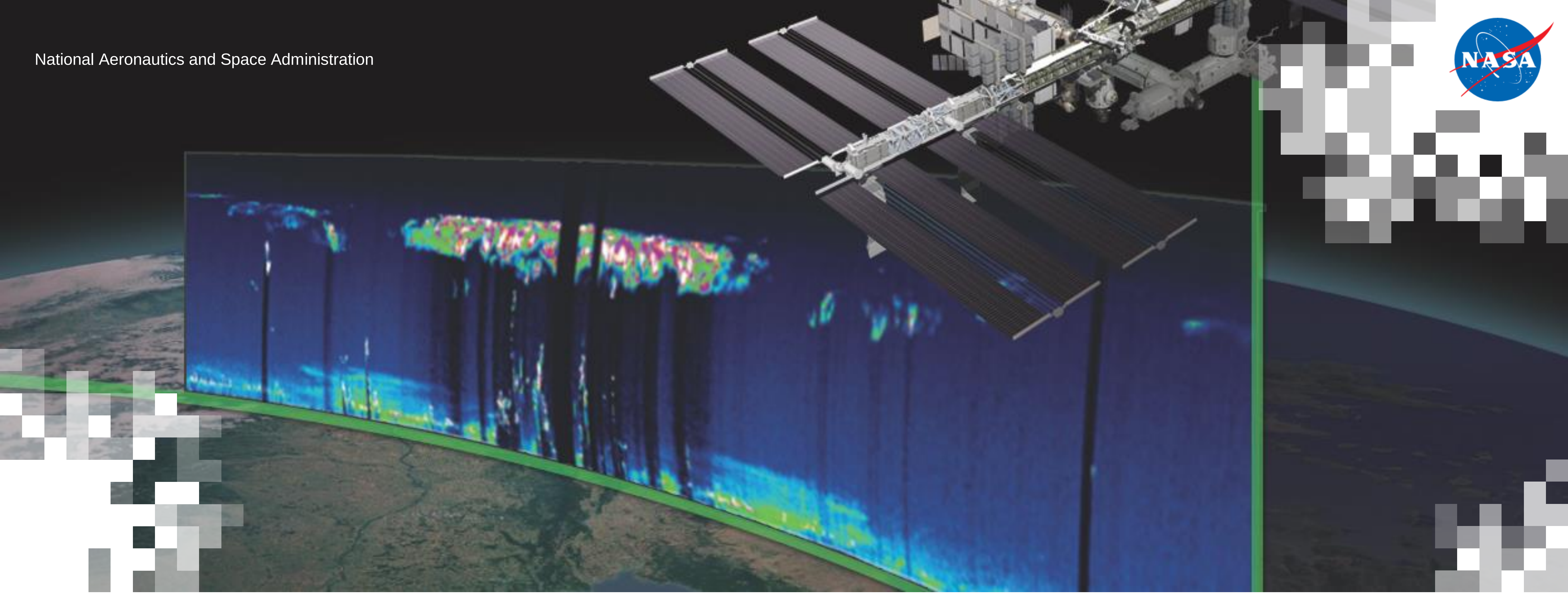
National Aeronautics and Space Administration

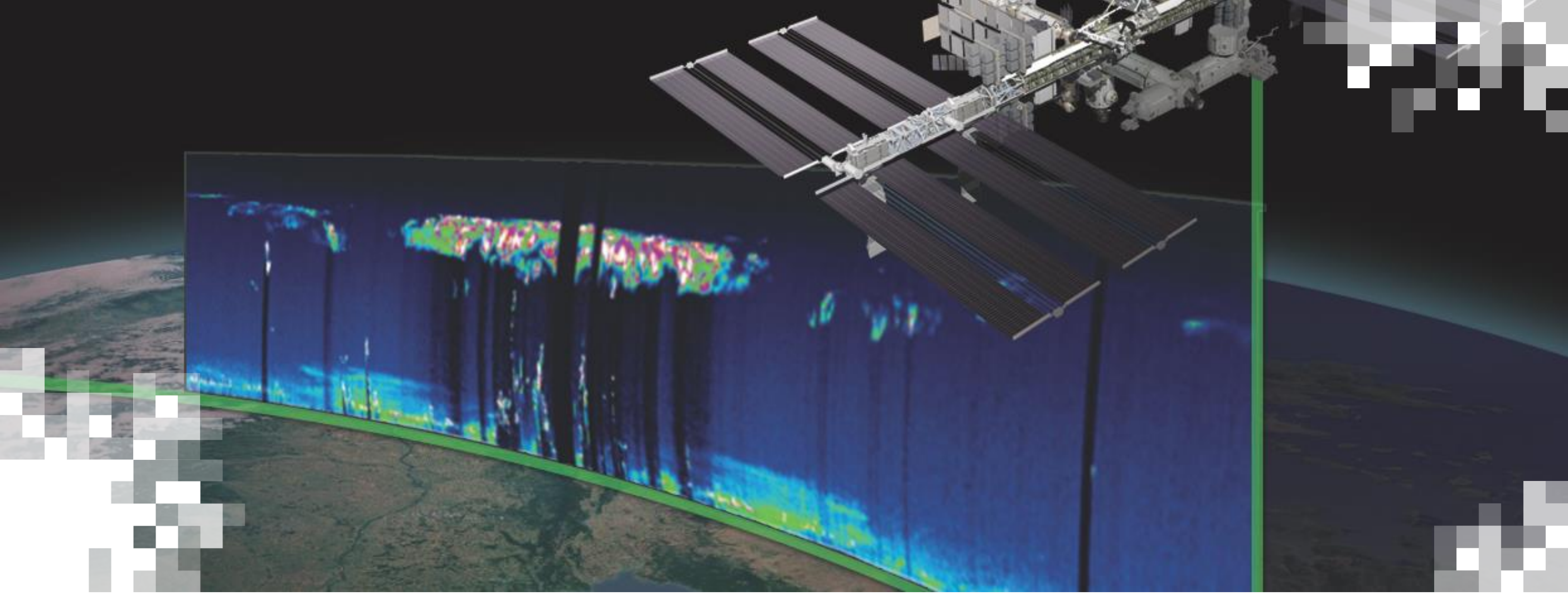


LiDAR Profiling Satellite Observations for Air Quality Applications

Part 1: Introduction to LiDAR Measurements and Missions

Ed Nowottnick (NASA Goddard Space Flight Center)

June 4, 2025



About ARSET

About ARSET

- **ARSET provides accessible, relevant, and cost-free training on remote sensing satellites, sensors, methods, and tools.**
- Trainings include a variety of applications of satellite data and are tailored to audiences with a variety of experience levels.

AGRICULTURE

CLIMATE & RESILIENCE

DISASTERS

ECOLOGICAL CONSERVATION

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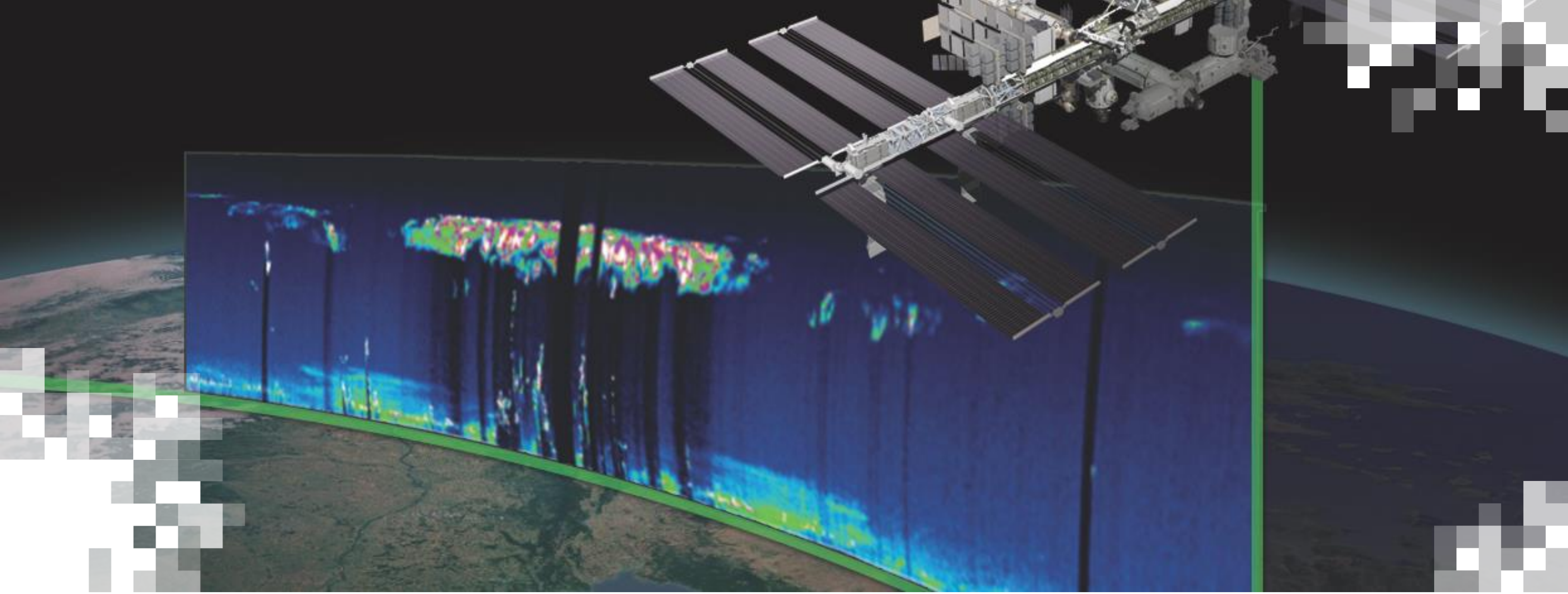
About ARSET Trainings

- Online or in-person
- Live and instructor-led or asynchronous and self-paced
- Cost-free
- Bilingual and multilingual options
- Only use open-source software and data
- Accommodate differing levels of expertise

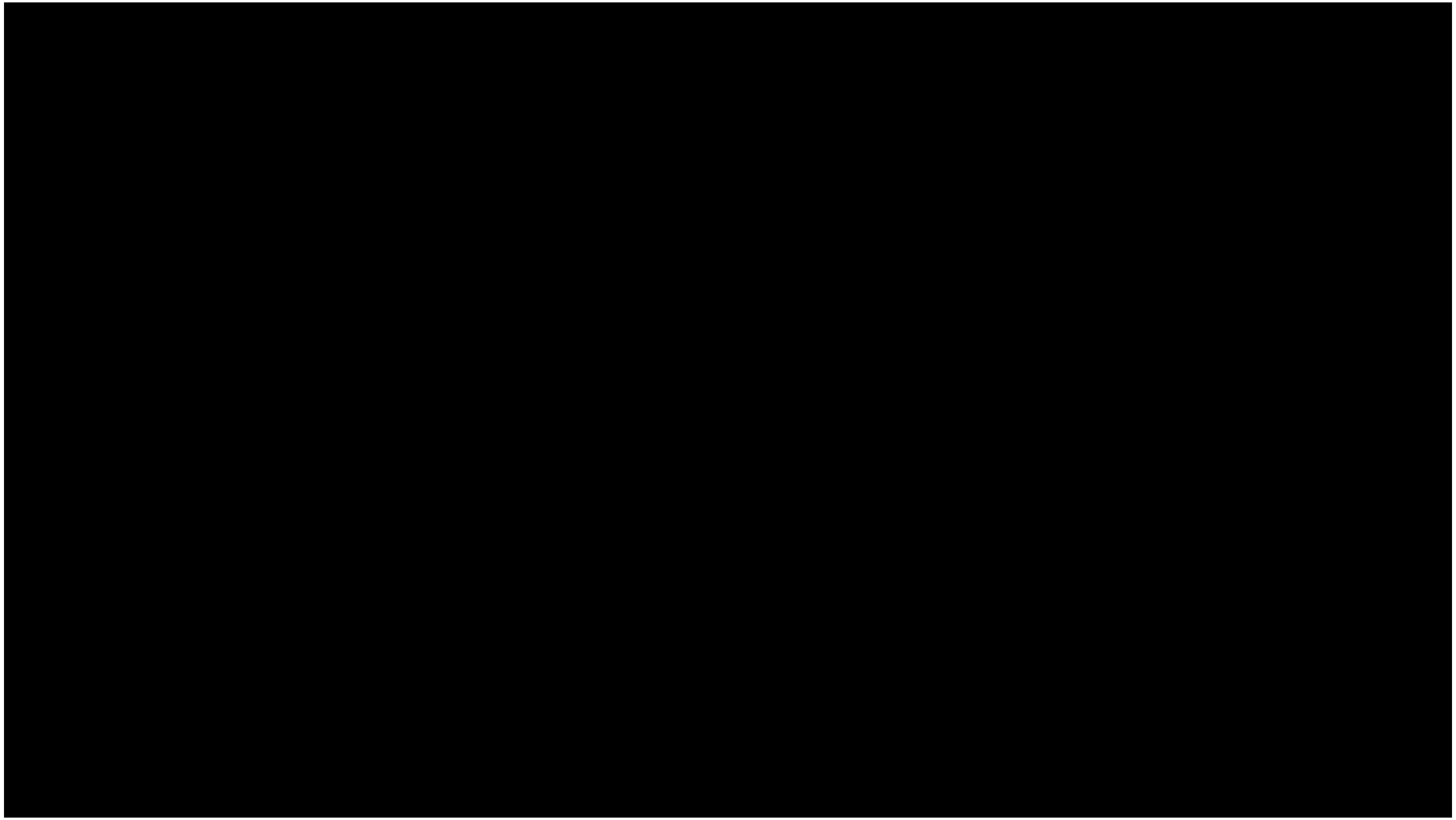
- Visit the [ARSET website](#) to learn more.



