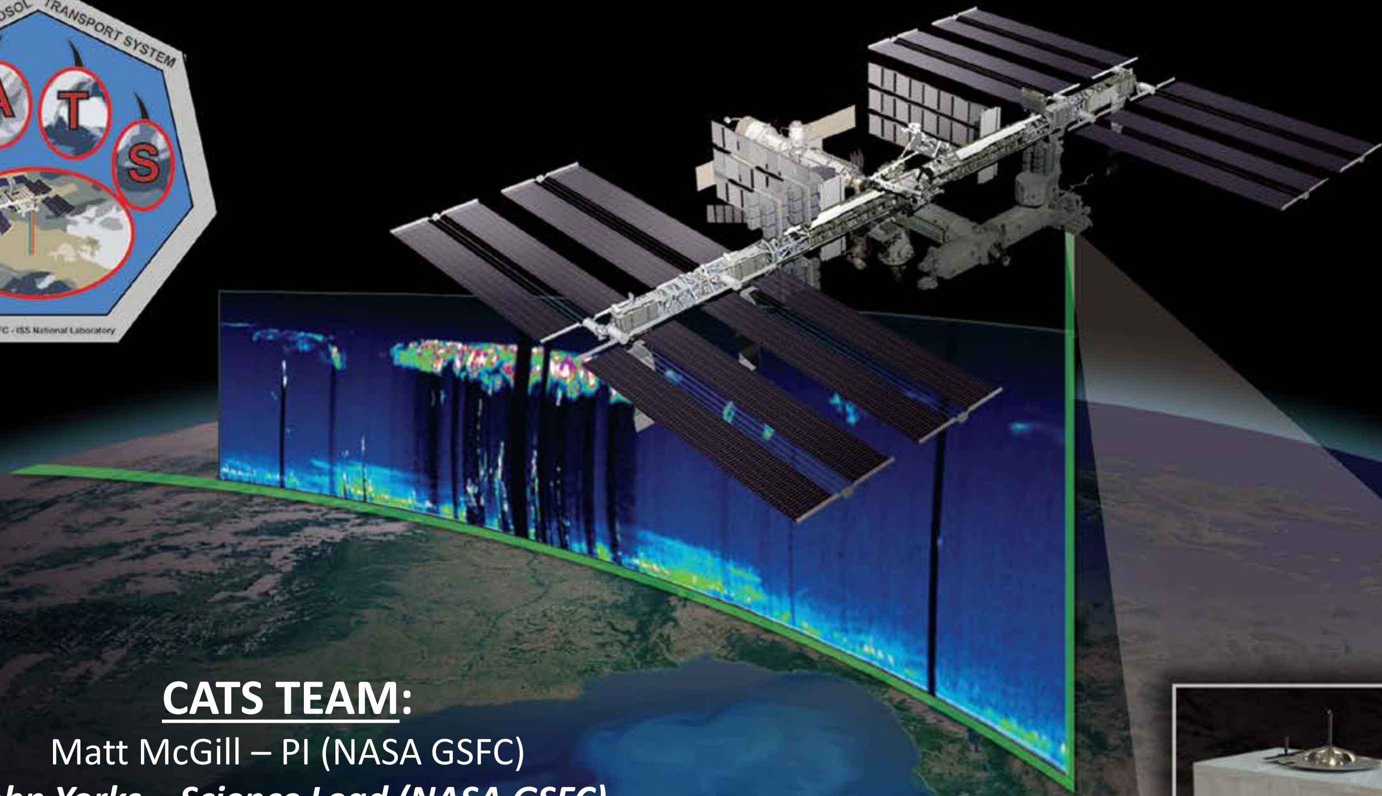
The Cloud-Aerosol Transport System (CATS): 33 Months of Aerosol Vertical Profiles from the ISS



<u>CATS TEAM</u>:

Matt McGill – PI (NASA GSFC)

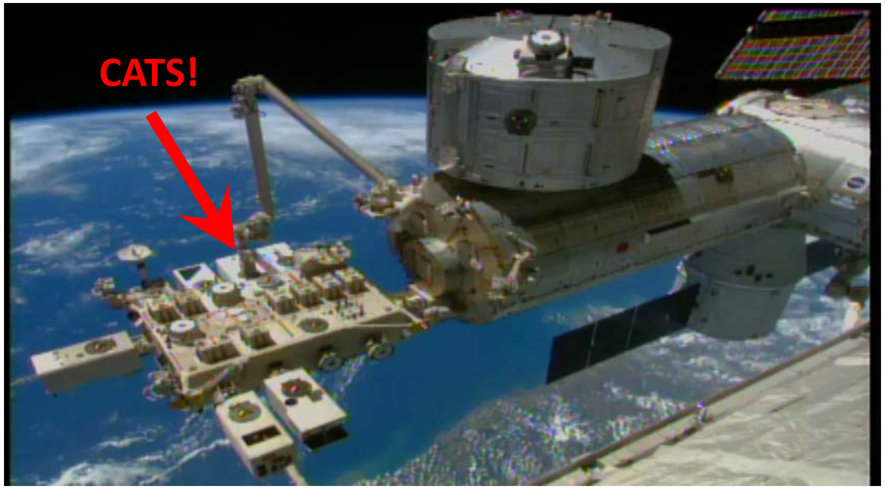
<u>John Yorks – Science Lead (NASA GSFC)</u>

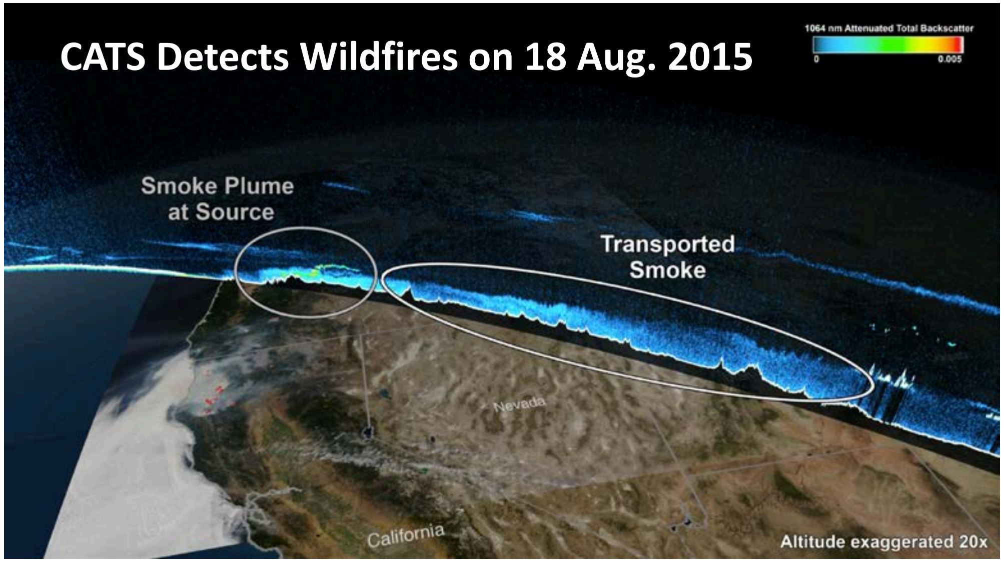
NASA GSFC Team - Ed Nowottnick, Stephen Palm, Dennis Hlavka, Patrick Selmer, Rebecca Pauly, Scott Ozog

NASA LaRC Team – Chip Trepte, Mark Vaughan, Sharon Rodier

CATS Overview

- **CATS was designed as a tech demo (6 month lifetime) utilizing ISS as an affordable Earth Science platform to:**
  - Complement CALIPSO data record w/ diurnally varying cloud/aerosol vertical profiles
  - Monitor dynamic events such as wildfires and volcanic eruptions
  - Provide in-space demonstration of technologies for future satellite missions
  - Demonstrate build-to-cost project development
- **CATS operated on the ISS for 33 months and fired 200+ billion laser shots**



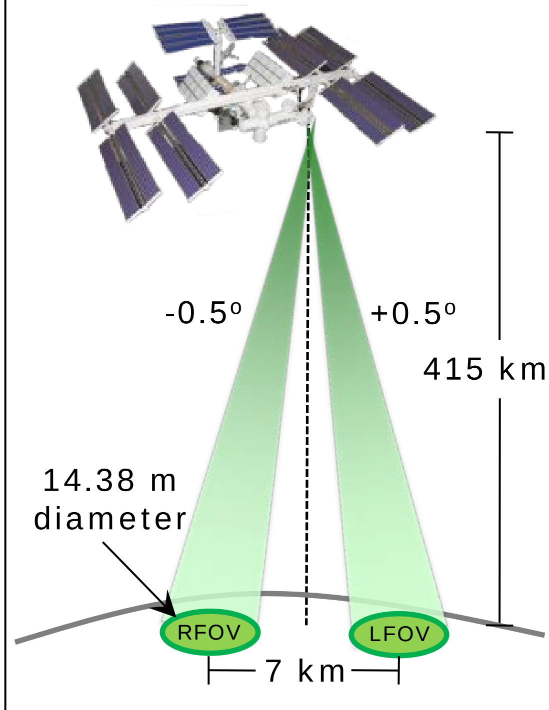


CATS Operation Modes

- **CATS demonstrated new technologies in space:**
  - Multiple beams separated by 7 km at surface (1.5 months of data)
  - First space-based measurements of depolarization at 1064 nm (& 2 wavelengths)
- **Early bumps in the road:**
  - Laser 1 failed 3/2015
  - Laser 2 cannot be stabilized for HSRL retrievals (Mode 2)
- **Mode 7.2 1064 nm data was very reliable**
  - Suspected power/data system failure on 30 Oct. 2017 ended science operations

