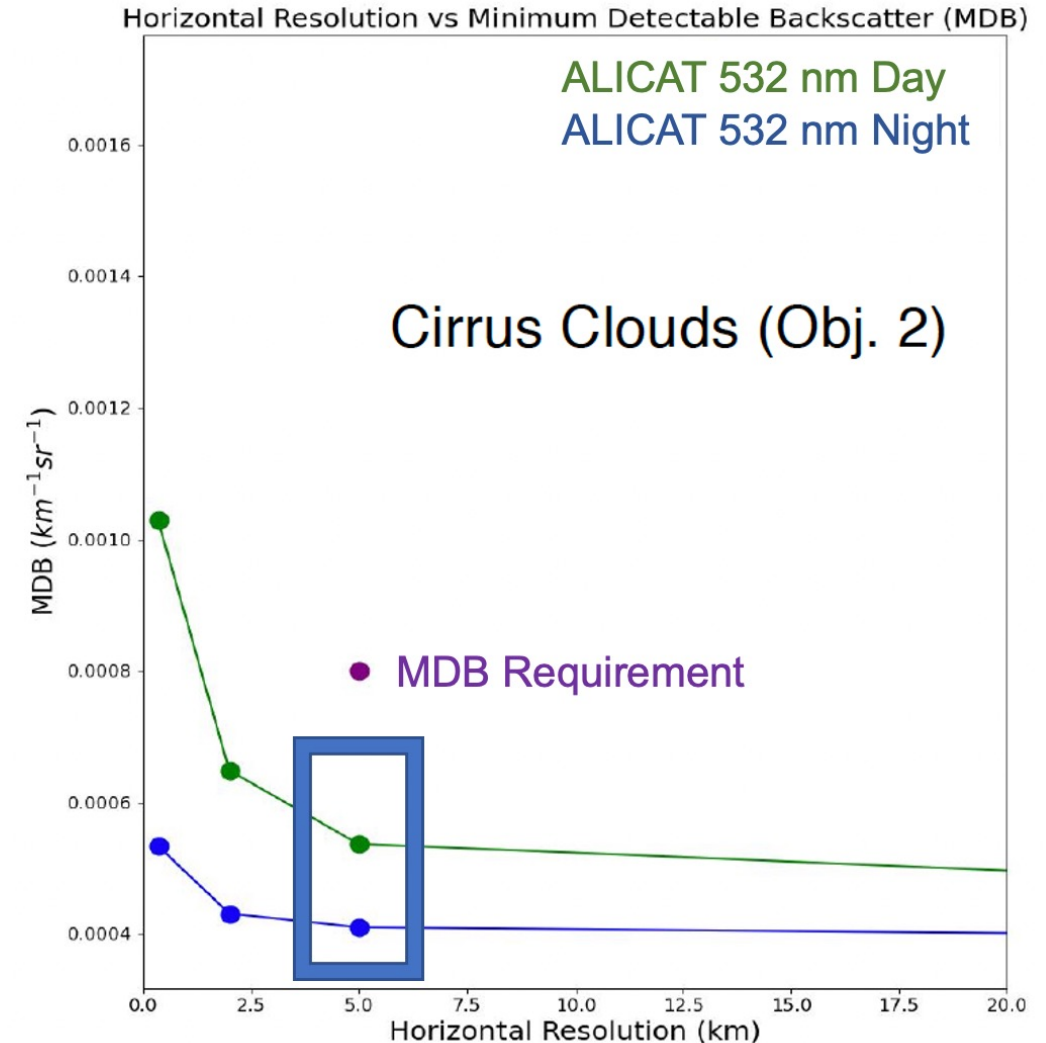
Measurement Requirements Mapped to GVs

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
<u>2A</u>	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
<u>2B</u>	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 $8.0E-4 \text{ km}^{-1} \text{ sr}^{-1}$ at 5 km	$4.1e-4$ (night) $5.3e-4$ (day)	B



Measurement Requirements Mapped to GVs

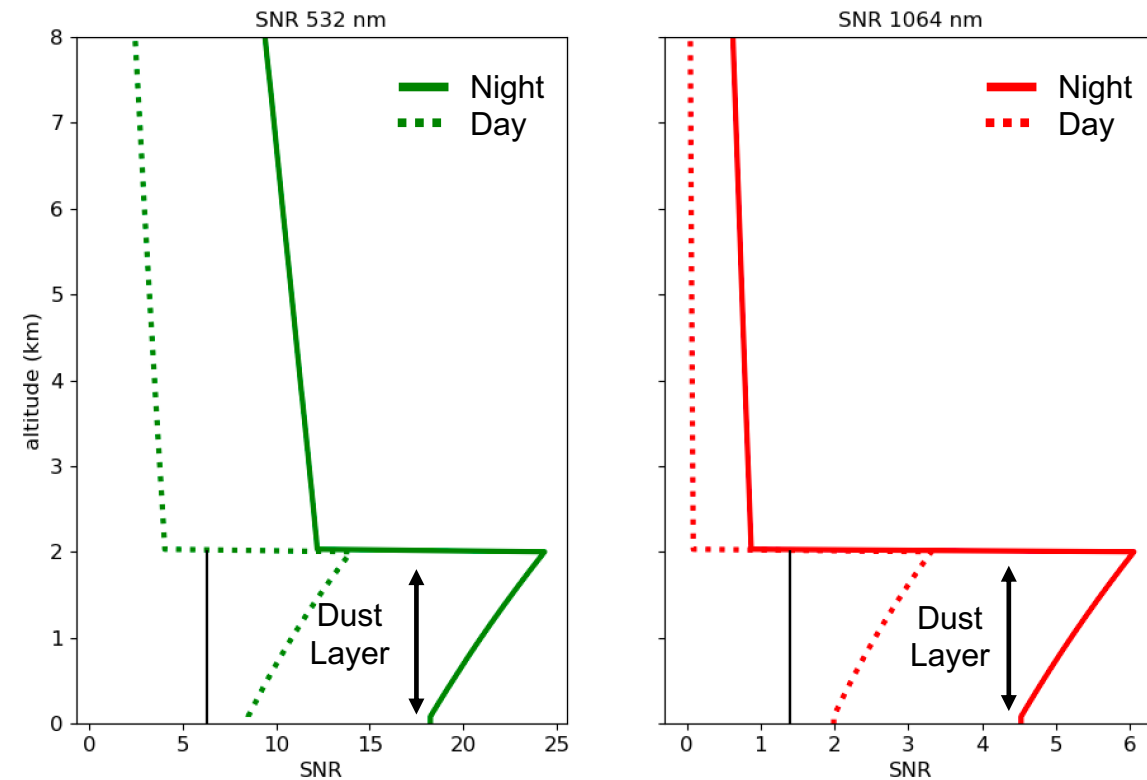
Aerosol Extinction Geophysical Variable Requirement