LiDAR Profiling Satellite Observations for Air Quality Applications

Overview

Lidar observations provide vertically resolved measurements aerosols– key for nose level air quality



Training Learning Objectives

By the end of this training, participants will be able to:

- Identify past and currently available lidar missions and their characteristics
- Recognize the capabilities of LiDAR active remote sensing in measuring vertical profiles of aerosols and clouds for informing air quality applications
- Interpret information within LiDAR curtains to discern cloud phase, aerosol type, and aerosol plume altitude for a given scene
- Recognize the strengths and limitations of LiDAR observations
- Find LiDAR images and data for a particular time period and location using NASA Earthdata and mission websites

Prerequisites

- Fundamentals of Remote Sensing

Training Outline

Part 1

Introduction to LiDAR Measurements and Missions

June 4, 2025

10 AM/2PM ET

Part 2

Interpreting LiDAR Observations

Accessing LiDAR data

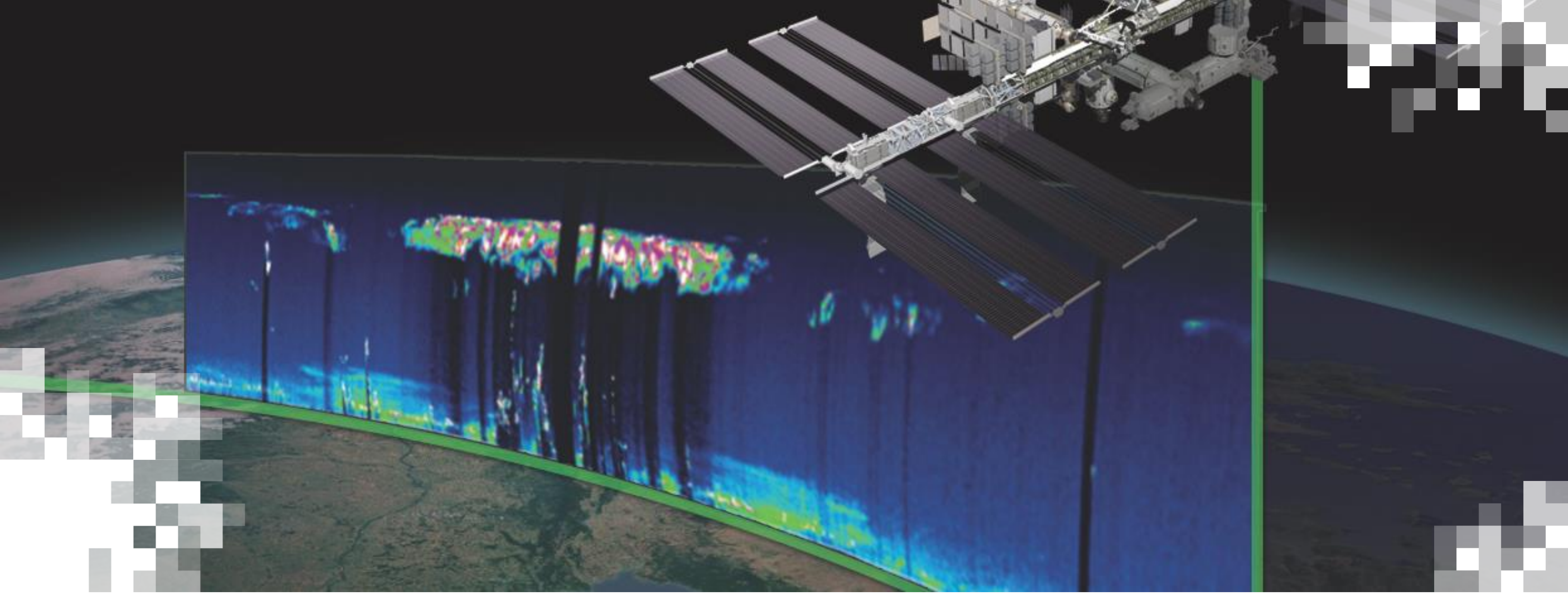
June 11, 2025

10 AM/2PM ET

Homework

Opens June 11 – Due June 25 – Posted on Training Webpage

A certificate of completion will be awarded to those who attend both live sessions and complete the homework assignment(s) before the given due date.



Part 1
LiDAR Profiling Satellite Observations for Air Quality Applications

Part 1 – Trainer

Ed Nowottnick

Research Physical Scientist

NASA Goddard Space Flight Center

Part 1 Objectives

By the end of Part 1, participants will be able to:

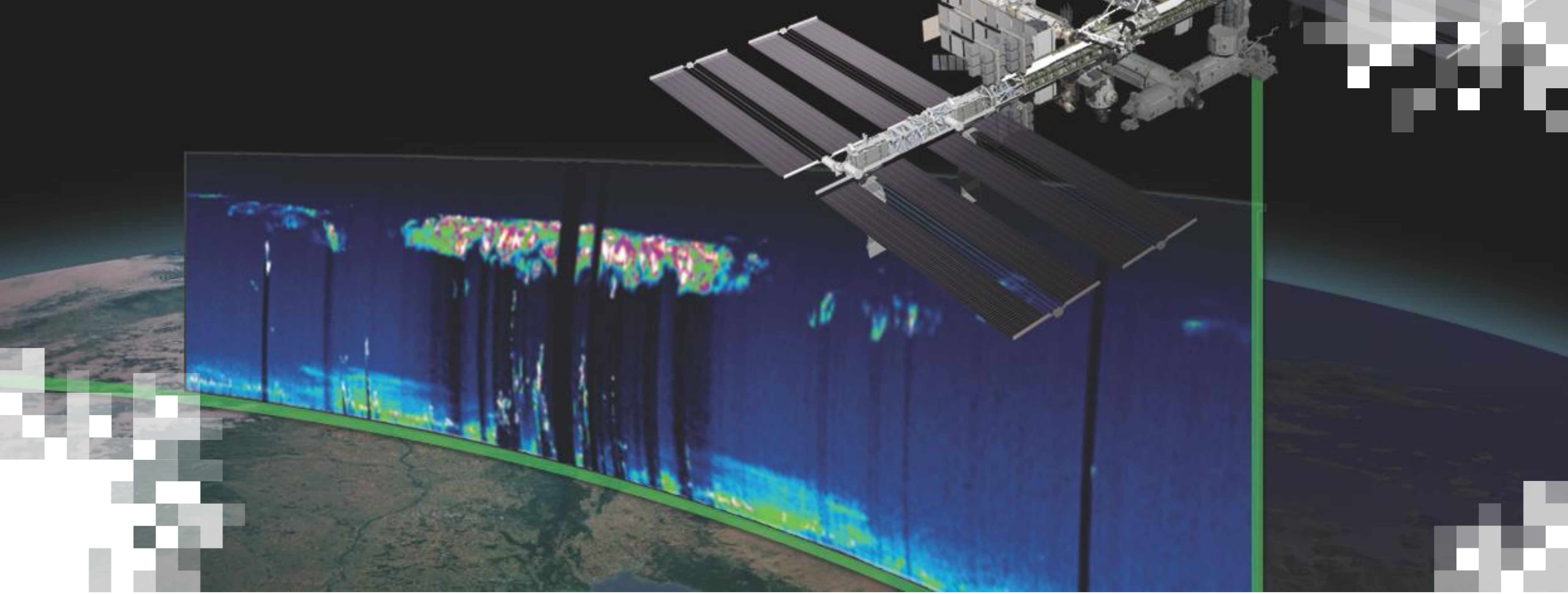
1. Recognize the capabilities of LiDAR active remote sensing in measuring vertical profiles of aerosols and clouds for informing air quality applications ✓
2. Recognize the strengths and limitations of LiDAR observations ✓
3. Identify past and currently available lidar missions and their characteristics ✓

Review of Prior Knowledge

- Differences between active and passive remote sensing
- Understanding of satellite orbit, swaths, and revisit time
- Aerosol definition and importance for air quality

How to Ask Questions

- Please put your questions in the Questions box and we will address them at the end of the webinar.
- Feel free to enter your questions as we go. We will try to get to all of the questions during the Q&A session after the webinar.
- The remainder of the questions will be answered in the Q&A document, which will be posted to the training website about a week after the training.

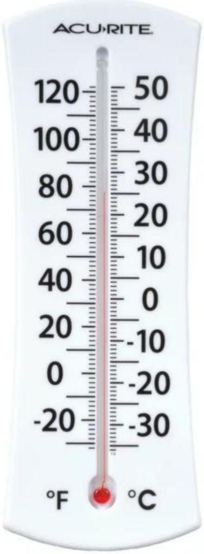


Section 1

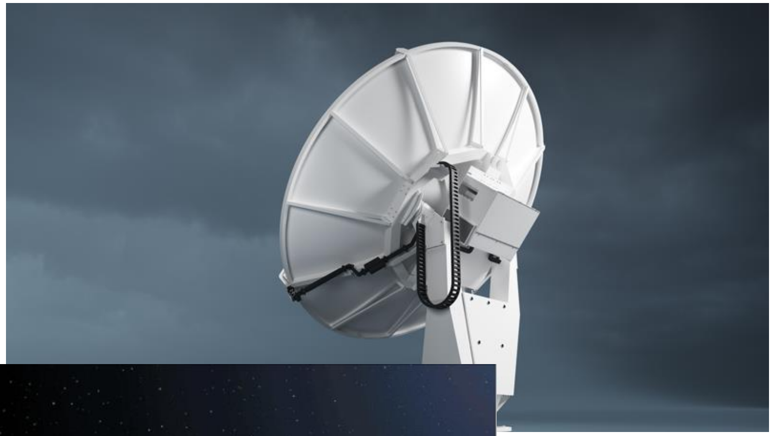
Use of LiDAR in Atmospheric Sciences

Approaches for Measuring the Atmosphere

In Situ
(Where You Are – “Ambient Conditions”)

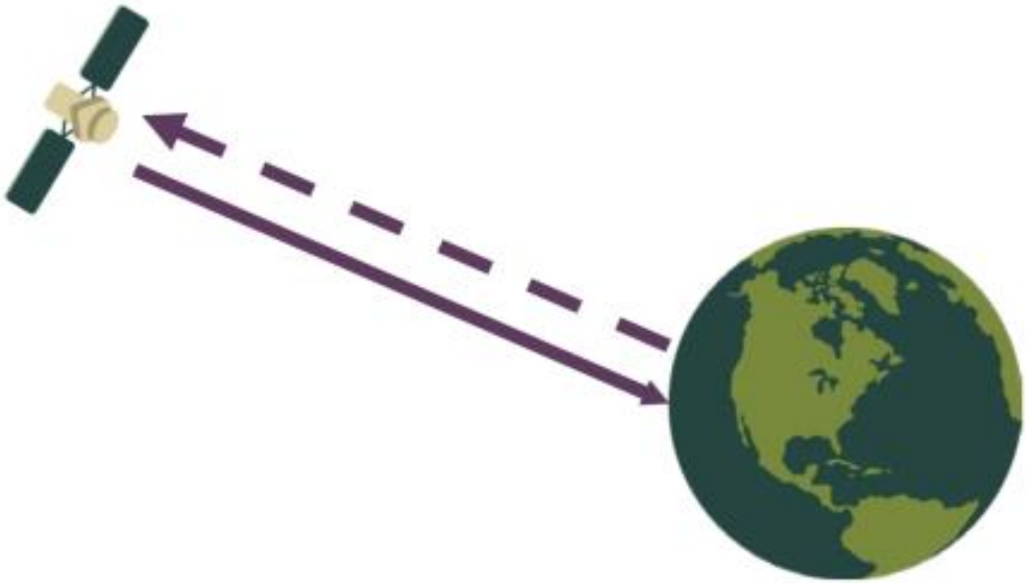


Remote Sensing
(Far Away)



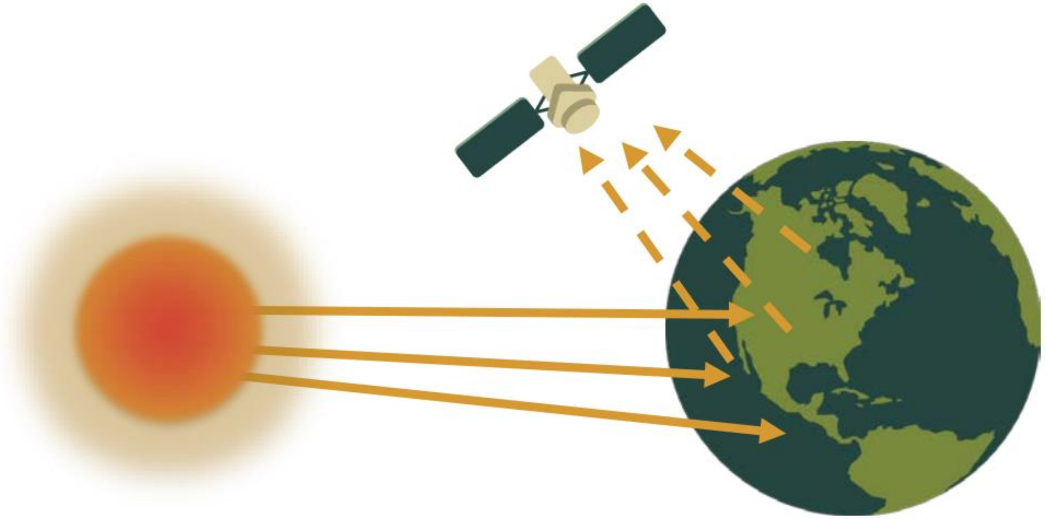
Active vs. Passive Remote Sensing Refresher

Active Sensors



Active Remote Sensing instruments emit their own energy source (e.g., visible light from a laser) and measure the returned signal.

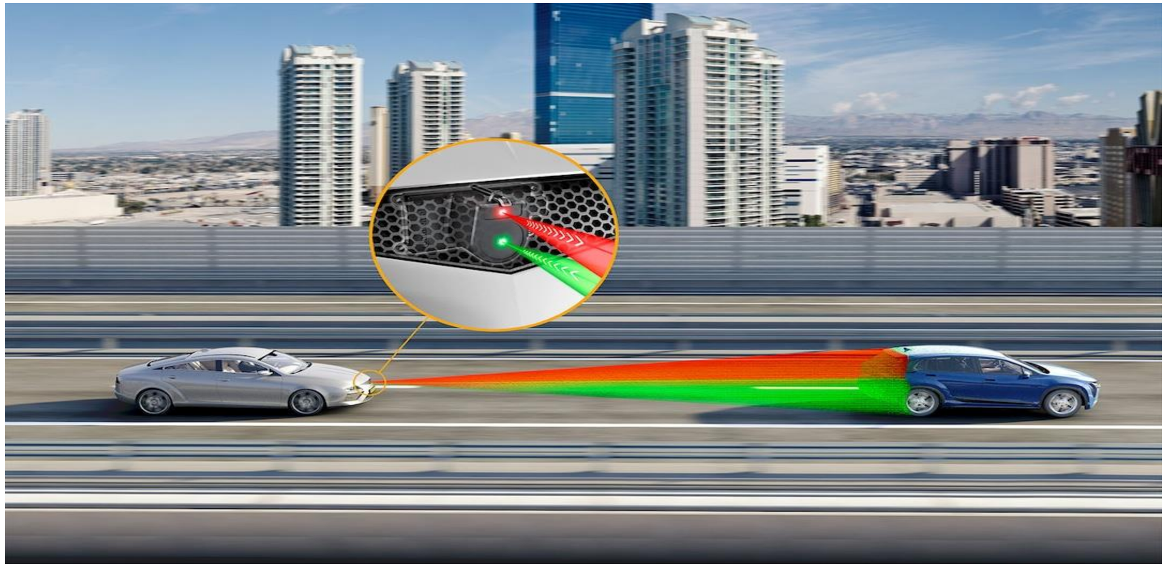
Passive Sensors

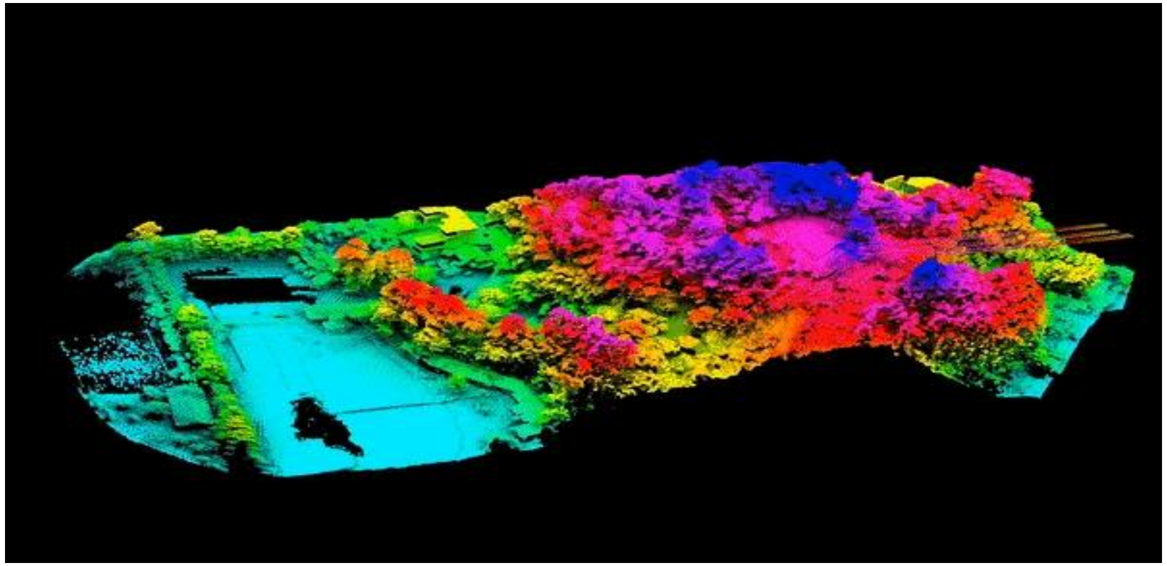


Passive Remote Sensing instruments rely on an external energy source (e.g., the Sun).