Mode 7.1: Multi-Beam

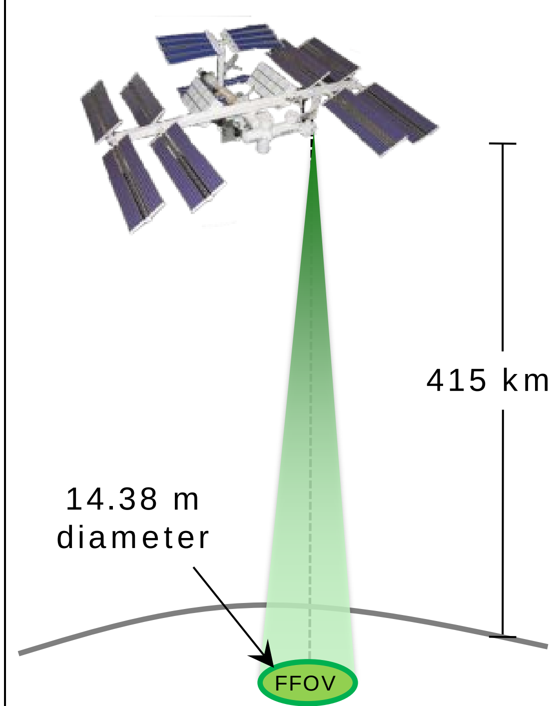
Backscatter: 532, 1064 nm
Depolarization: 532, 1064 nm
L2 Products: 532, 1064 nm



Semi-continuous operation: Feb. 10 – Mar. 21 (2015)

Mode 7.2: Laser 2

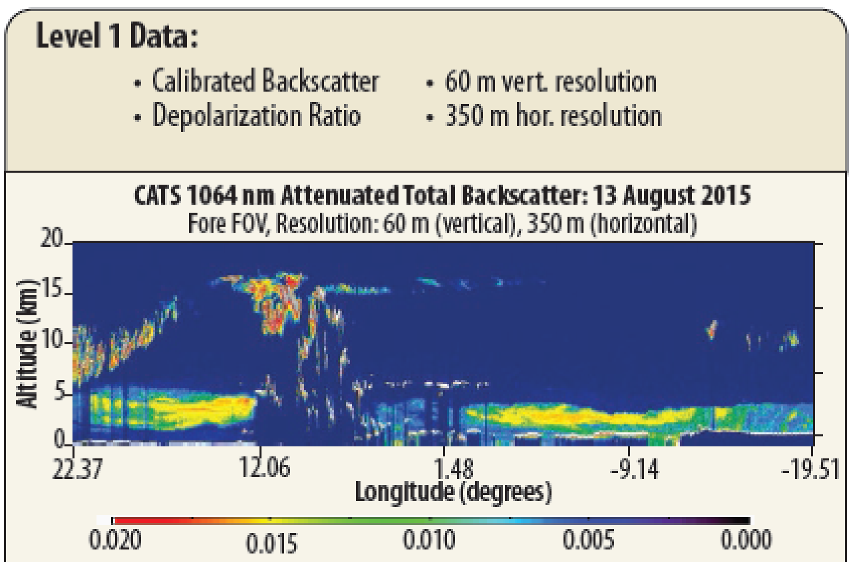
Backscatter: 532, 1064 nm
Depolarization: 1064 nm
L2 Products: 1064 nm

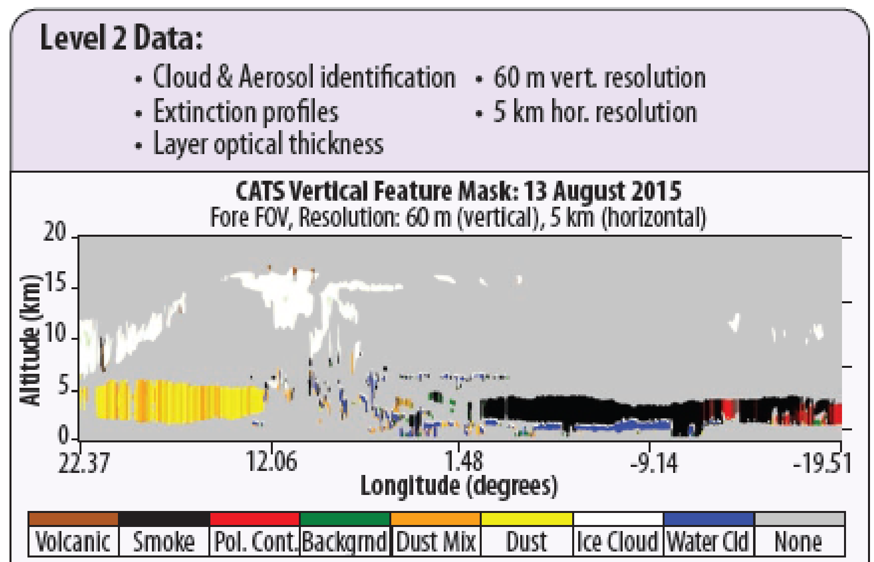


Semi-continuous operation: 25 Mar. 2015 – 30 Oct. 2017

CATS Data Products

- **CATS team worked with CALIPSO team to incorporate lessons learned and make products/browse images similar for lidar user community**
- **The final version of CATS "Operational" data products to be released in coming months**
  - **<u>L1B Version 3.00</u> includes more accurate daytime backscatter calibration**
  - **<u>L2O Version 3.00</u> includes improved cloud-aerosol discrimination (especially at daytime) using horizontal persistence tests and other tests, and updates to optical properties (AOD/COD, extinction, lidar ratio) algorithm**
  - **Most accurate products yet and easy for CALIPSO data users to work with**
- **New "Heritage" data products soon - CATS data run through CALIPSO algorithms**



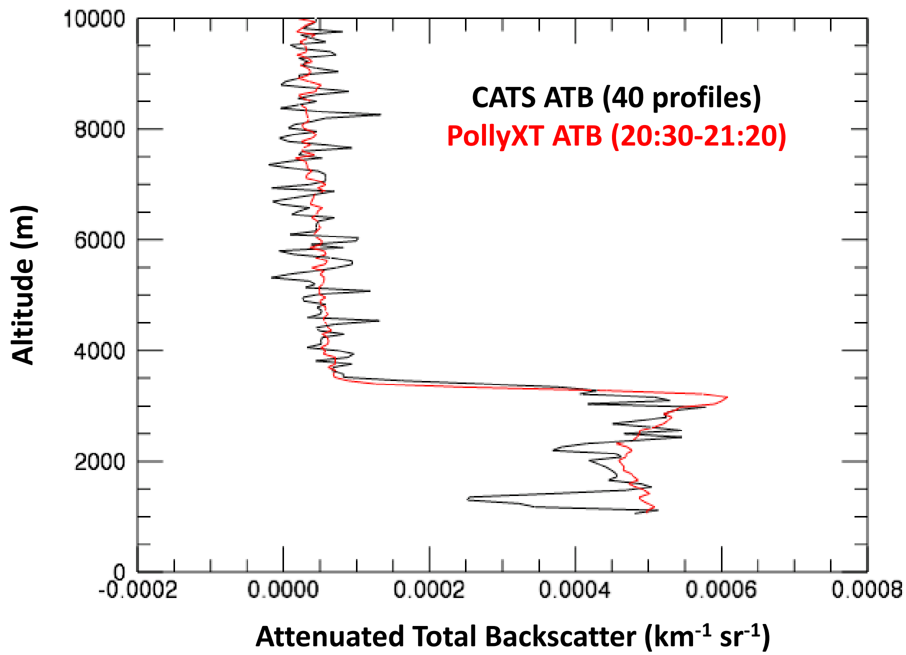


CATS Calibration

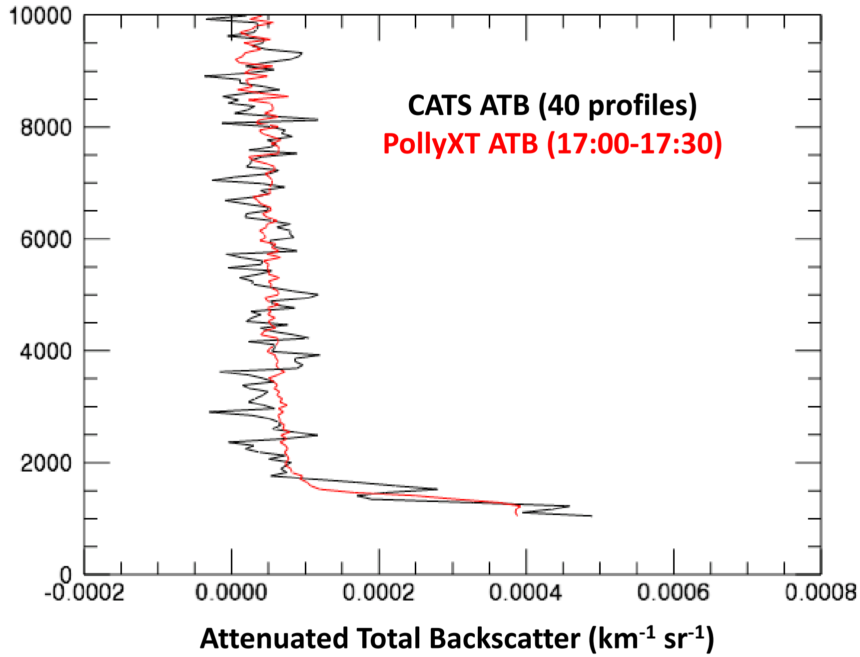
The CATS 1064 nm signal is calibrated by directly normalizing to the Rayleigh profile assuming an aerosol loading (22-26 km) based on CALIPSO 532 nm data. Comparisons with the EARLINET 1064 nm PollyXT Raman lidars suggest CATS nighttime data is well calibrated (below).

The 1064 nm CALIOP data is calibrated using 1064-532 cirrus color ratio assumptions. Initial comparisons with CATS 1064 nm data show the 2 different calibration techniques converging to the same answer (not shown).