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 $\leq 5 \text{ km}$ and a vertical resolution of $\leq 60 \text{ m}$ for aerosol backscatter $> 6 \times 10^{-4} \text{ km}^{-1} \text{ sr}^{-1}$ under clear sky conditions.



#	Aerosol Extinction Measurement Requirements	Projected Performance	B/T
<u>2C</u>	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
<u>2D</u>	ALICAT shall calibrate attenuated total backscatter profiles with a relative calibration uncertainty of $\leq 8\%$ at 532 nm and $\leq 10\%$ at 1064 nm.	3-8% (532) 5-10% (1064)	T
<u>2E</u>	ALICAT shall measure 532 nm backscatter at resolutions of $>5 \text{ km}$ (vertical) and $>1500 \text{ km}$ (horizontal) within the calibration altitude region (32.5-35 km) with SNR of >75 .	750 km (hori) 2.5 km (vert.)	T
<u>2F</u>	ALICAT shall measure 532 nm backscatter at resolutions of $\leq 60 \text{ m}$ (vertical) and $\leq 5 \text{ km}$ (horizontal) within a dust aerosol layer (dust AOD over ocean = 0.3) with SNR of >6.3	20.7 (night) 11.0 (day)	B
<u>2G</u>	ALICAT shall measure 1064 nm backscatter at resolutions of $\leq 60 \text{ m}$ (vertical) and $\leq 5 \text{ km}$ (horizontal) within a dust aerosol layer (dust AOD over ocean = 0.3) with SNR of >1.4	5.2 (night) 2.6 (day)	B

ALICAT SNR for Dust AOD=0.3 Over Ocean



Measurement Requirements Mapped to GVs

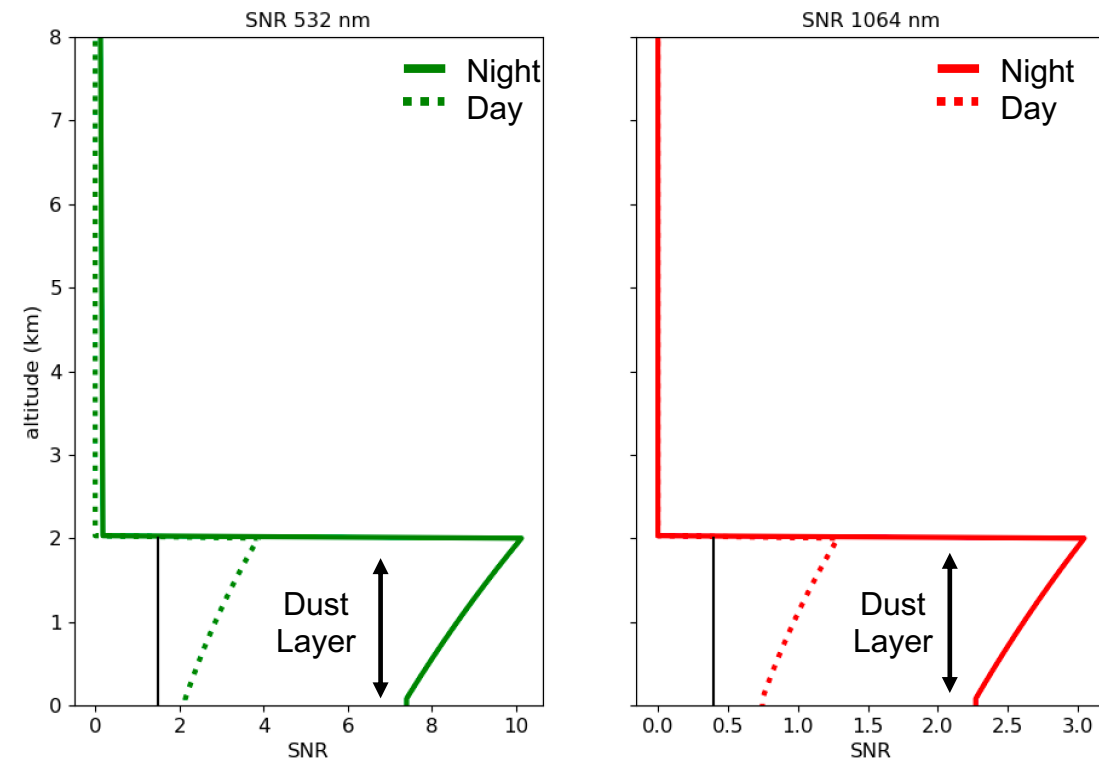
Volume Depolarization Ratio Geophysical Variable Requirement

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 $> 6 \times 10^{-4} \text{ km}^{-1} \text{ sr}^{-1}$ 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 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) 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/testing