What is a LiDAR and its Common Uses?

- LiDARs – **Li**ght **D**etection **A**nd **R**anging
- **LiDAR Definition:**
  Active remote sensing instruments that transmit laser light and measure the return time of backscattered light to determine distance of an object with high precision (e.g. sub meter measurements).
- LiDAR non-science applications
  - vehicular object detection
  - range finders
  - airplane landing guidance
  - 3-D topography mapping.
- Known colloquially as “lidar”

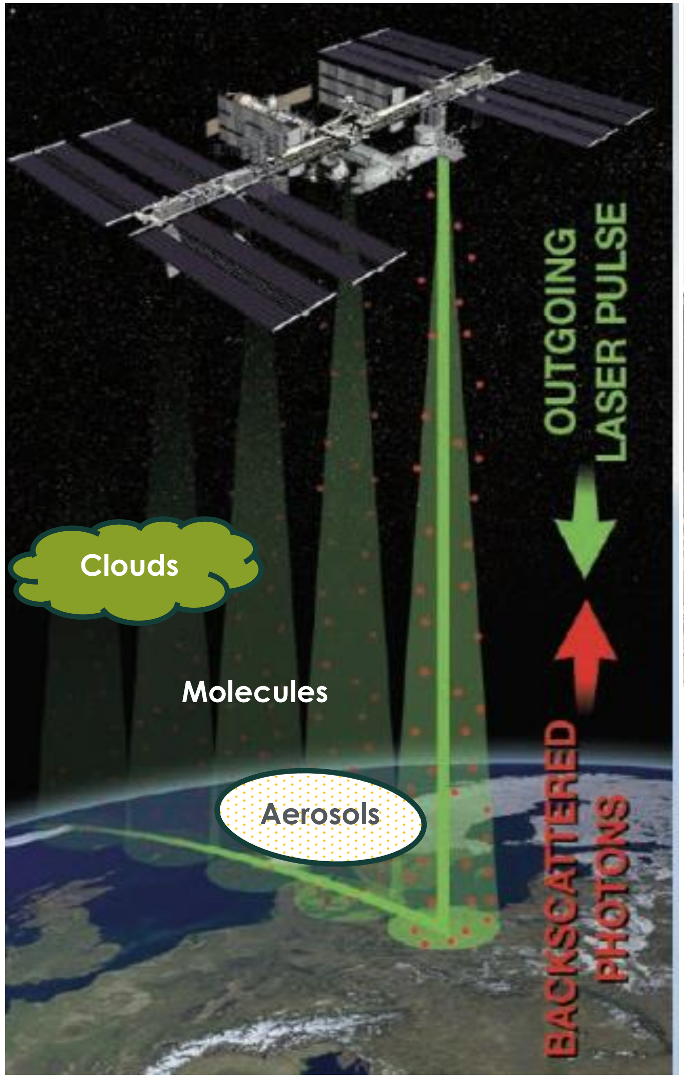




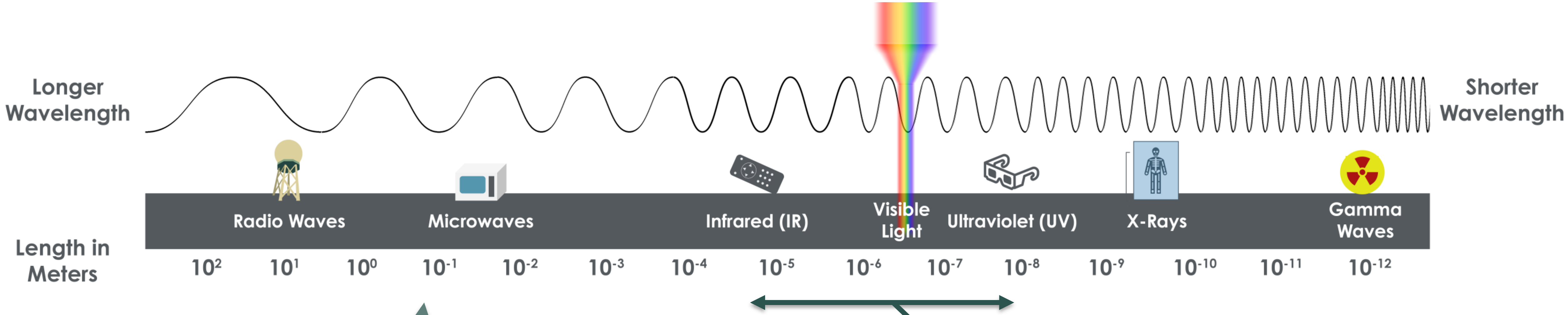
LiDAR Uses and Platforms for the Atmospheric Sciences

- LiDARs for science applications
  - Aerosols
  - Clouds
  - Winds
  - Water vapor
  - Gases
  - Height of trees and ice sheets

- Varying levels of sophistication and platforms, including:
  - Satellites
  - Ground-Based (Trailers, Ships)
  - Aircraft



LiDAR EM Range Usage for Atmospheric Sciences



- Active sensors that target longer wavelengths (e.g., microwave) are classified as radars.

- For atmospheric science applications, LiDARs measure within the ultraviolet to visible to infrared wavelengths.

LiDAR Strengths for Air Quality Applications vs. Passive Sensors

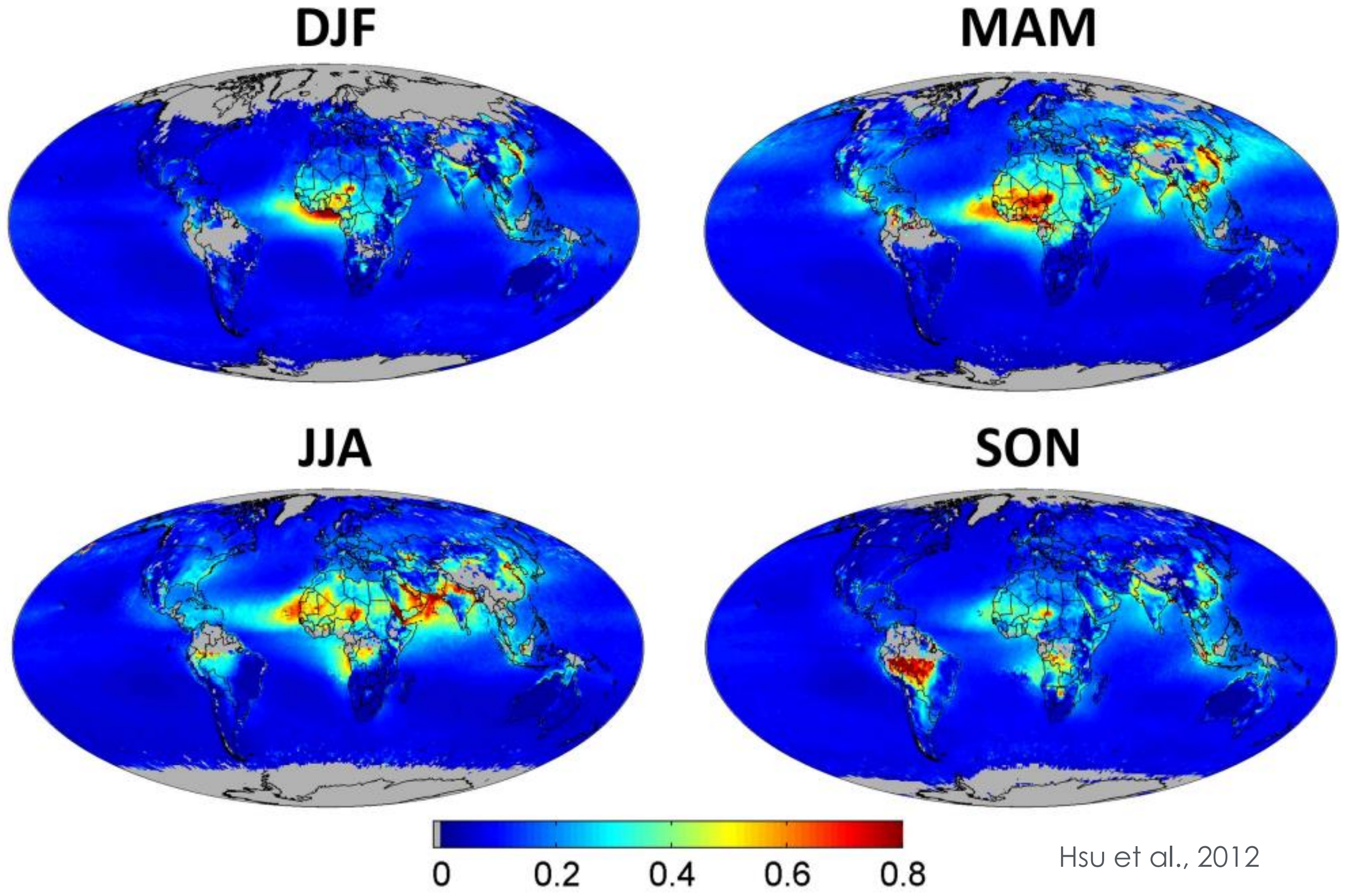
For air quality applications, **LiDAR strengths** are:

- high-resolution spatial capabilities (i.e., on the order of meters)
- vertically-resolved measurements that usually extend to the surface

In comparison, spaceborne **passive remote sensors** (see images):

- Only measure column integrated quantities
- Have very limited and coarse vertical information

Seasonal AOD Measurements via SeaWiFS 1998-2010



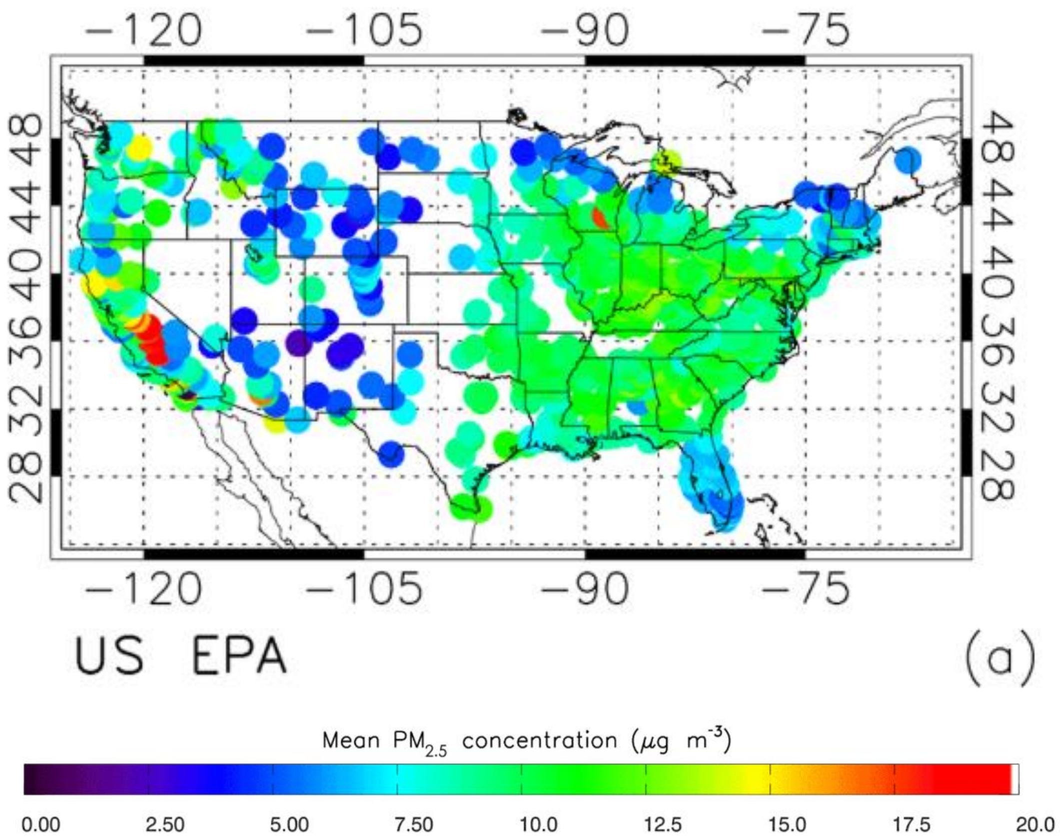
Hsu et al., 2012

Passive sensors provide spatial distributions but lack vertical information.

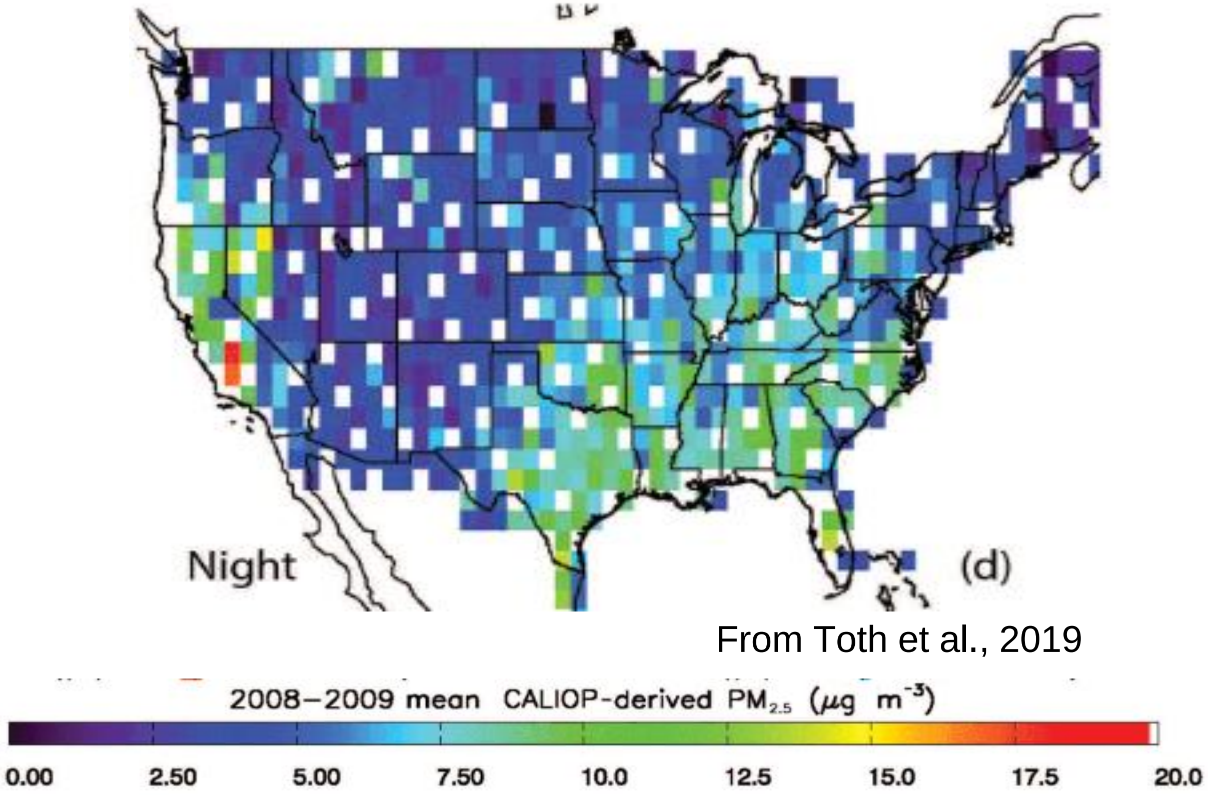
LiDAR Strengths for Air Quality Applications vs. In Situ

LiDAR-derived PM2.5 from space helps fill in coverage gaps between in situ sensors.