CATS-PollyXT Comparison
06 August 2015: Leipzig, Germany



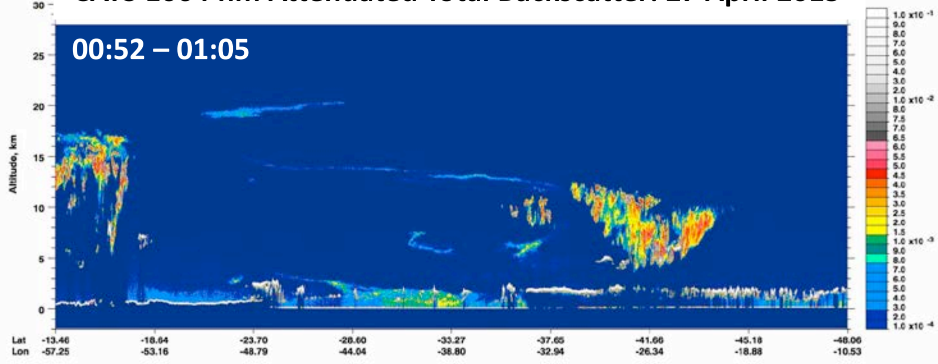
CATS-PollyXT Comparison
01 February 2016: Athens, Greece



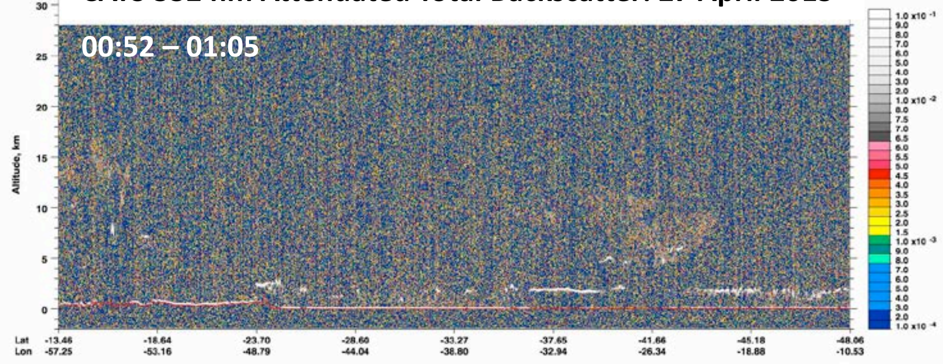
CATS-CALIOP Differences

1. <u>ORBIT:</u> ISS 51° inclination orbit at ~415 km enables CATS measurements at different local time every overpass with variable coverage of the tropics and mid-latitudes
   - CALIPSO only measures local ~1:30 AM/PM overpass times
2. <u>TECHNIQUE:</u> Implications for sampling complex scenes and daytime SNR
   - CATS is high rep. rate, low energy, photon counting detection
   - CALIOP is low rep rate, high energy, analog detection
3. <u>PREFERRED WAVELENGTHS:</u> The two instruments use different wavelengths for depolarization and layer detection
   - CATS 1064 signal is very robust and sensitive to subvisual layers, but Mode 7.2 532 nm data is very noisy (see below). CATS does depolarization at 1064 nm (M7.1 -> both wavelengths)
   - CALIOP 532 nm signal is stronger than 1064 nm signal, 532 nm depolarization

CATS 1064 nm Attenuated Total Backscatter: 27 April 2015



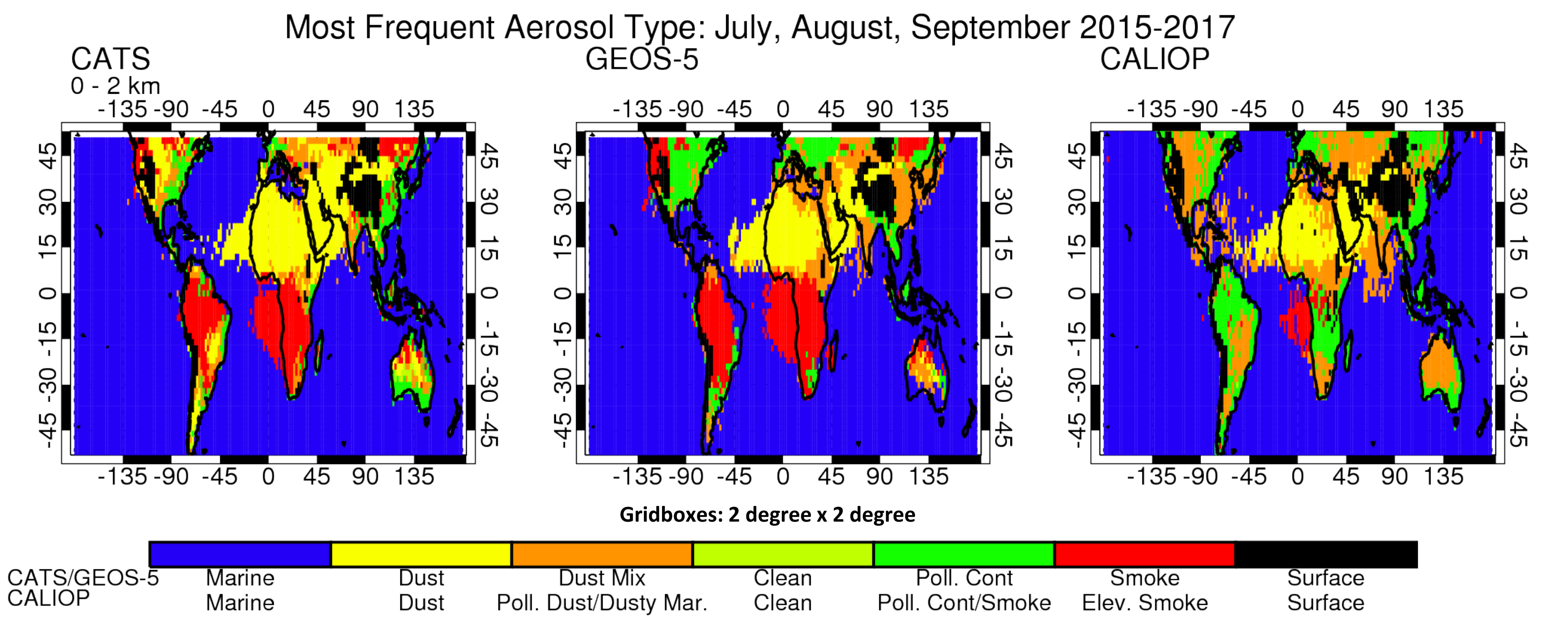
CATS 532 nm Attenuated Total Backscatter: 27 April 2015



CATS Aerosol Typing

CATS aerosol typing algorithm for M7.2 has heritage from CALIOP, but differences are:

1. **LAYER DETECTION: CATS uses 1064 nm and 5, 60 km horizontal averaging. CALIOP uses 532 nm and 333 m – 80 km horizontal averaging. More differences in daytime data than night.**
2. **NUMBER OF WAVELENGTHS: CALIOP algorithms employ backscatter color ratio for cloud-aerosol discrimination. CATS is essentially a single wavelength system in Mode 7.2, but uses horizontal persistence and other tests to differentiate aerosols and clouds.**
3. **AEROSOL TYPE: CATS & CALIOP have different categories, like CALIOP's Polluted Continental & Smoke (PBL) vs. Elevated Smoke, while CATS has one type "Smoke" for elevated and PBL smoke.**

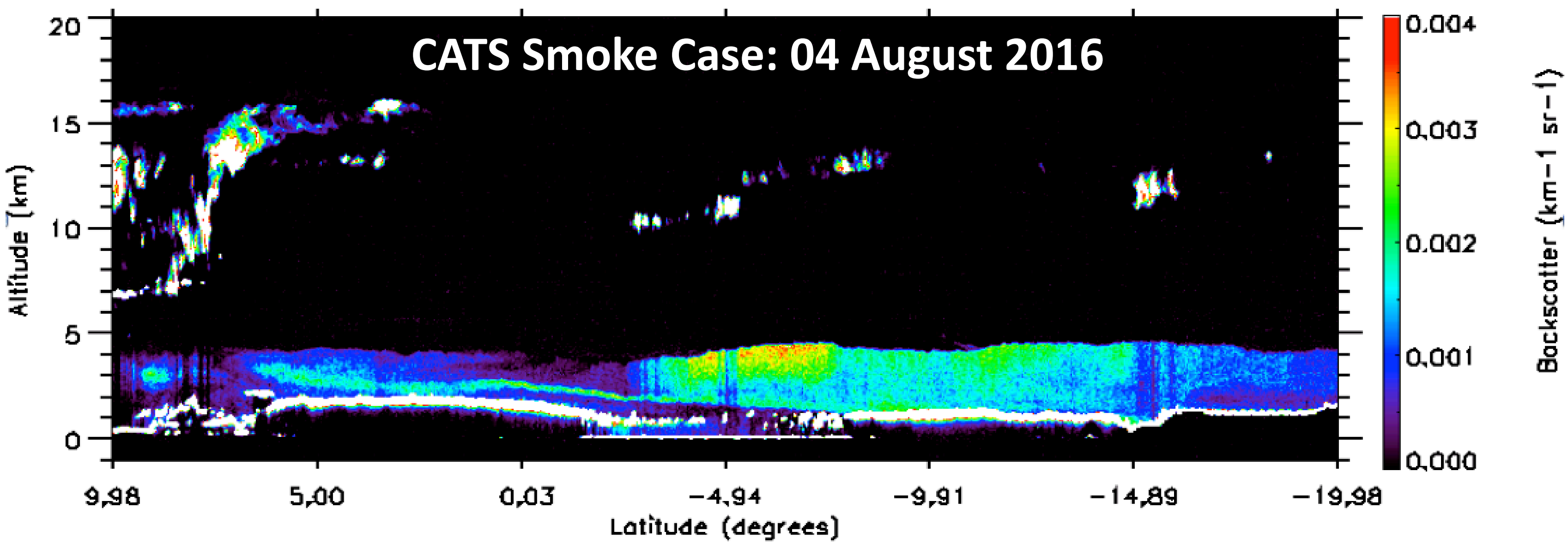


ACA 1064 nm Lidar Ratios

- **Retrieve 1064 nm lidar ratios for ACA (dust and smoke) utilizing the method outlined in Hu et al. 2007**
  - **Optical depth of a transparent layer above an opaque water cloud can be determined.**
  - **The attenuated total backscatter of the water cloud is decreased by an amount equal to the 2-way transmittance of the transparent layer.**

$$\tau_{top} = -\frac{1}{2}\ln\left(2S_c\gamma'_{water}\left(\frac{1-\delta}{1+\delta}\right)^2\right)$$