EPA *In Situ* 2008-2009 Averaged PM2.5



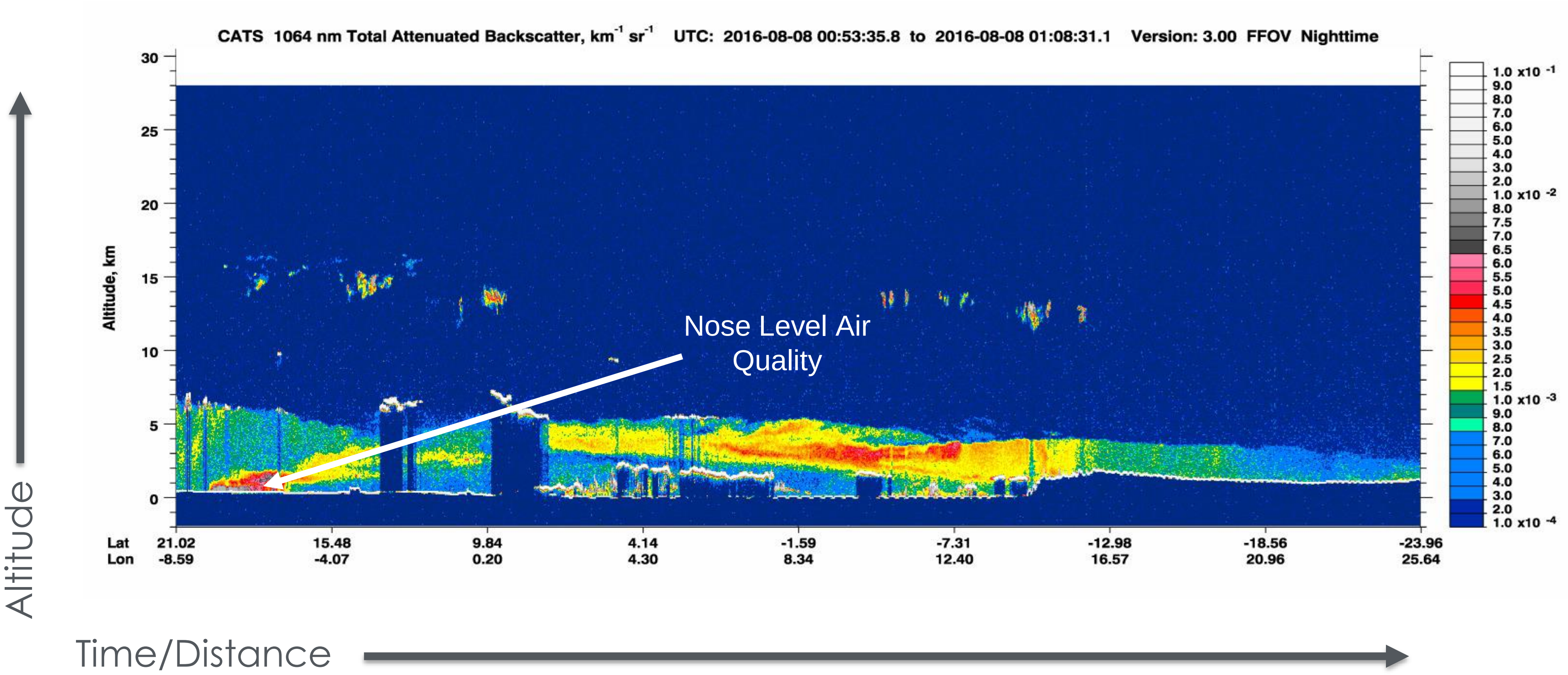
Spaceborne LiDAR Derived 2008-2009 Averaged PM2.5



From Toth et al., 2019

Viewing LiDAR Data

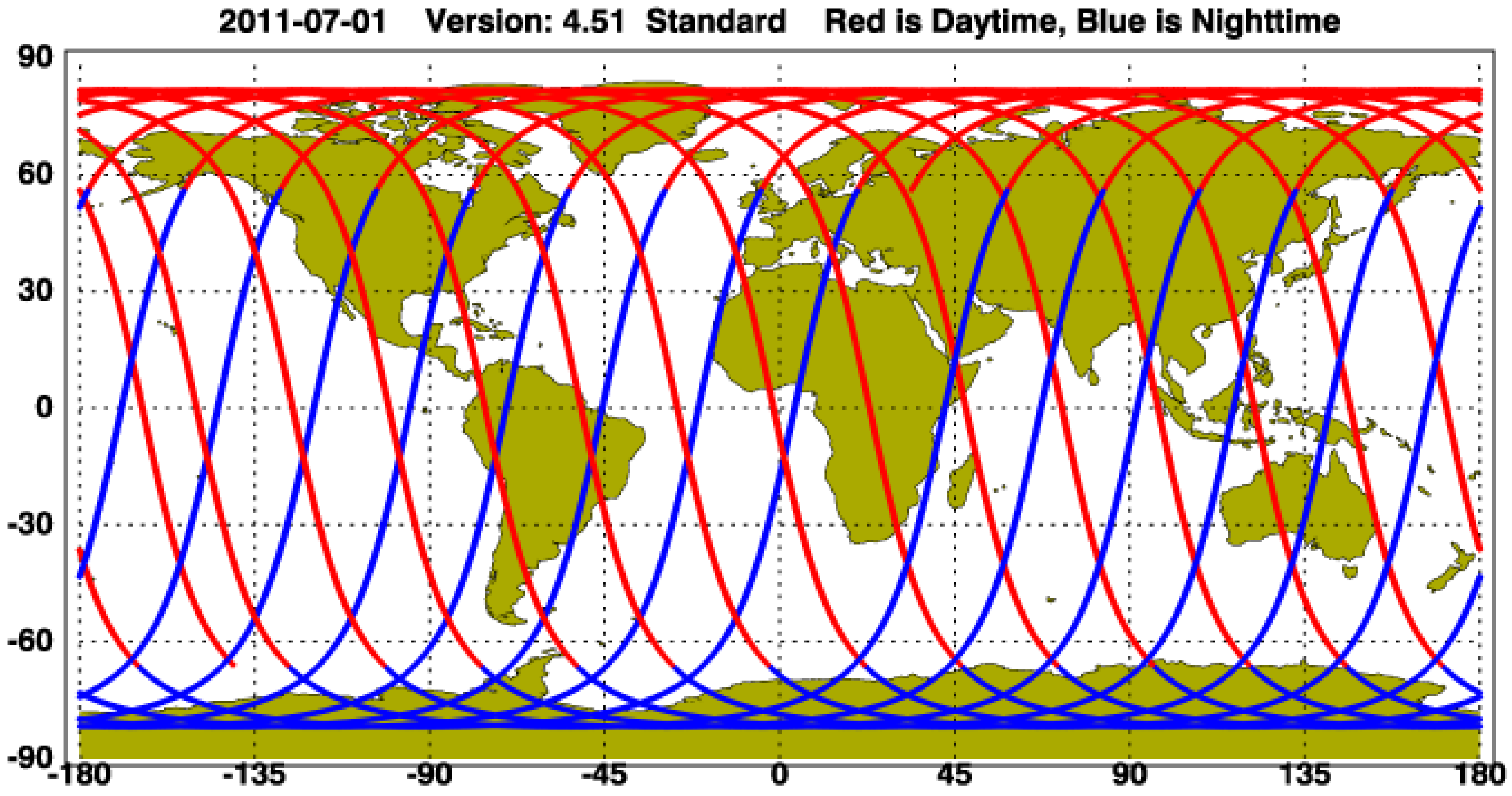
- LiDAR provides vertical measurements of the atmosphere with high vertical resolution (10s of meters).
- Data is often depicted with time/distance on the x-axis and altitude on the y-axis (unlike 2-D passive maps).



LiDAR Strength vs UV/Visible Passive Sensor

Since LiDAR generates their own energy source, measurements occur during **both day and night**.

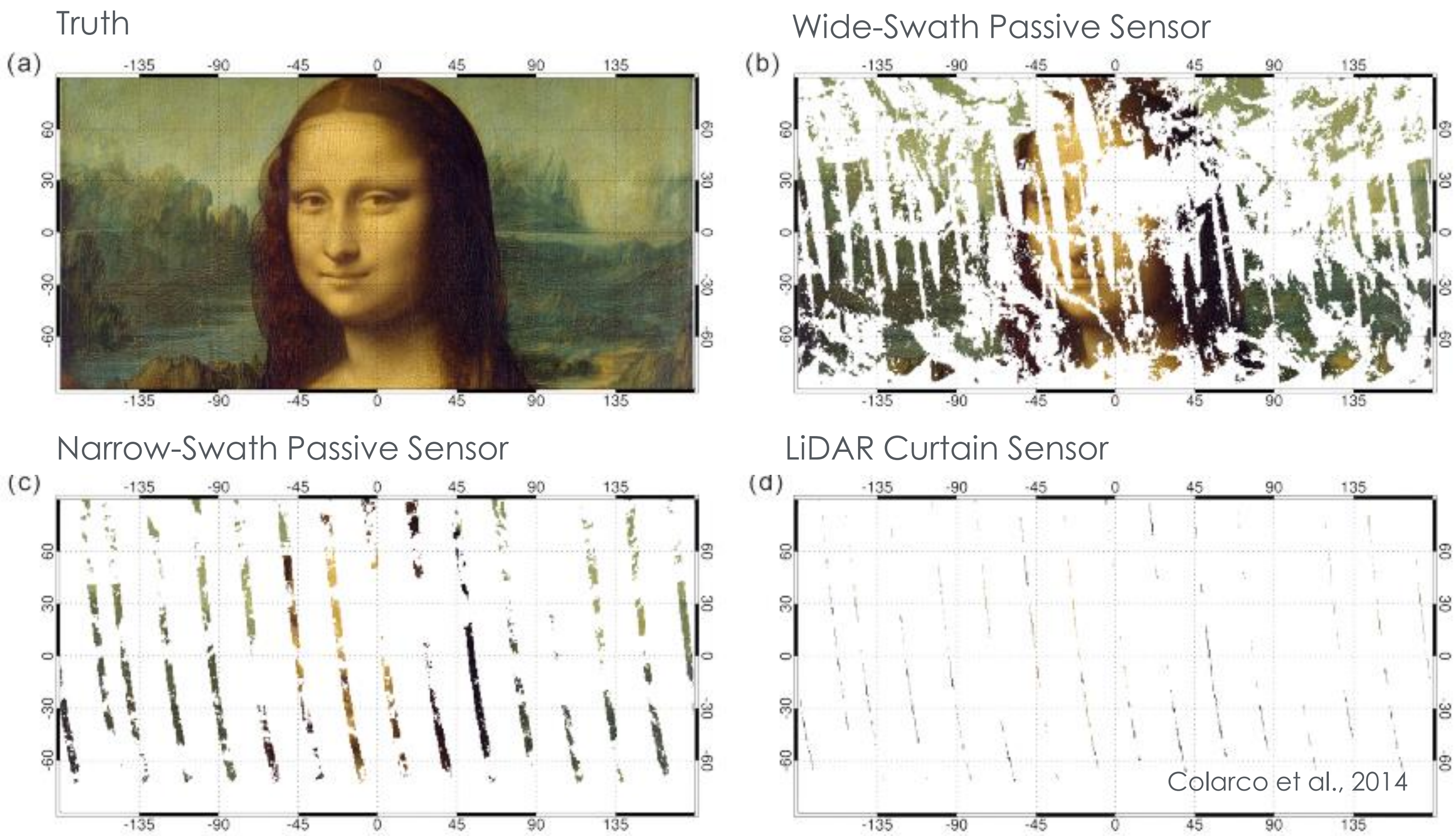
Day (Red) and Night (Blue) Sampling from the NASA CALIPSO Satellite for July 1, 2011



…and Disadvantages of Using LiDAR

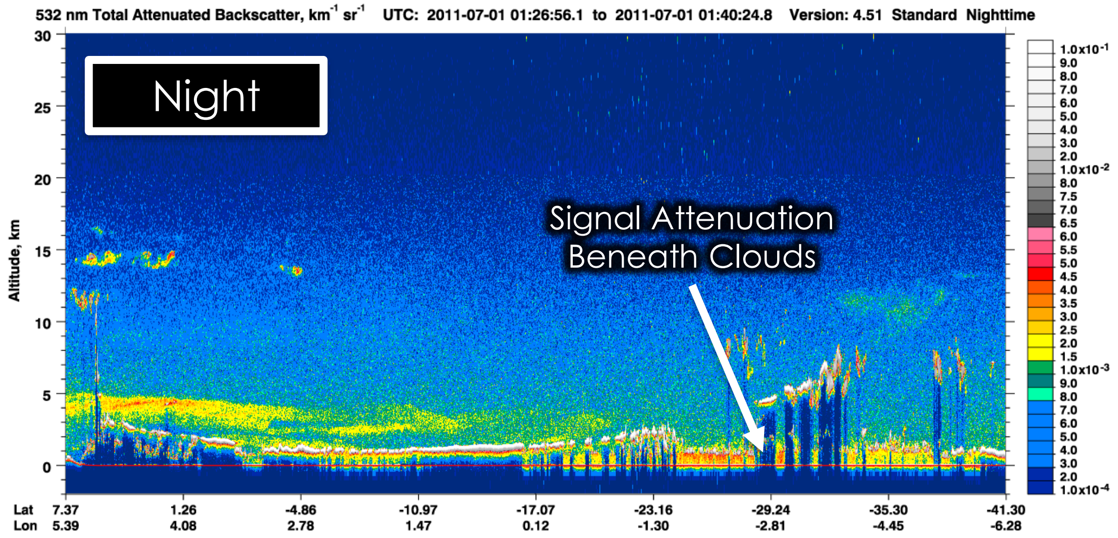
- LiDAR measurements are narrow curtains
- Unlike passive sensors they are limited in swath