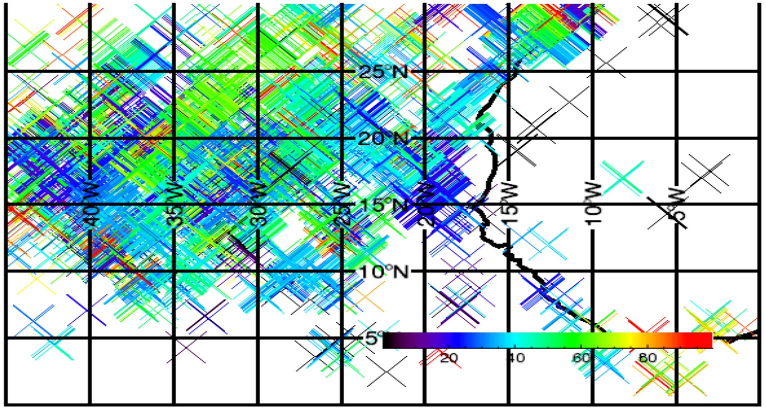
Water cloud multiple scattering factor (Hu et al. 2007)



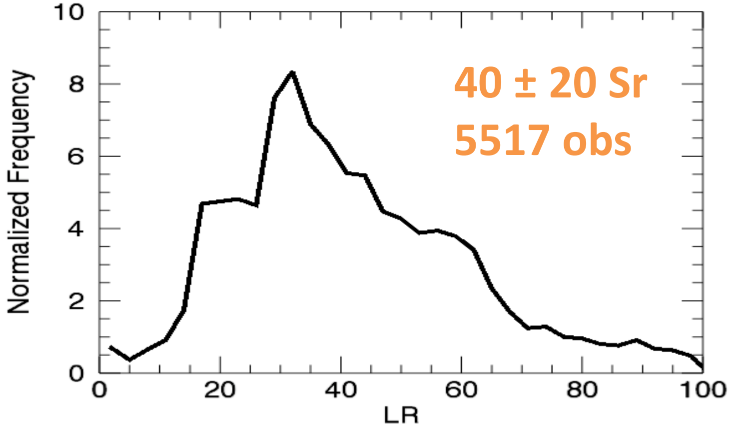
ACA 1064 nm Lidar Ratios

Dust Off the African Coast: CATS JJAS 2015-2017

CATS Dust Lidar Ratio
JJAS 2015-2017

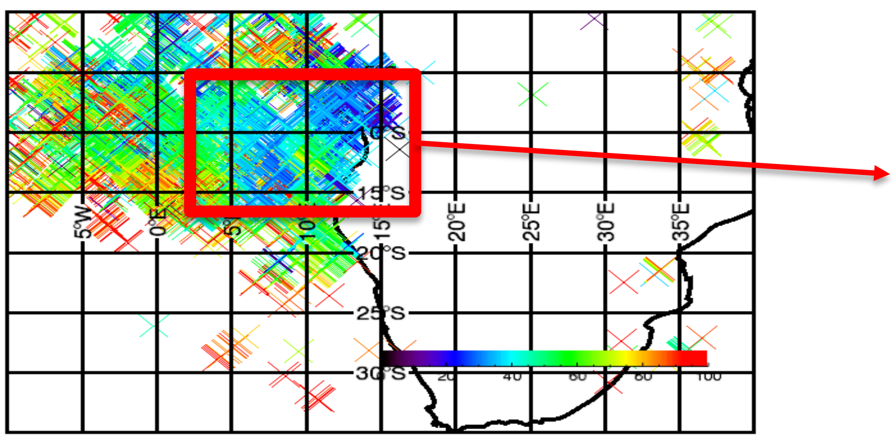


CATS Dust Lidar Ratios
JJAS 2015-2017

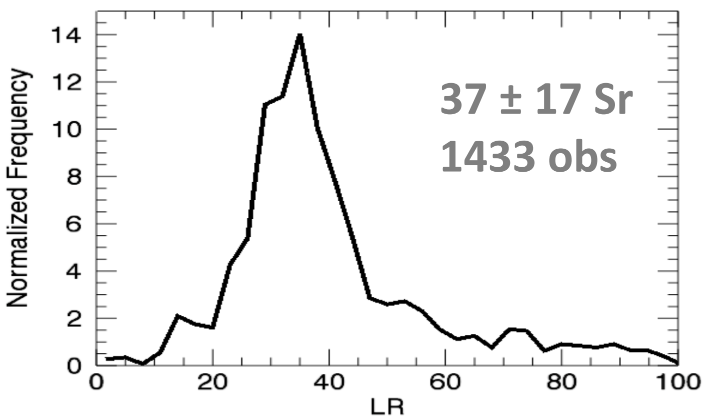


Smoke Off the African Coast: CATS JJAS 2016

CATS Smoke Lidar Ratio
JJAS 2016

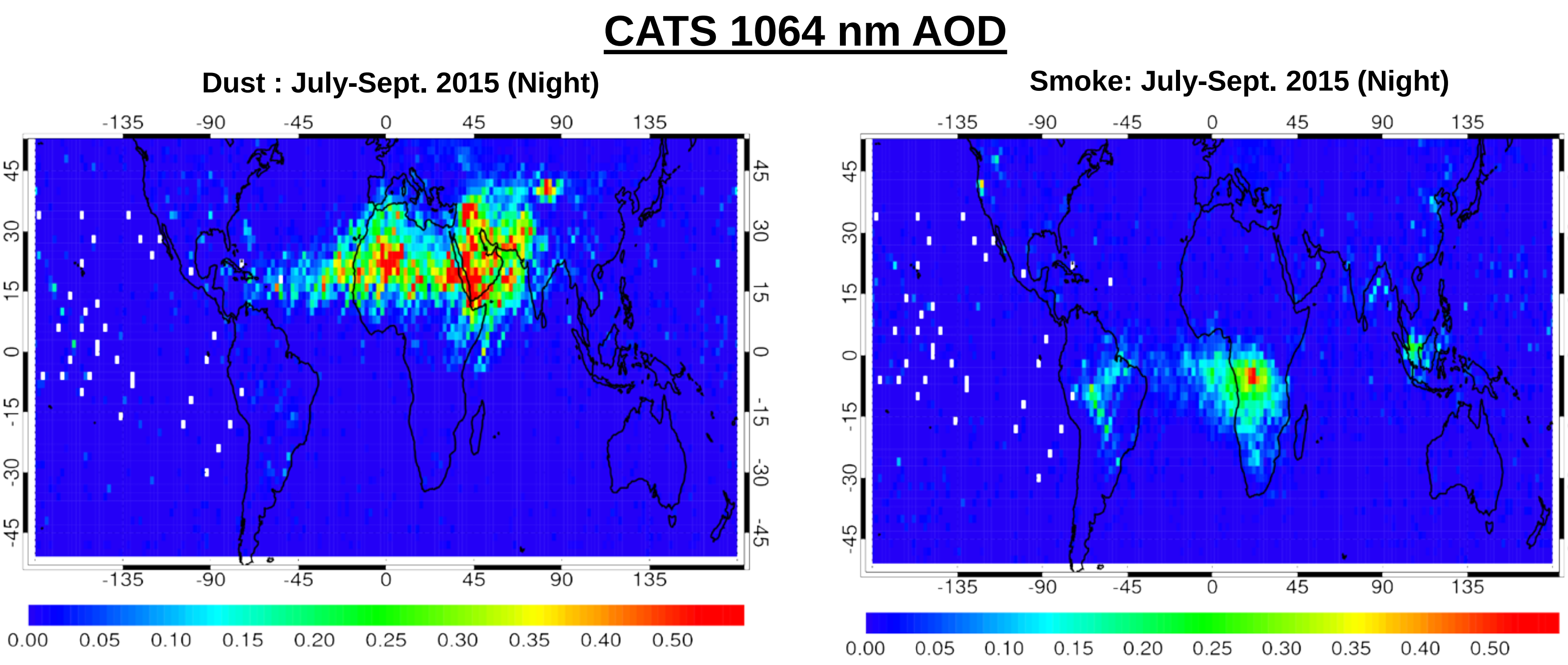


CATS Smoke Lidar Ratios
JJAS 2016



CATS Speciated AOD

- CATS provides speciated AOD and total AOD despite being single wavelength.
- 1064 nm dust and elevated smoke AODs in good agreement with CALIPSO.



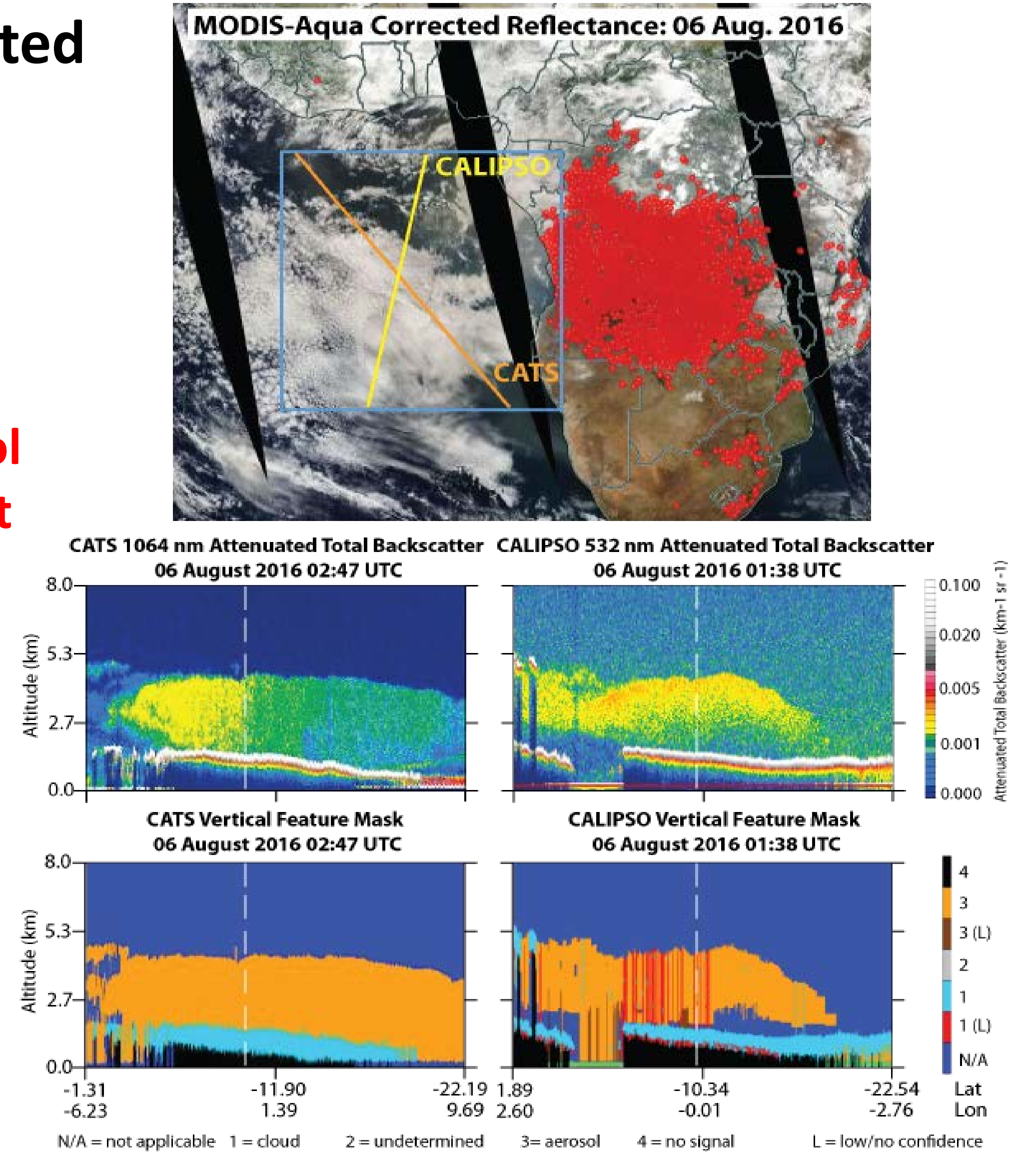
Above Cloud Aerosols

CATS data products are well suited for above cloud aerosols (ACA)

CATS L2O product uses 1064 nm attenuated scattering ratio for layer detection (given results above) and separates clouds embedded in aerosol layers, enabling it to detect full extent of aerosol plume above clouds

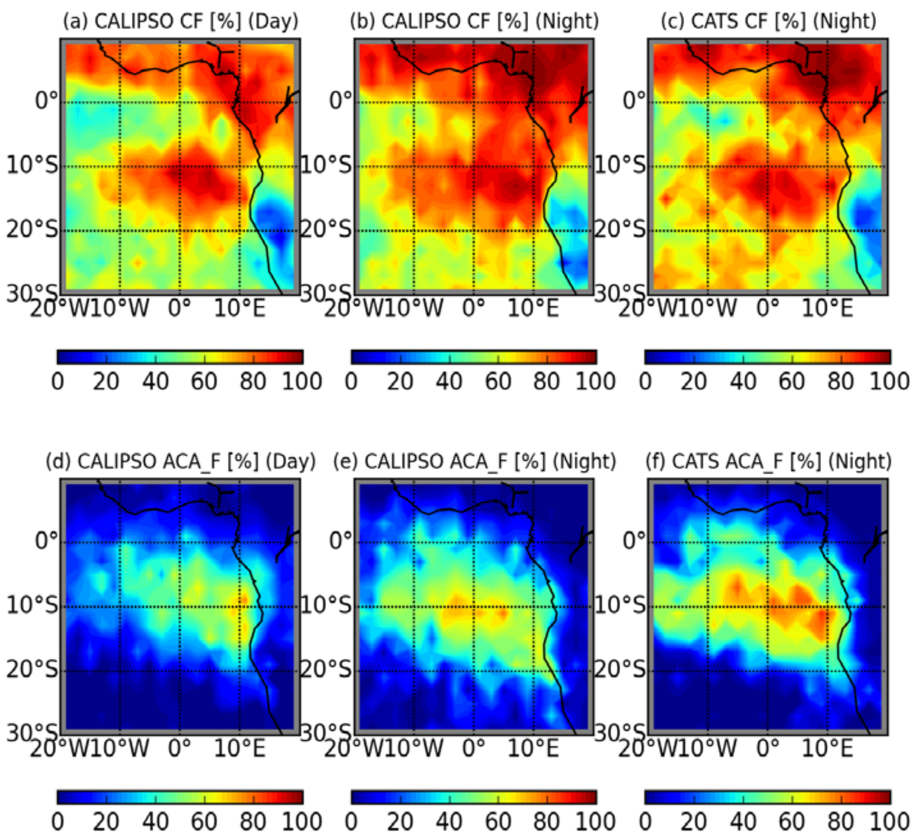
The 532 nm backscatter CALIPSO uses for layer detection works well overall, but for ACA it attenuates before reaching aerosol layer base, causing separation between aerosols and clouds.

Rajapakshe et al. [GRL, 2017]

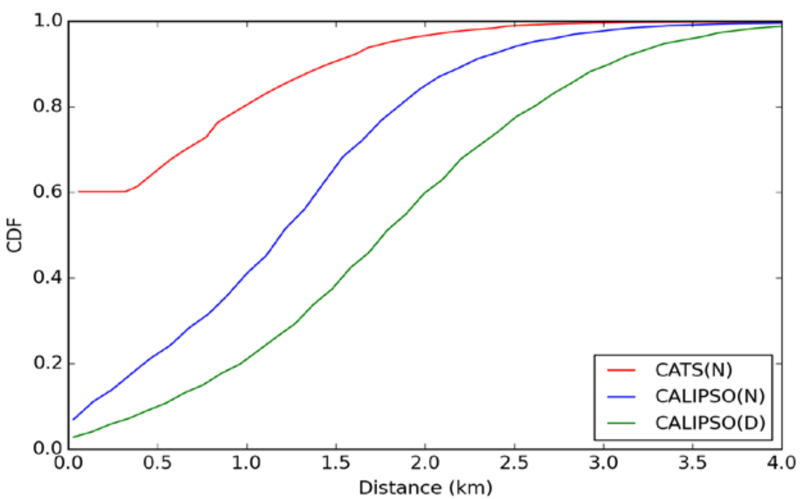


Above Cloud Aerosols

- Above cloud aerosols (ACA) are common in the SE Atlantic during JJASO due to transport of smoke from biomass burning
- According to CATS 60% of ACA cases in the SE Atlantic have an aerosol base to cloud top distance smaller than 250 m
  - Much higher than CALIPSO: 11% (night) and 4% (day)

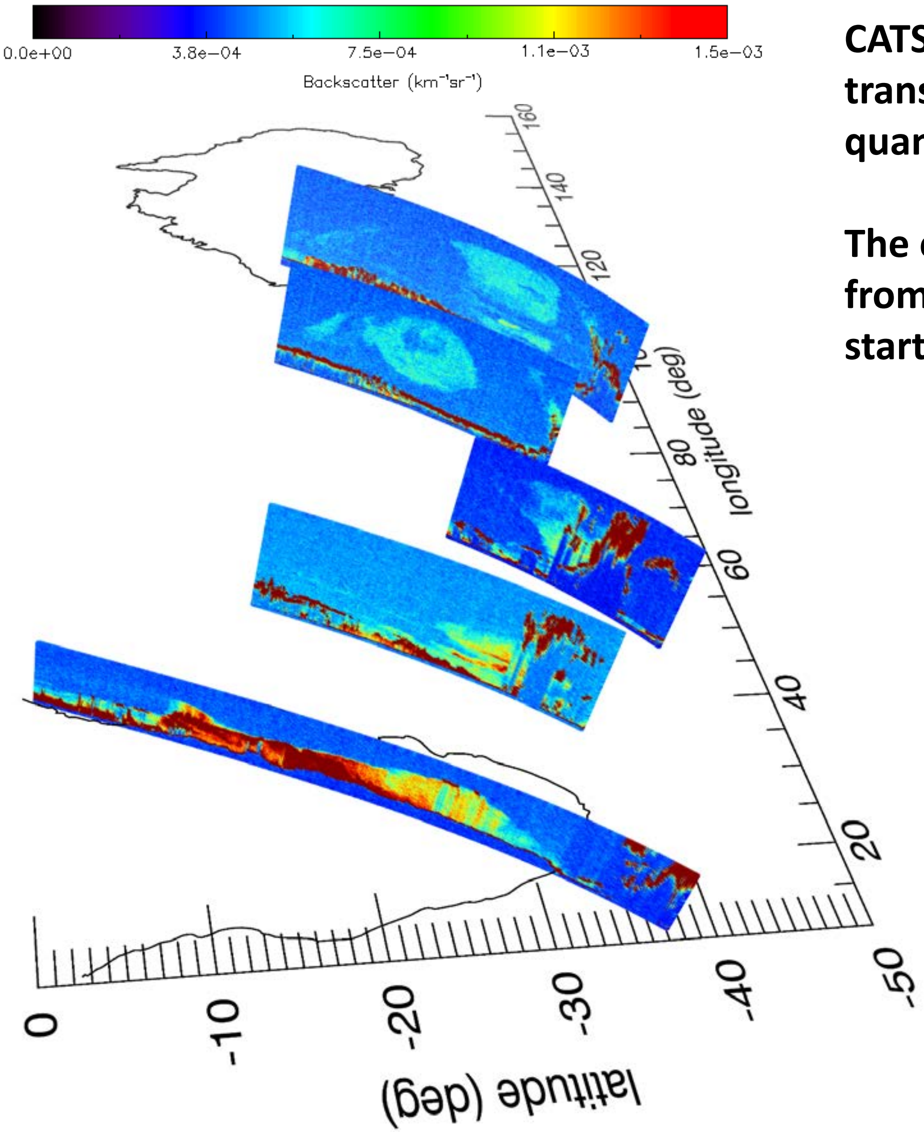


This implies that aerosol indirect effects (microphysical) could be an important mechanism for SE Atlantic radiation budget.