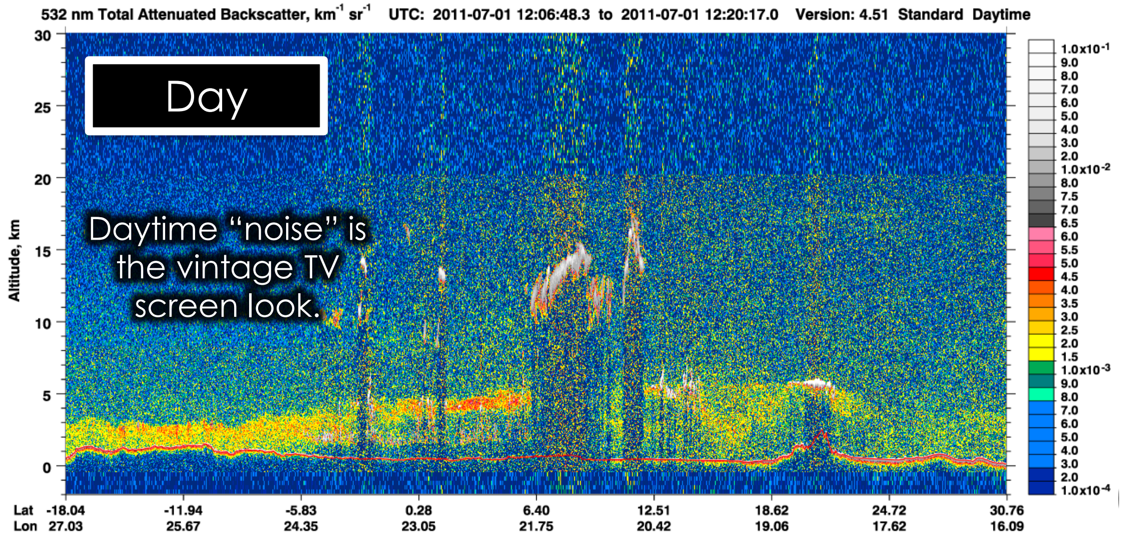
One Day of Daytime Satellite Sampling

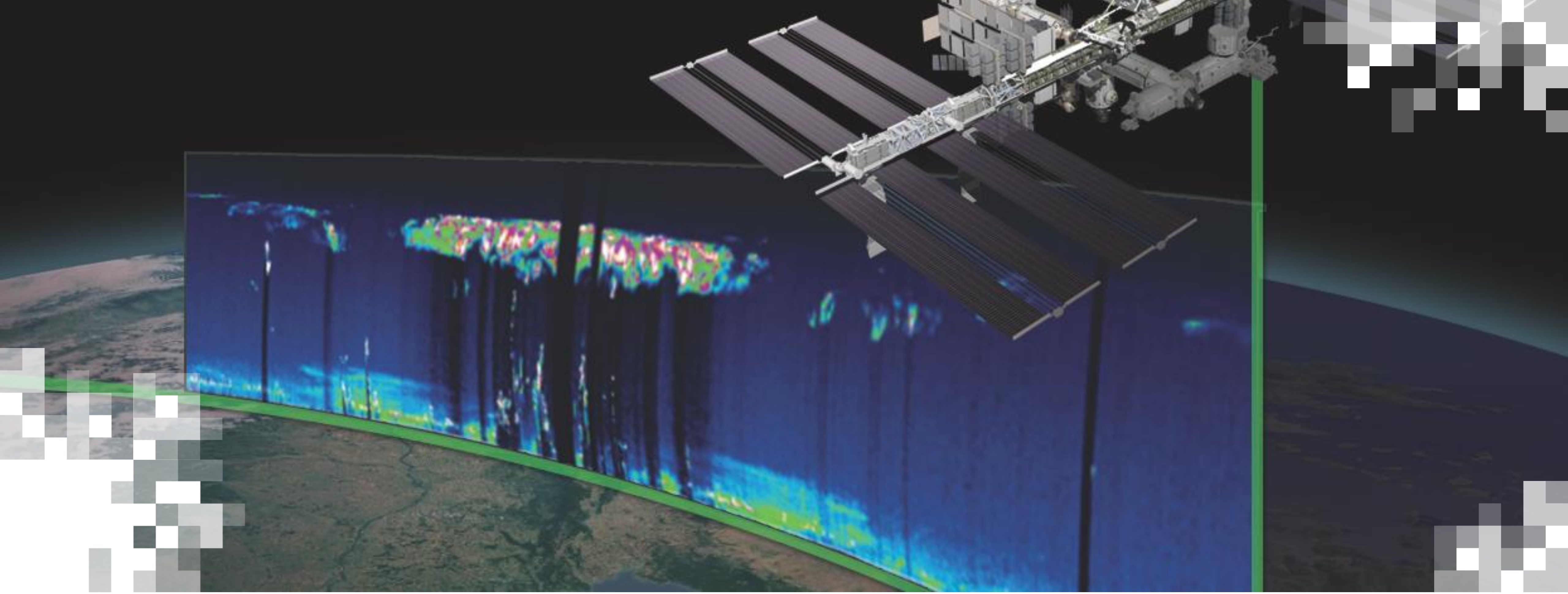


Disadvantages / Limitations of Using LiDAR

- Only a few wavelengths of the EM spectrum are used
- May "miss" cloud and aerosol detection in daytime due to sunlight impacts (signal noise)
- Strongly absorbing features (e.g. clouds or thick smoke) can block retrieval of underlying layers
  - A good indication of this is not being able to "see" the ground return.







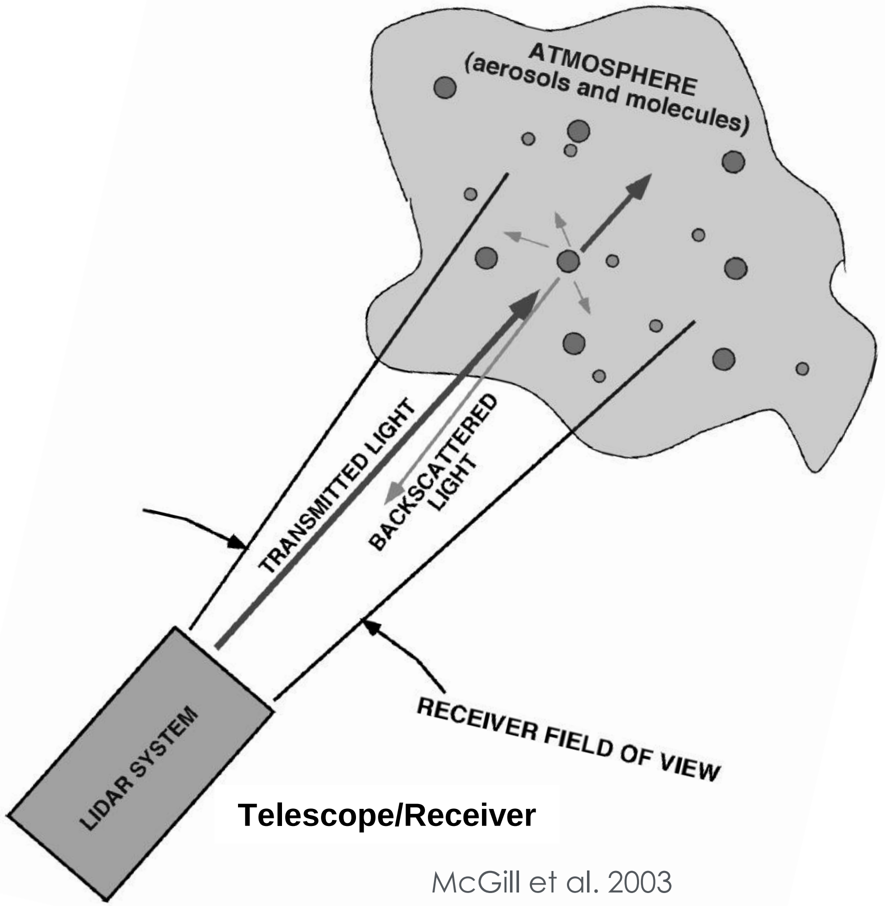
Section 2

How do LiDARs work?

Basic Concept of LiDAR Atmospheric Remote Sensing

The LiDAR System:

- Transmits laser light into the atmosphere.
  - This is known as the transmitter.
- Aerosols and molecules scatter this light.
- Some of the light is scattered back (known as backscatter) into the receiving telescope.
  - This is known as the receiver,
- Detectors in the LiDAR system measure the returned signal.
- Together, the transmitter and receiver are often referred to as the transceiver.



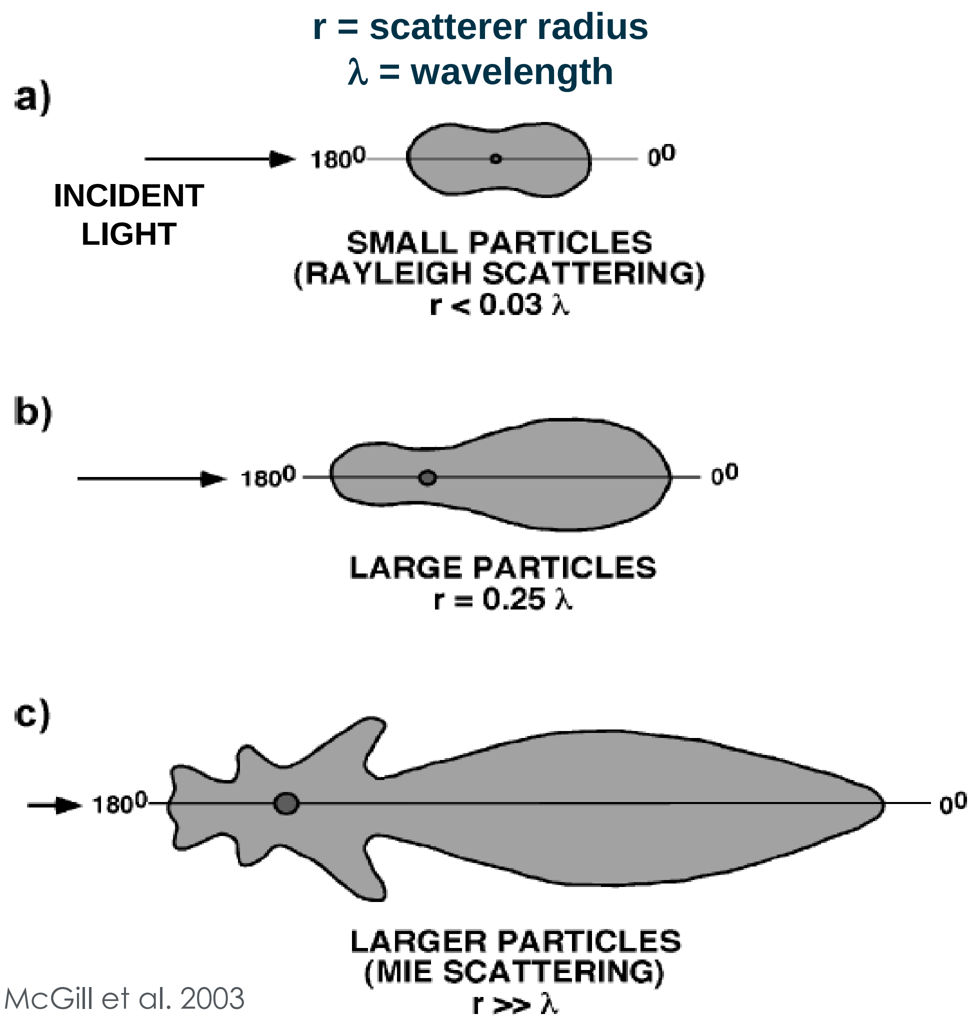
McGill et al. 2003

Scattering Properties as a Function of Wavelength

Key concept: The amount of light backscattered to the LiDAR telescope has dependence on the size of the scatterer relative to the wavelength transmitted by the LiDAR system.

a) Small Particles:
Smaller scatterers in the LiDAR wavelength regime are typically molecules and produce **Rayleigh Scattering**.

b,c) Larger Particles:
Larger scatterers, such as aerosols and cloud particles scatter more in the forward direction, known as **Mie Scattering**.



McGill et al. 2003

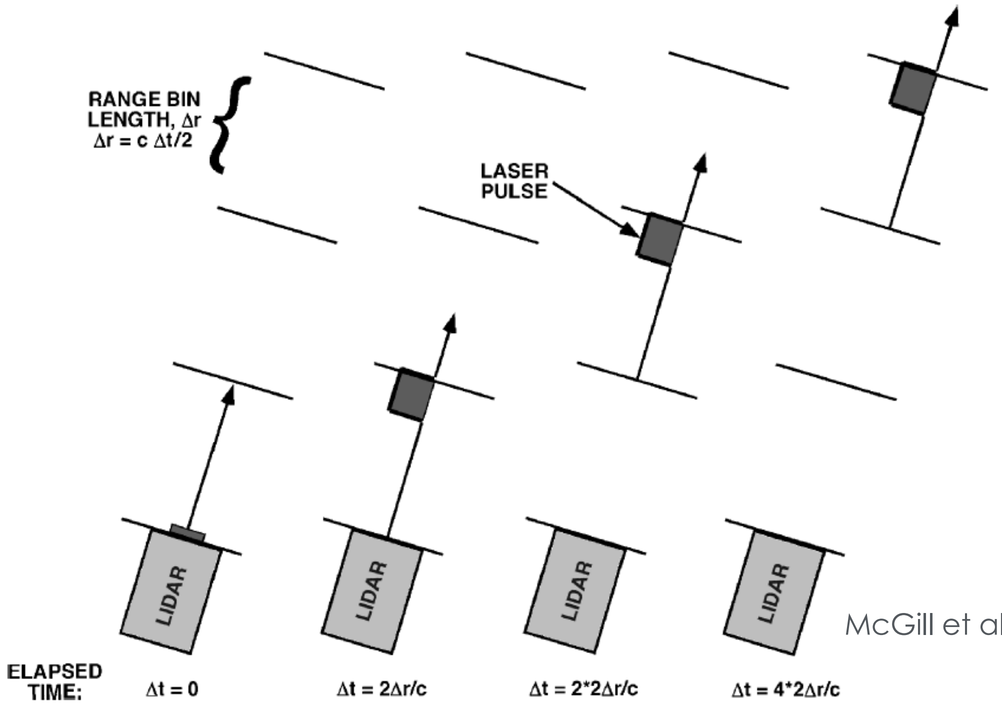
LiDAR Ranging Approach for Atmospheric Measurements

Range Bin Length = Vertical Resolution of a LiDAR System

- $\Delta r = c\ \Delta t / 2$
- If Δr = 150 m, then how long will it take for the laser pulse to cover the round-trip distance?

A common misconception about LiDAR is that signal can only be measured from 1 range bin/laser pulse.

- Signal can be measured from all range bins (up to the limit of signal attenuation) from each laser pulse.

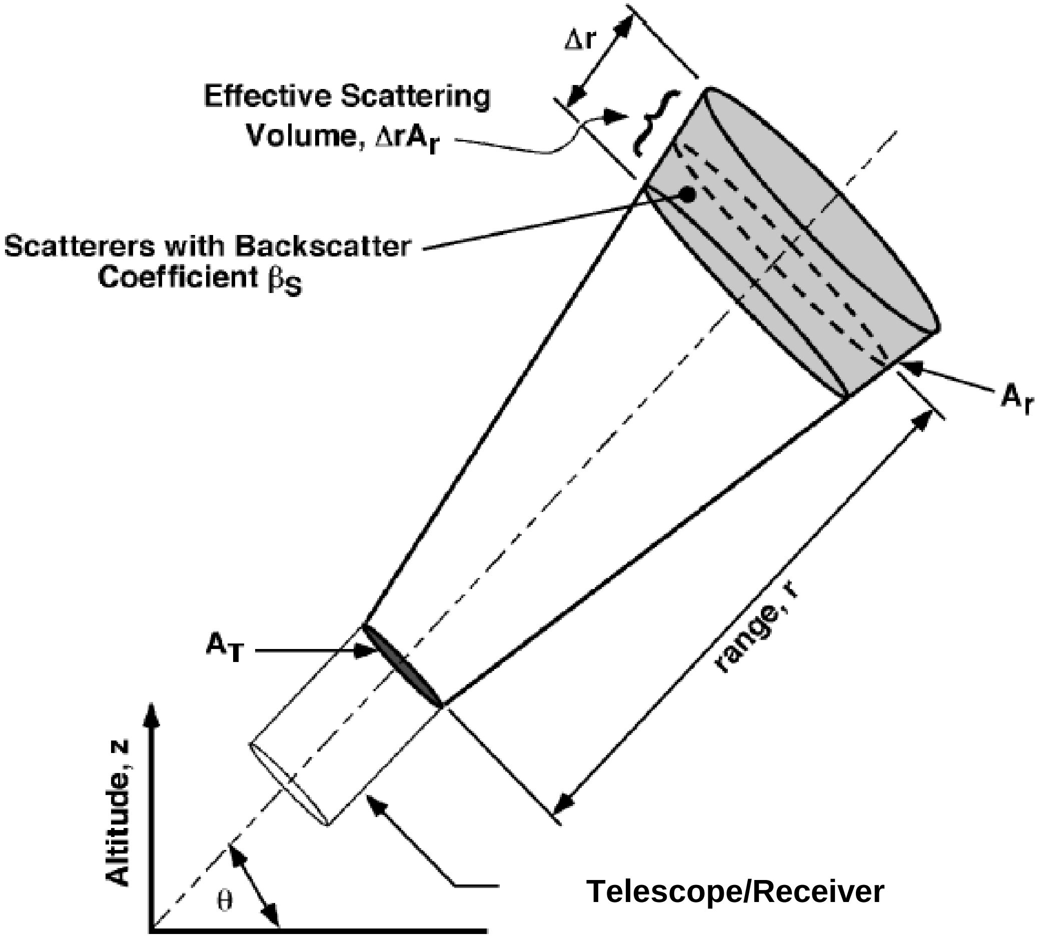


McGill et al. 2003

Key concept: The vertical resolution of a LiDAR system is determined by the instrument design and can be as fine (or as coarse) as desired

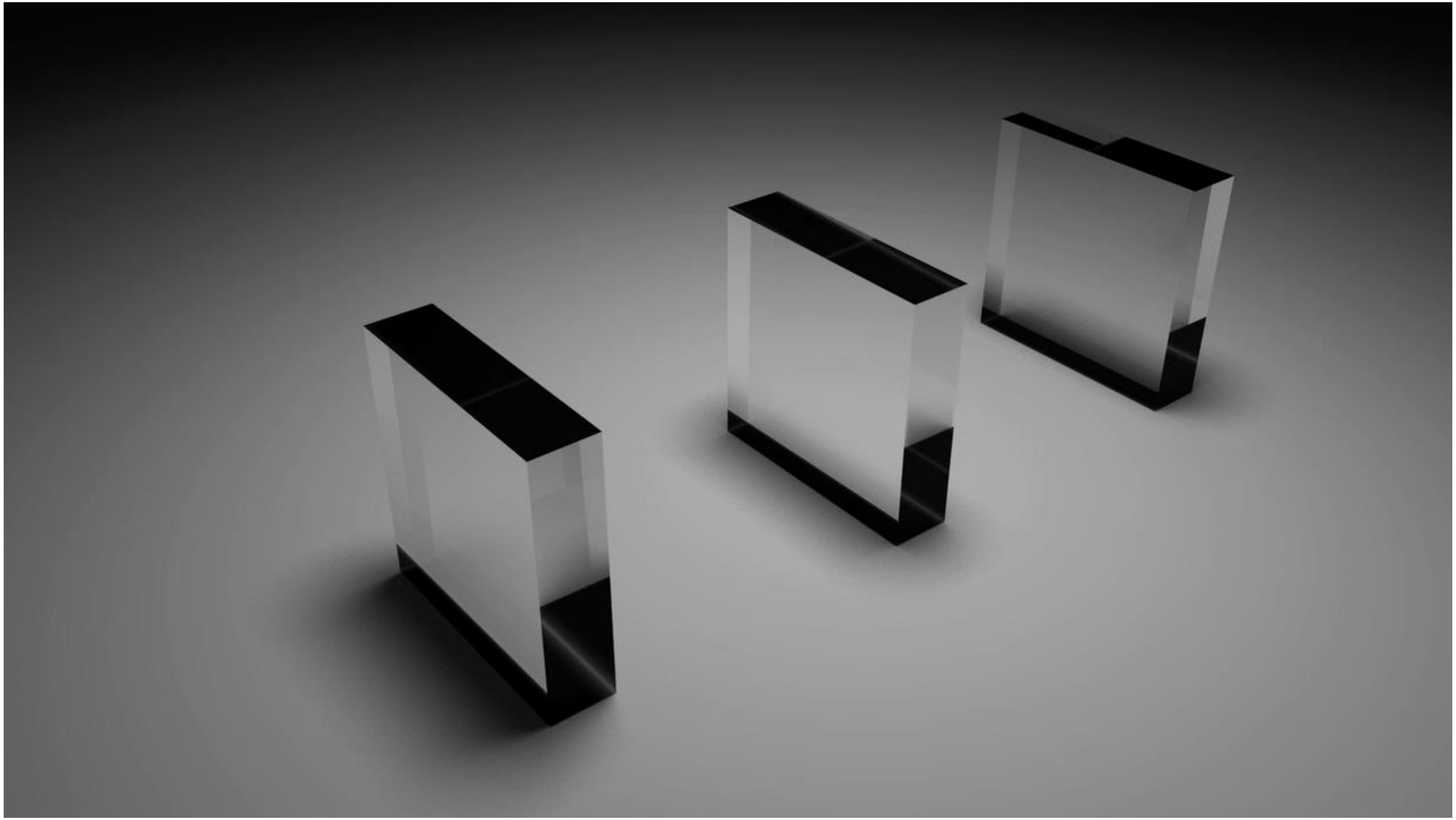
LiDAR Remote Sensing Approach for Measuring Atmospheric Volumes

- LiDAR systems provide measurements over a volume.
  - **Not** point measurements associated with *in situ* instruments.
  - More representative of atmospheric state because spatially averaged measurements minimize the effects of turbulence and localized structure.
- Volume being averaged can be varied by changing:
  - Range Bin Length
  - Telescope Field of View
- Scanning telescopes increase the volume being probed.



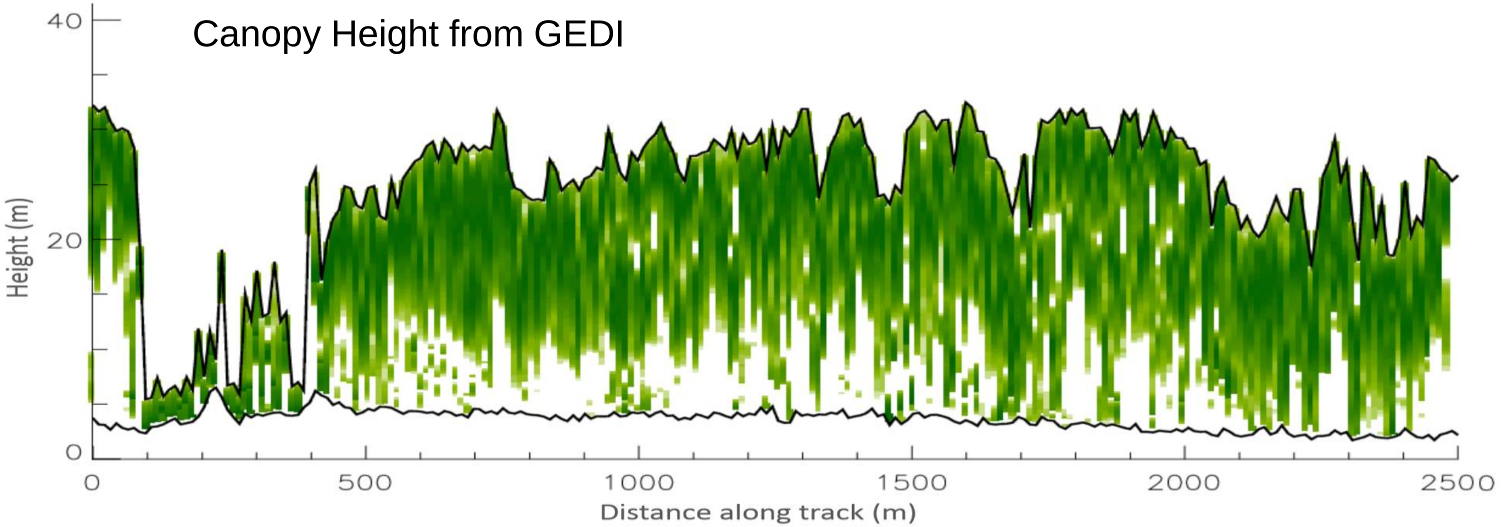
McGill et al. 2003

LiDAR Remote Sensing Basics



Types of LiDAR

- **Cloud-Aerosol LiDARs**
  - Elastic Backscatter LiDARs – Simplest
  - High Spectral Resolution LiDARs (HSRL)
    - Direct extinction retrievals
- **Doppler Wind LiDARs**
  - Use Doppler shift to determine wind velocity
- **Raman LiDARs**
  - Mostly used for water vapor measurements
- **Differential Absorption LiDARs (DIAL)**
  - Profiles of water vapor
  - Profiles of trace gases (Ozone)
- **Laser Altimetry**
  - Vegetation canopies, ice sheet elevation

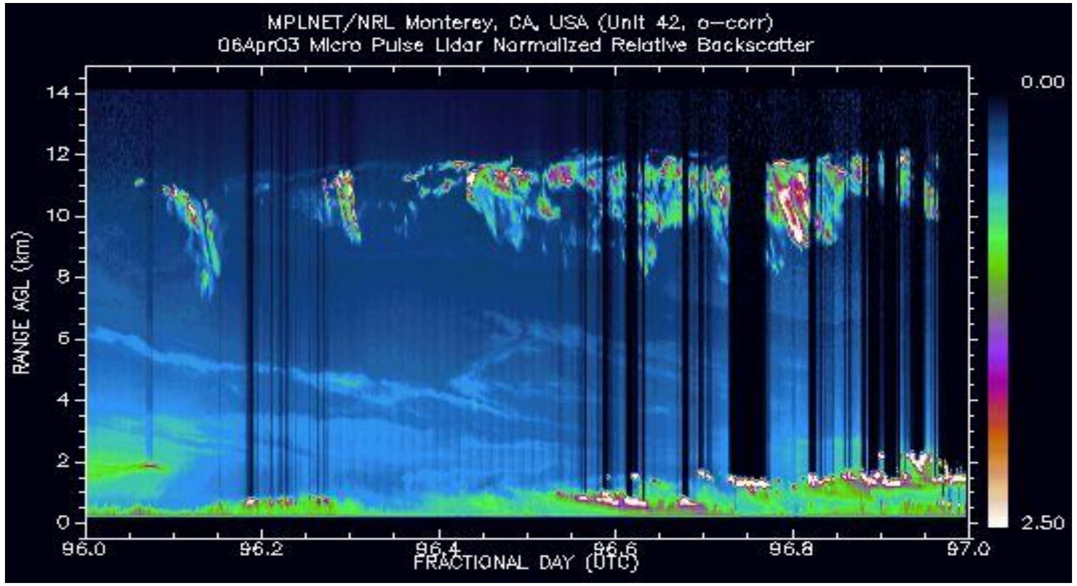


LiDAR Platforms: Ground-Based LiDARs

Ground-Based LiDARs:

- Measures continuously from a fixed point, so advantageous for diurnal evolution of aerosols, clouds, gases, and planetary boundary layer.
- Often are not limited by power constraints and can transmit with high power for improved return signals.
- Can be paired with other instrumentation (e.g., radars, meteorological instrumentation, air quality measurements) to establish supersites.

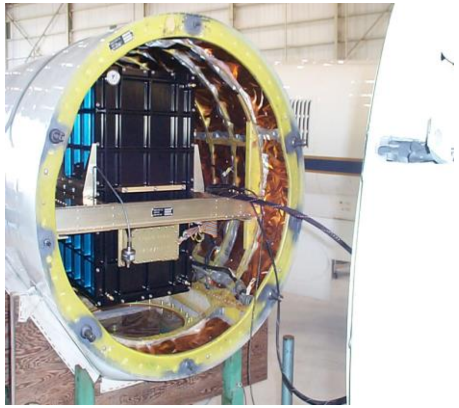
Data from NASA's Micro-Pulse Lidar Network (MPLNet)

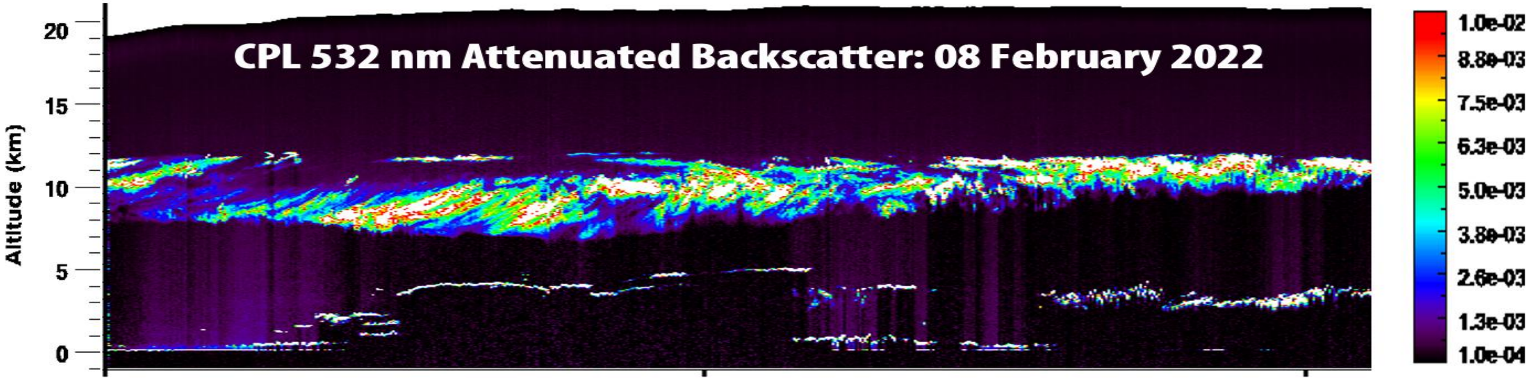


The Department of Energy's Southern Great Plains Supersite

Airborne LiDARs

- Are advantageous for targeted measurements of atmospheric constituents and processes.
- Are mobile for dedicated sampling of phenomena as they move with the atmosphere.
- Also, can be paired with other remote sensing and *in situ* instrumentation.