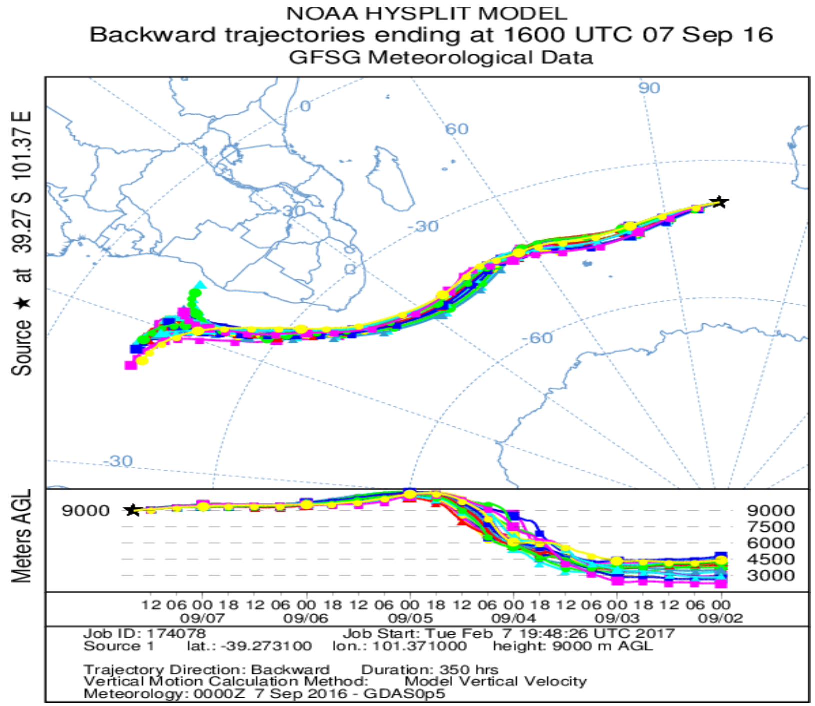
Rajapakshe et al. [GRL, 2017]

Smoke Transport



CATS observed several cases of long-range smoke transport from Africa across the Indian Ocean, quantifying evolution of loading and vertical distribution.

The elevated layer near Australia is distinct and extends from 3 - 11 km, but AOD is only 0.04 +/- 0.008. The layer starts with higher AOD (0.15 +/- 0.05) over Africa.

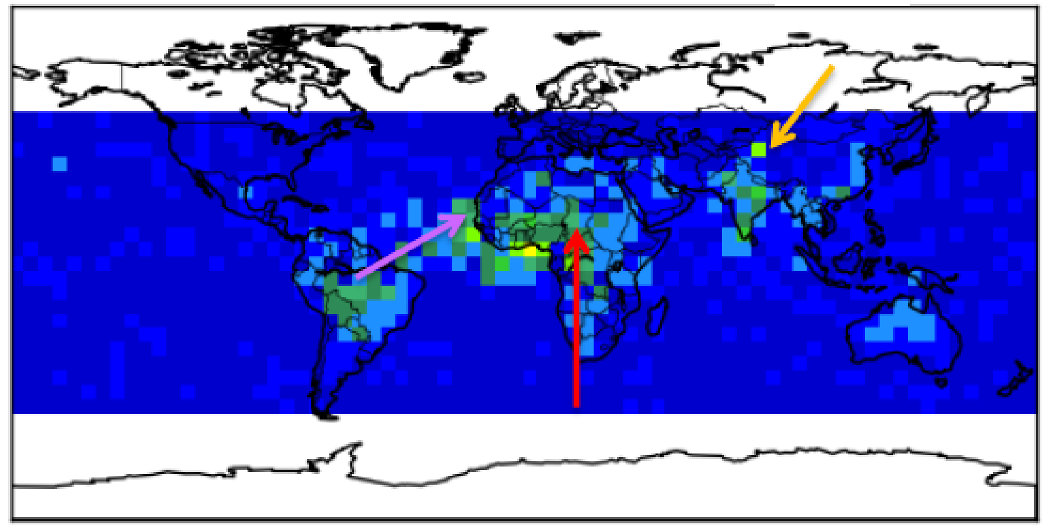


Diurnal Variability

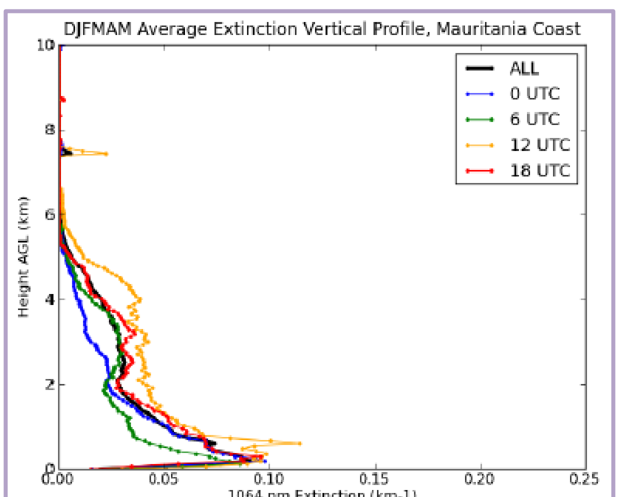
CATS data shows that, depending on season and region, the diurnal variability of the aerosol extinction profile is as high as 0.10 km^{-1}.

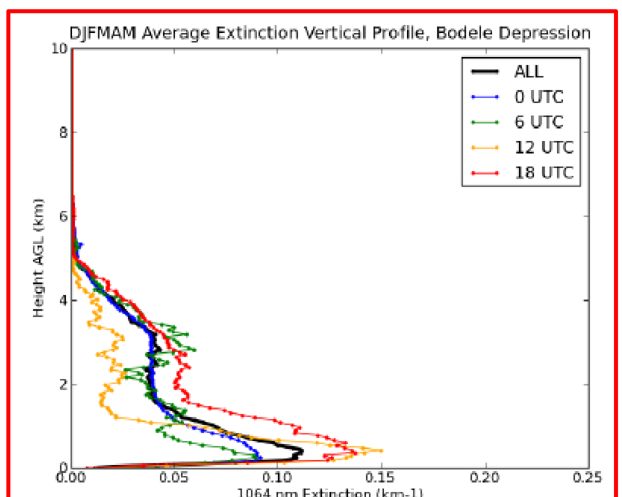
- **South America, Sahara and Sahel regions in Africa, and Tarim Basin in Asia are 3 noted locations.**
- **A-Train sensors are not capturing this variability and geostationary sensors cannot capture the vertical profile.**

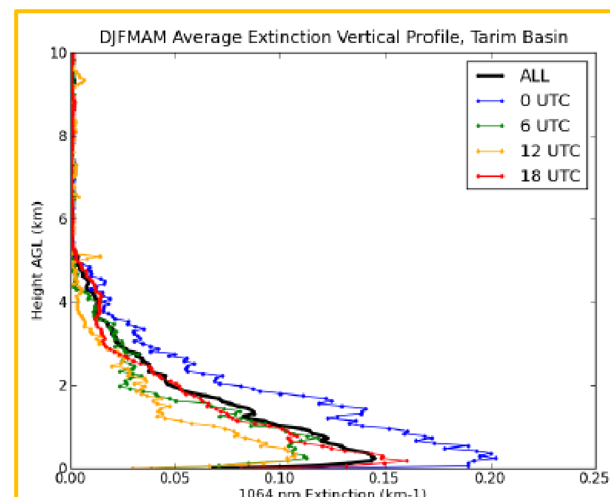
DJFMAM Max.-Min. Mean AOD



Courtesy of Logan Lee and Jianglong Zhang, Univ. North Dakota

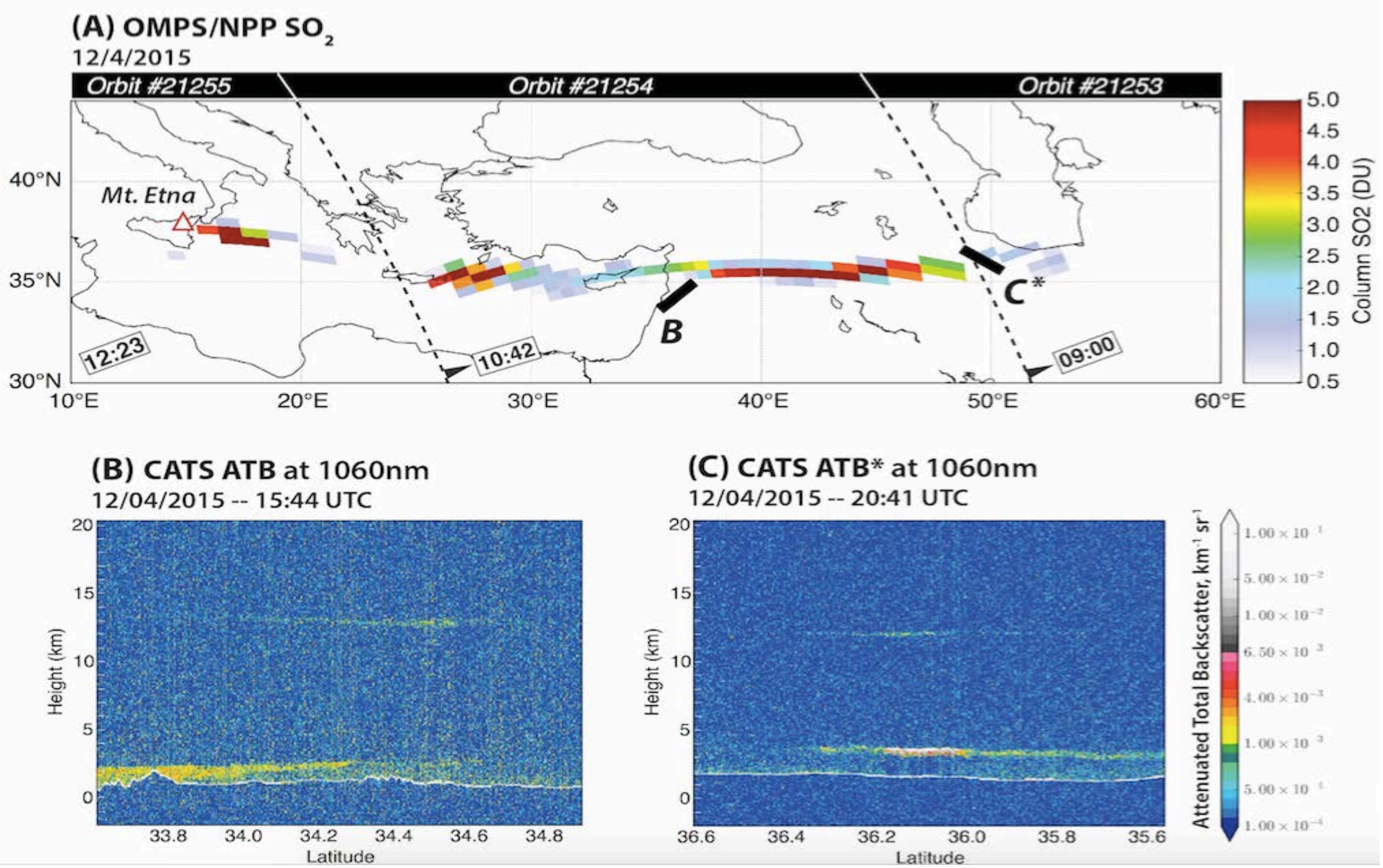






Forecasting Volcanic Plumes

- **CATS NRT data products were created within 6 hours of data acquisition**
  - **Includes profiles of backscatter, depolarization ratio and feature mask**
- **CATS observed the Mt. Etna plume on 04 Dec. at altitude of 12-14 km**
  - **Much higher than estimated using trajectory analysis after eruption (8-12 km)**