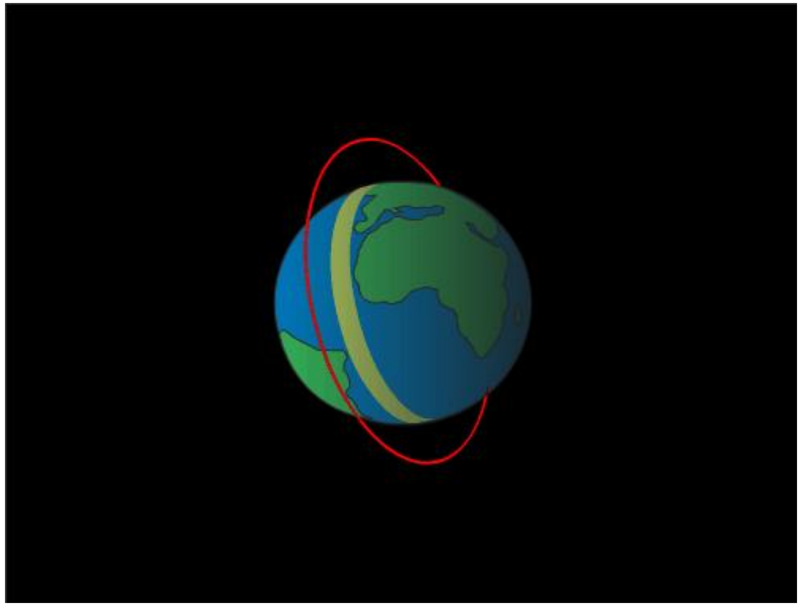
https://cpl.gsfc.nasa.gov/

Spaceborne LiDAR Orbits

- To date, spaceborne LiDARs launched for Earth Science have been in a **Low Earth Orbit (LEO)**.
- To date, geostationary altitudes are too high for LiDAR remote sensing of Earth.
- Depending on the science, different types of LEO have been employed:

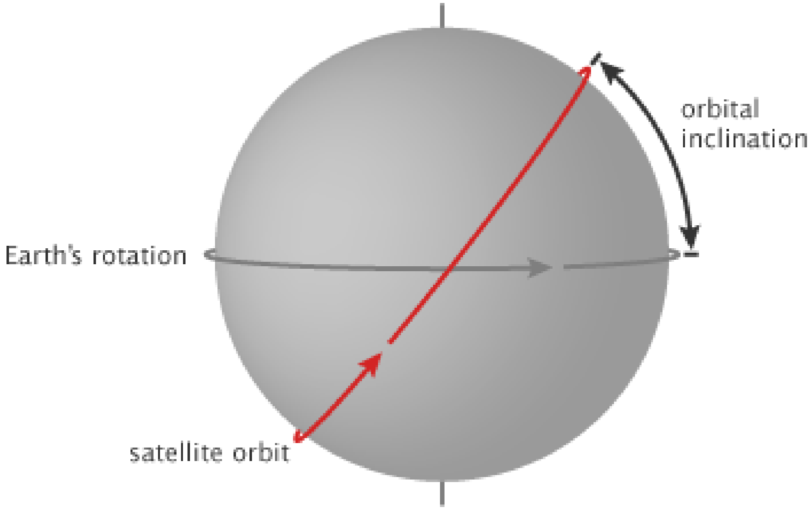
Polar Orbit (High Inclination)

Can see the whole globe, but only once per day. May be Sun-synchronous or precessing.



Low Inclination Orbit

Measure's a portion of the Earth at the expense of polar for diurnal sampling – known as a precessing orbit.

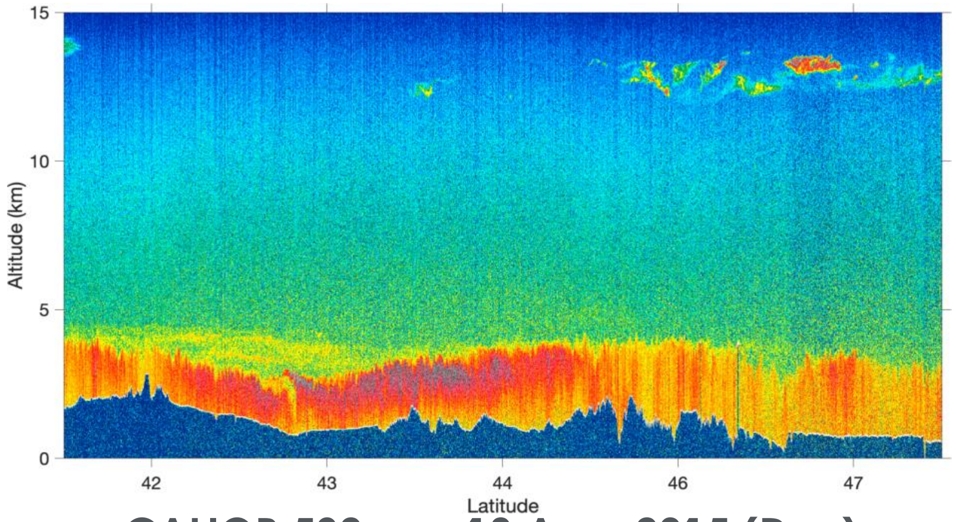


LiDAR Signal-to-Noise Ratio (SNR)

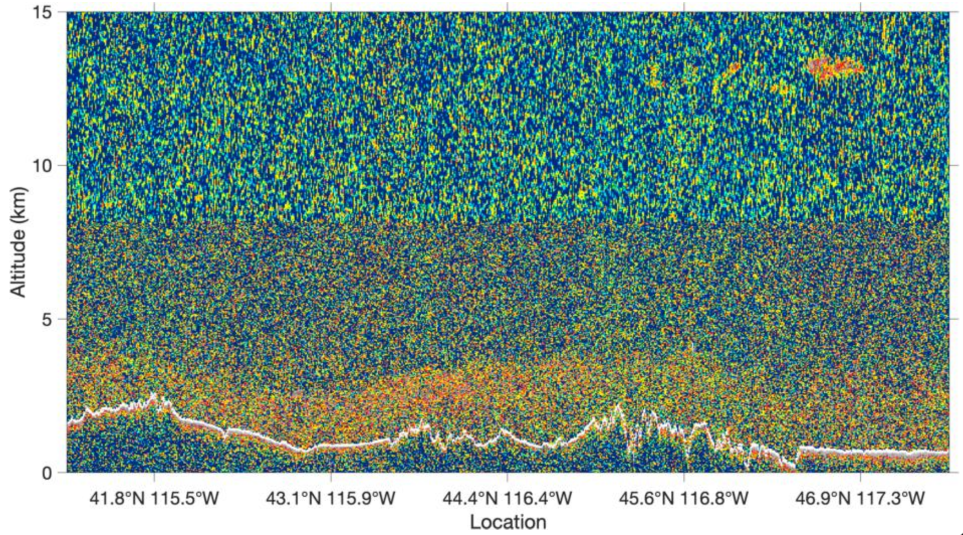
$$SNR = \frac{P_{signal}}{P_{noise}}$$

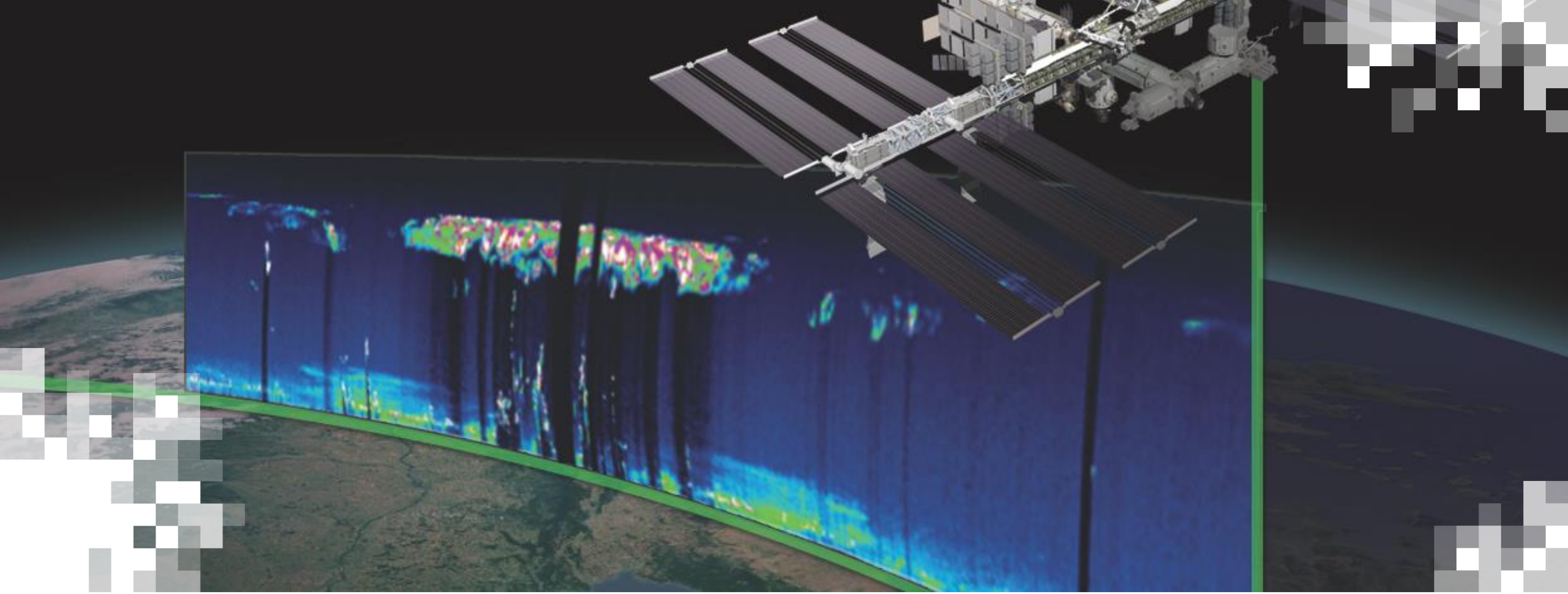
- The accuracy with which a LiDAR can derive spatial and optical properties depends on its SNR.
- SNR depends on many things, such as:
  - Instrument field of view
  - Distance between instrument and target
  - Limitations in laser pulse energy by available electrical power
- Consequently, SNR of space-based lidars is lower than that of ground/aircraft LiDARs due to these factors (right)
- SNR is lower during daytime hours due to high solar background from most sky scenes.
  - Lower SNR makes it more challenging to detect aerosols and clouds
  - Traditionally requires averaging to increase SNR

Airborne CPL 532 nm: 18 Aug. 2015



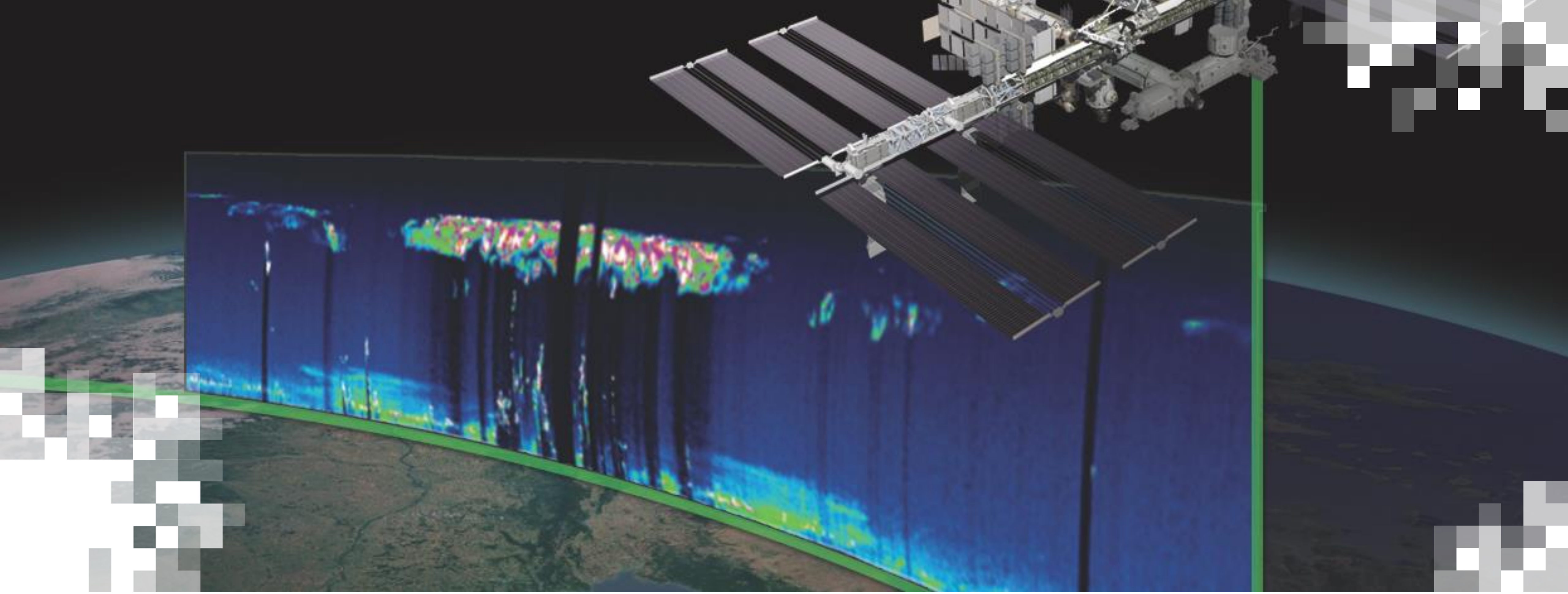
CALIOP 532 nm: 18 Aug. 2015 (Day)





Section 3

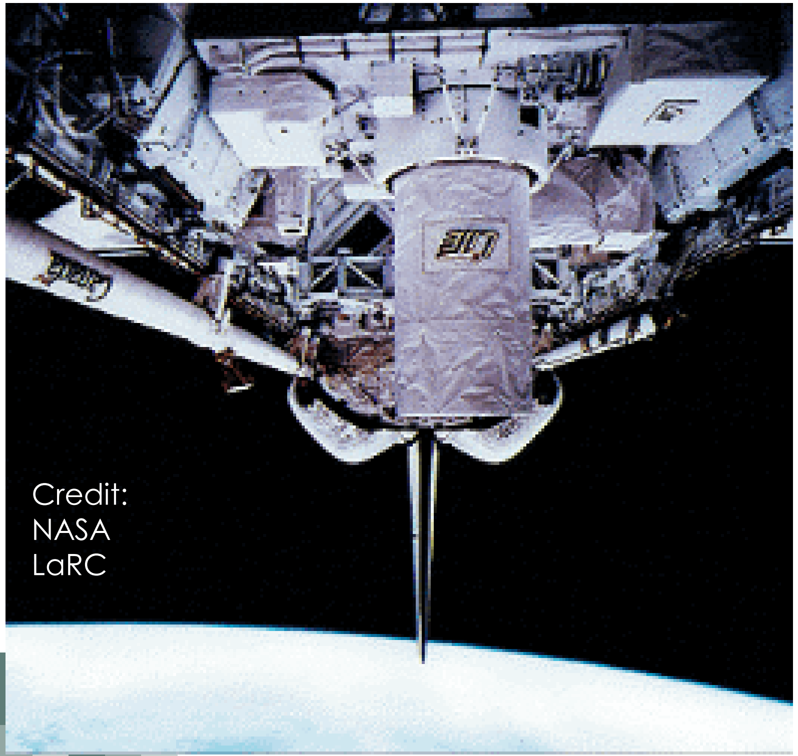
Past, Current, and Future Spaceborne LiDAR Missions