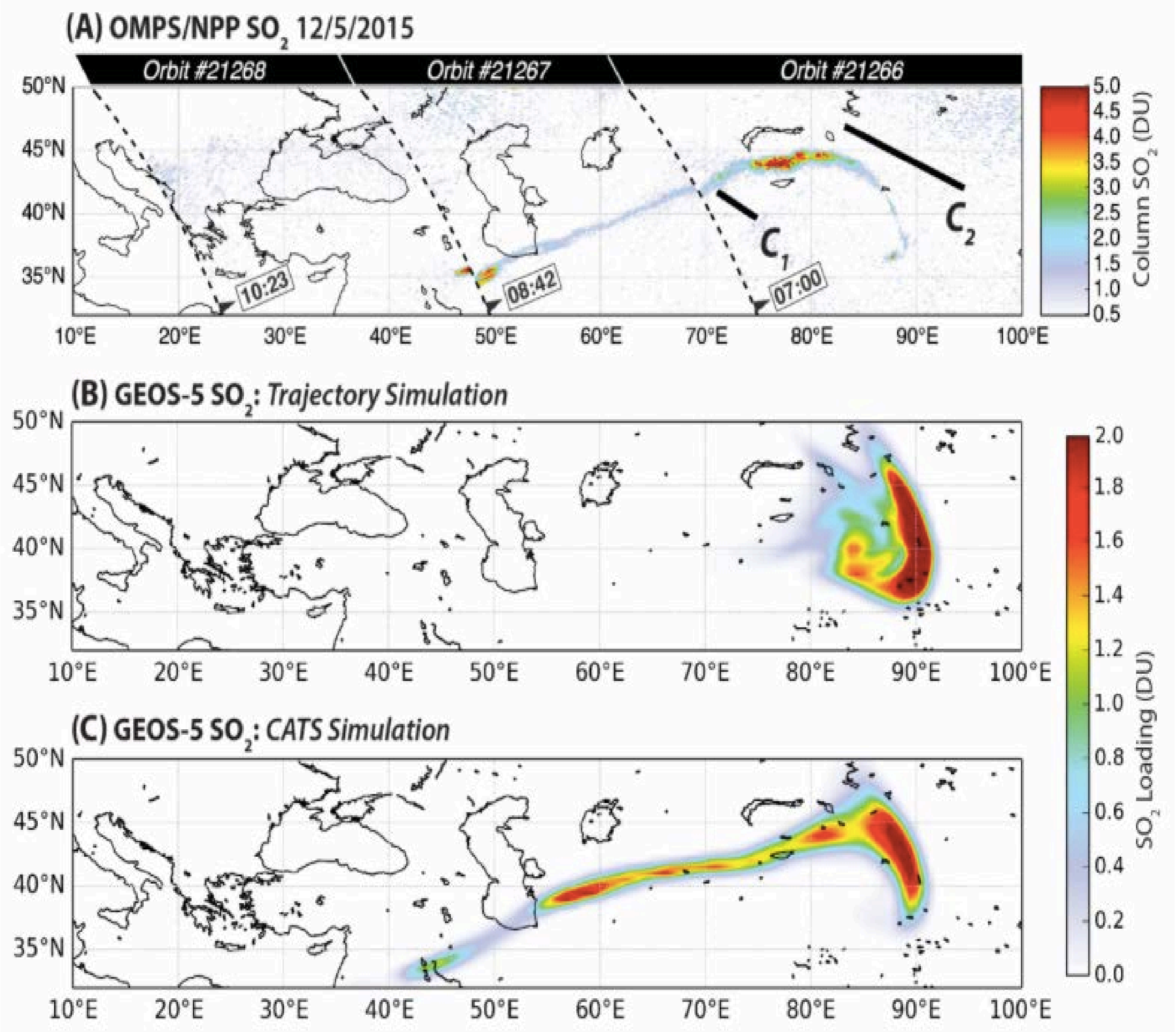
Forecasting Volcanic Plumes

Eric Hughes and Nick Krotkov (GSFC) forecasted Etna volcanic SO_2 transport using GEOS-5/GOCART

Forecast using CATS data to initiate volcanic plume injection height (C) agrees better with observations (A) than forecast using trajectory analysis (B)

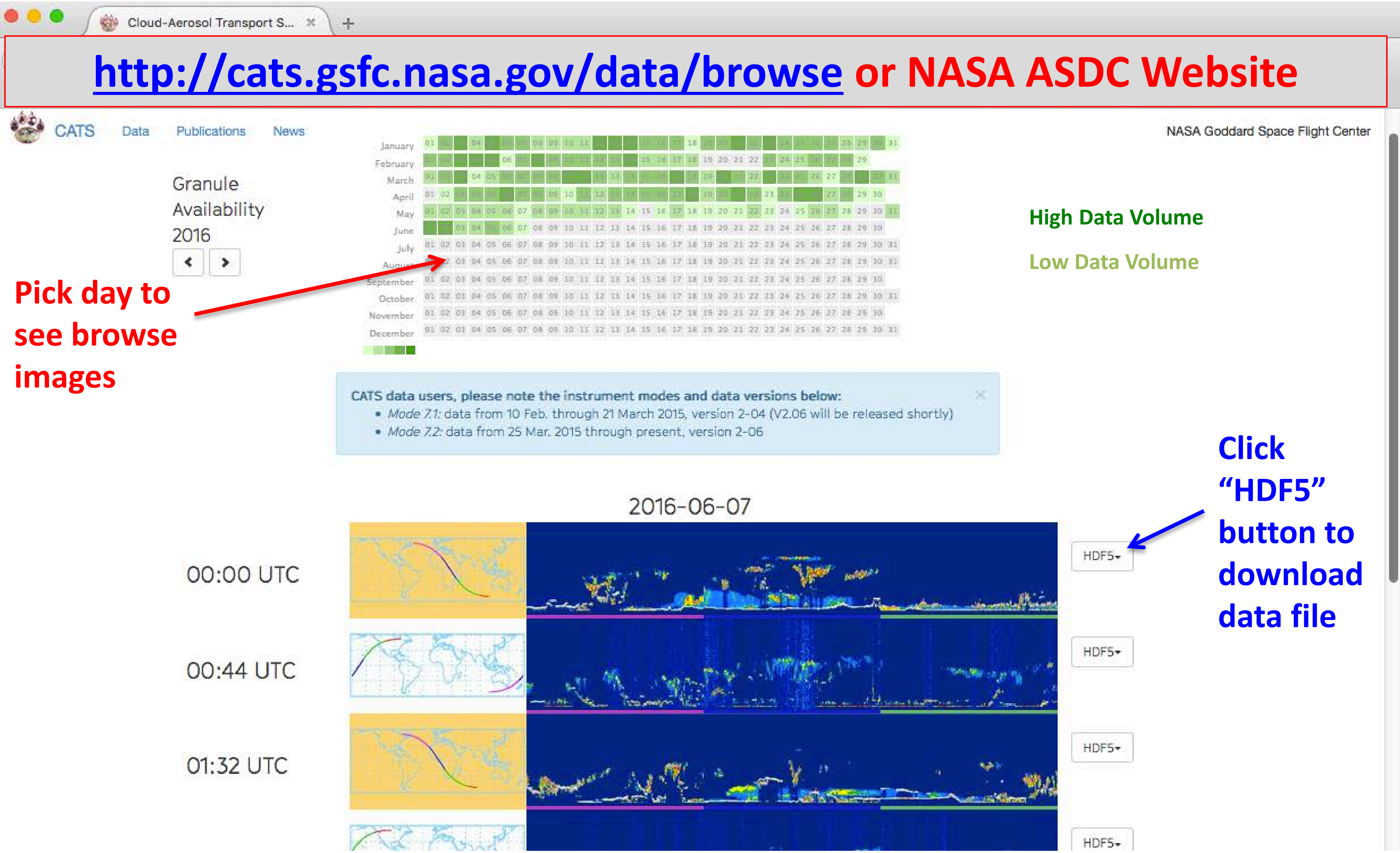
<u>CATS NRT data provided an unprecedented opportunity to assimilate global lidar data into aerosol forecast models.</u>

Hughes et al. [GRL, 2016]



CATS Data Availability

http://cats.gsfc.nasa.gov/data/browse or NASA ASDC Website



Pick day to see browse images

Click "HDF5" button to download data file

CATS Lessons Learned

1. PROGRAMATICS: You can design a quick-turnaround, lost cost Class D project that has science impact!
2. SINGLE WAVELENGTH: A single backscatter/depolarization wavelength can provide important data products! CATS Data Products: Yorks al. [GRL, 2016]
3. 1064 NM: Robust 1064 nm data can help improve layer detection and Near-IR retrievals
4. LIDAR RATIOS: Dust lidar ratios at 1064 nm are similar to 532 nm, while smoke lidar ratios at 1064 nm are much lower than 532 nm.
5. ACA: Smoke layers from biomass burning in the SE Atlantic are much closer to stratocumulus decks than previously thought: Rajapakshe et al. [GRL, 2017]
6. TRANSPORT: Biomass burning smoke plumes become physically thicker but optically thinner during long-range transport from Africa into the Indian Ocean: McGill et al. [2018]; Vaughan et al. [ACP, 2018]
7. DIURNAL VARIABILITY: Significant diurnal variability of cloud and aerosol vertical profiles exists on regional/seasonal scales that is not captured by the sun-synchronous sensors due to sampling times: Logan Lee (UND) and Noel et al. [ACP, 2018]
8. PLUME FORECASTING: Space-based lidar data latency of <6 hours has a big impact on forecasting and monitoring hazardous events (i.e. volcanic eruptions and wildfires): Hughes et al. [GRL, 2017]
9. NRT DATA ASSIMILATION: CATS NRT data provided an unprecedented opportunity to assimilate global lidar data into aerosol forecast models for improved vertical structure: See Ed Nowottnick's poster.

Special thanks to:

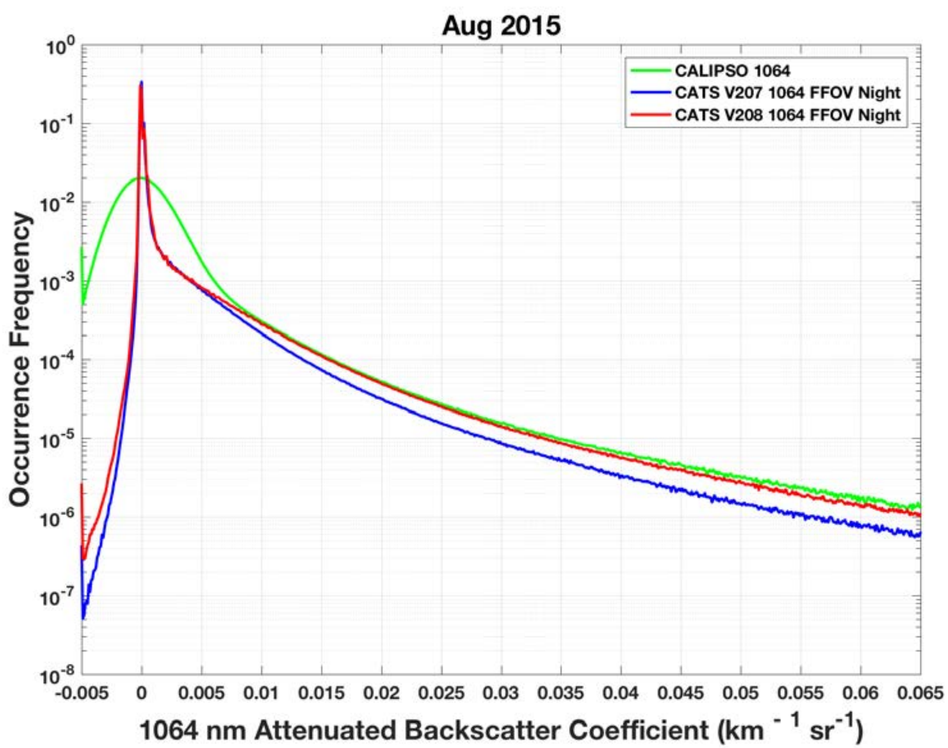
- ISS Program (HEOMD) for funding the instrument
- NASA SMD for funding algorithms/data products (joint w/ LaRC)
- ROSES CCST 2015 for CATS-CALIPSO comparisons and analysis of aerosol properties

Backup

Dust	Smoke
~56±16 Sr (Omar et al., 2010)	**21-37 Sr** (Sayer et al., 2014)
~50 Sr (Liu et al., 2011)	**29 Sr** (Vaughan et al., 2015 ILRC talk)
40 Sr (Vaughan et al., 2015 ILRC talk)	**32-35 Sr** (McGill et al., 2003)
44 Sr – CALIPSO Default (V4-10)	**30 Sr** – CALIPSO Default (V4-10)
40 Sr – CATS Default (V2-01)	**40 Sr** – CATS Default (V2-01)
40 ± 20 Sr (CATS preliminary above cloud method)	**37 ± 17 Sr** (CATS preliminary above cloud method -fresh smoke)

Backup

- **Statistical comparisons of CATS and CALIPSO 1064 nm backscatter and calibration are underway**
  - 2 Different calibration techniques converging to same answer
  - Leading to improved data product maturity for both instruments
  - Higher confidence in combining the 1064 nm data from both instruments.



CALIPSO:
Calibrated using 1064-532 cirrus color ratio assumptions

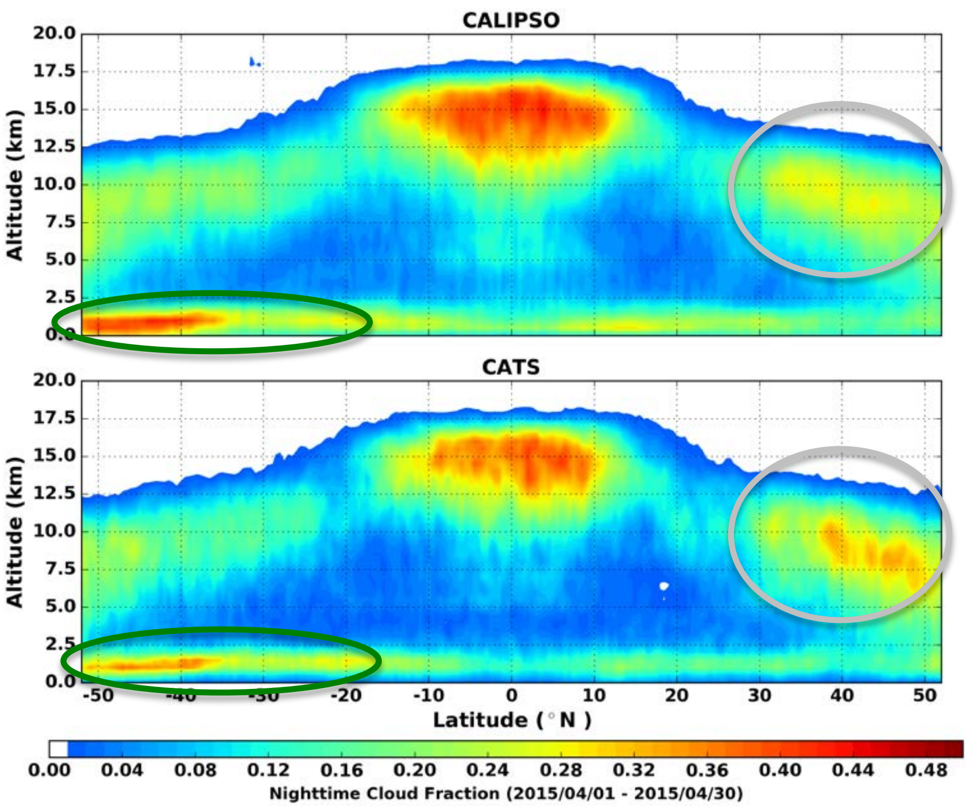
CATS V2-07:
Low bias in normalization of CATS backscatter signal to Rayleigh profile

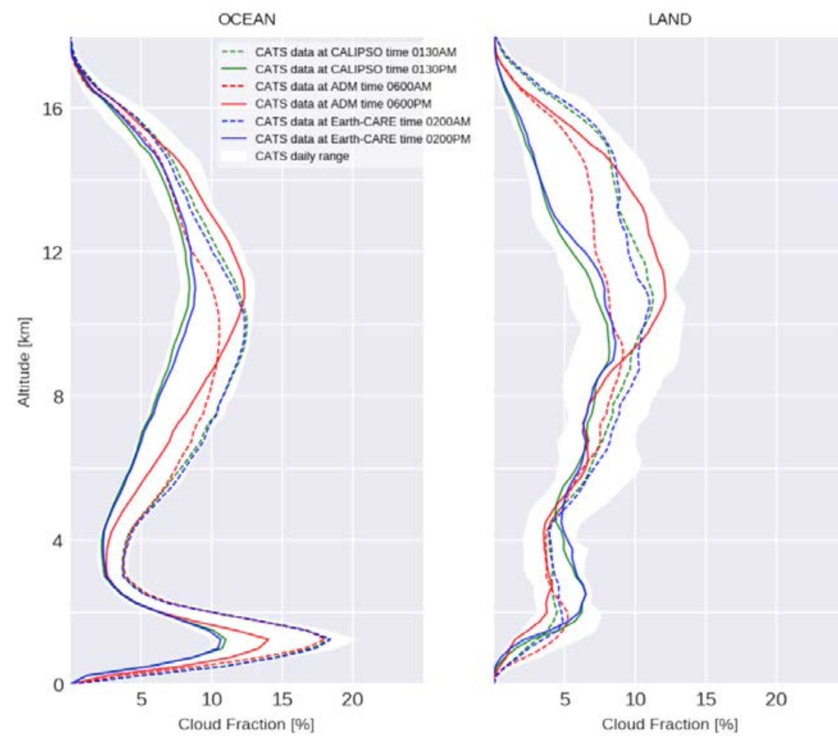
CATS V2-08:
Backscatter signal ACCURATELY calibrated directly using Rayleigh profile

Diurnal Variability: Clouds

Why are we seeing different cirrus frequencies in the NH mid-latitude?

- Differences in sampling times: CATS provides measurements at different local time every overpass.
- CALIPSO, other NASA A-Train instruments, ADM, and EarthCARE only observe clouds and aerosols at the same 2 local times every overpass. Thus, they only capture a "snapshot" of the diurnal variability seen by CATS (below).





Noel et al. [ACP, 2018]

Smoke Transport

The long-range smoke transport from Africa across the Indian Ocean is observed by CATS over the Sept/Oct season in which the synoptic conditions are perfect for this transport.

The smoke transport is observed at ~40 S across the Indian Ocean from Africa to Australia.