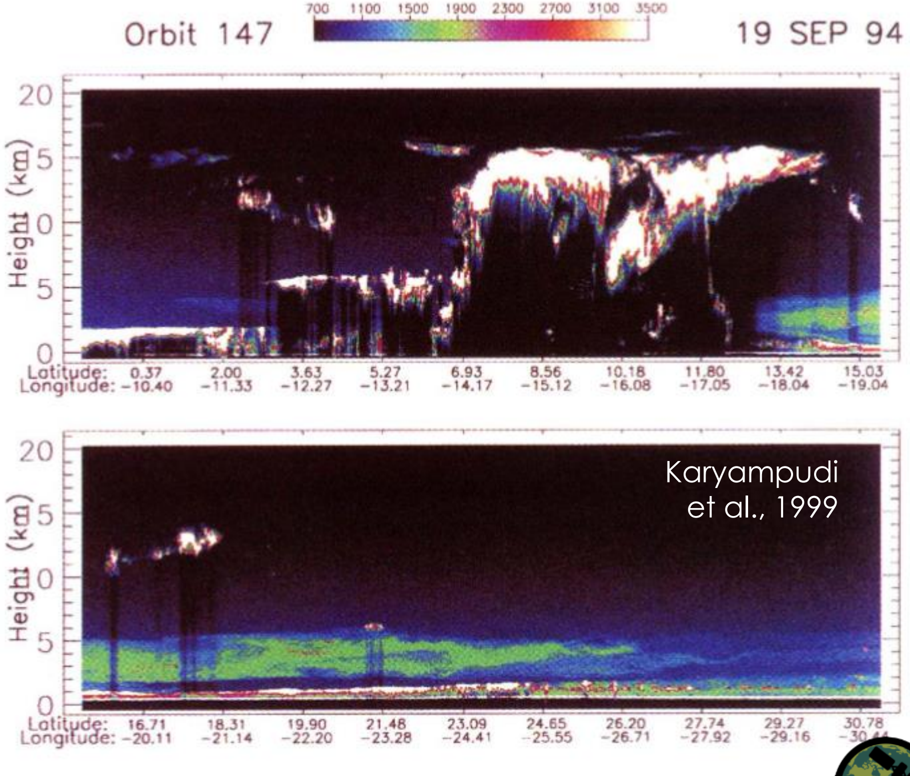


Past LiDAR Missions

First LiDAR Measurements from Space: NASA's LITE Mission

- In 1994, the <u>L</u>idar <u>I</u>n-space <u>T</u>echnology <u>E</u>xperiment launched on the NASA Space Shuttle Discovery.
- The mission provided 53 hours of key LiDAR measurements of aerosol and cloud vertical distributions and helped to:
  - Evaluate how Saharan dust vertical distributions vary with transport
  - Provide valuable case studies to tie to emission and synoptic conditions over North Africa
  - Supplied vertical measurements of dust optical properties, necessary for understanding dust radiative impacts on the atmosphere

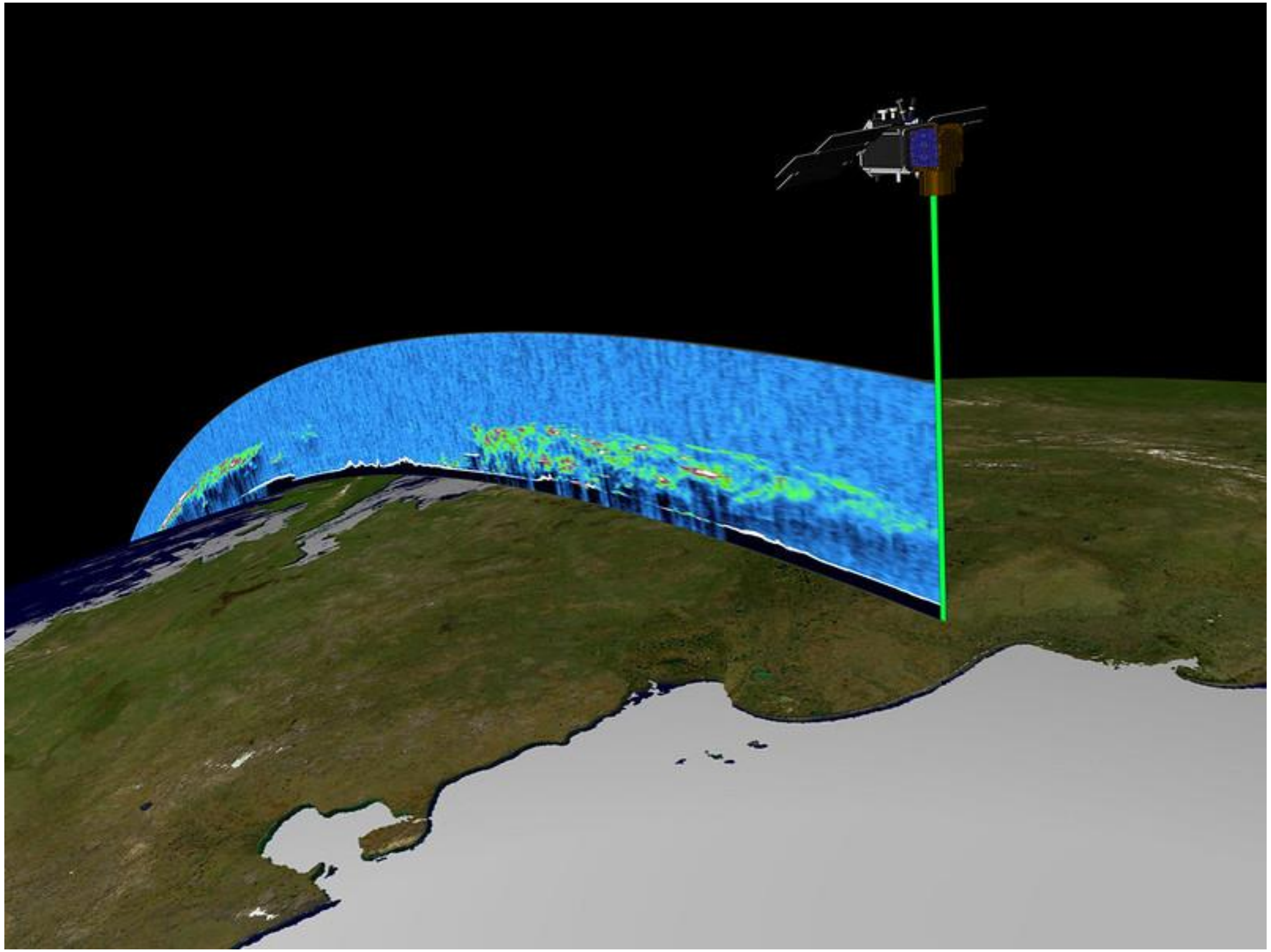

Credit: NASA LaRC



Karyampudi et al., 1999

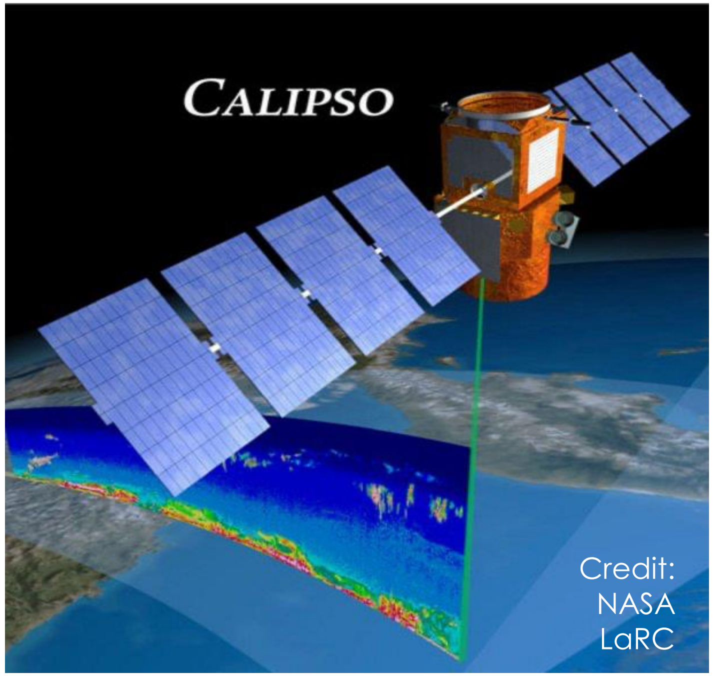
ICESat – The First Satellite Lidar in Space

- In 2003, NASA launched the **G**eoscience **L**aser **A**ltimeter **S**ystem (GLAS) on the **I**ce, **C**louds, and **E**levation **Sat**ellite (ICESat) to measure ice sheet elevation and change.
- GLAS also provided elastic backscatter measurements of aerosols and clouds at both 1064 and 532 nm in a precessing polar orbit.
- GLAS demonstrated spaceborne LiDAR remote sensing for future atmospheric science missions.

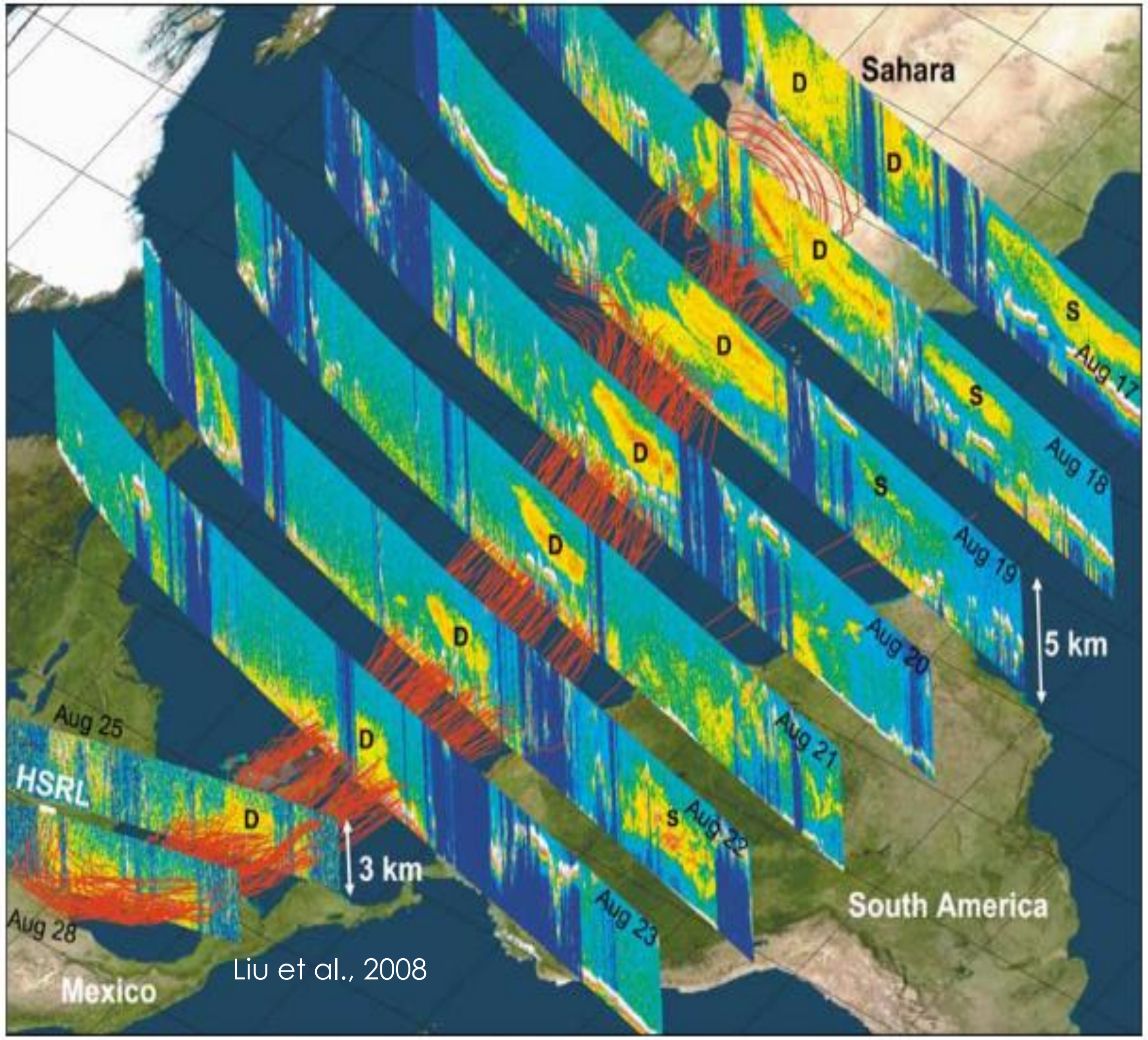


CALIPSO

- In 2006, NASA and CNES launched the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission into the NASA A-train as a dedicated polar-orbiting LiDAR to measure the vertical distribution of aerosols and clouds at both 532 and 1064 nm.
- Provided unprecedented opportunity to track the vertical distribution of aerosols and clouds globally
- Helped validate cloud lifetimes and aerosol transport in global models
- Ceased operations in 2023



Credit: NASA LaRC



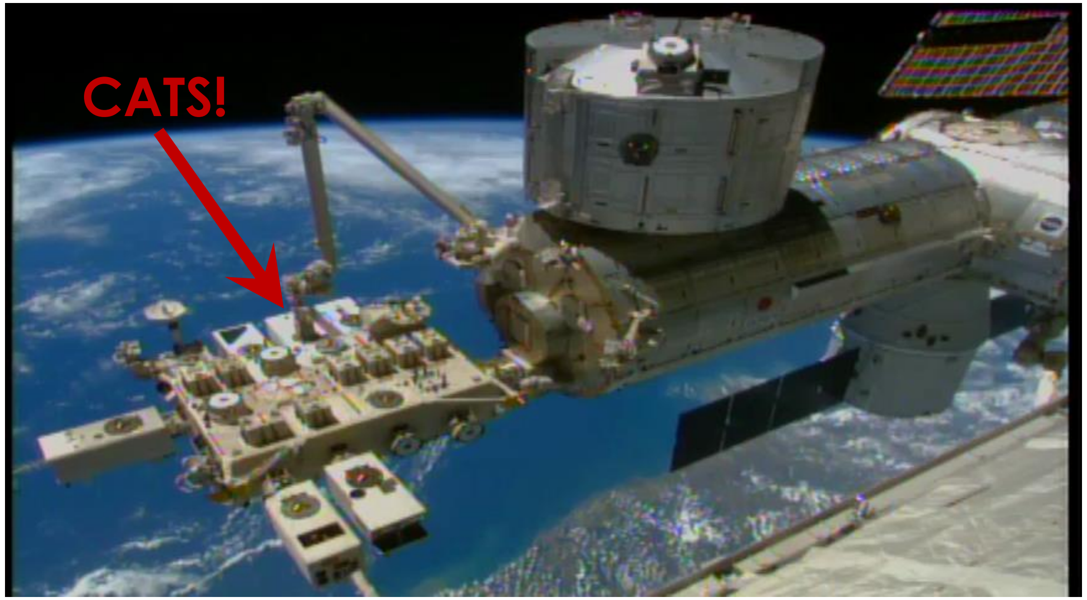
Liu et al., 2008

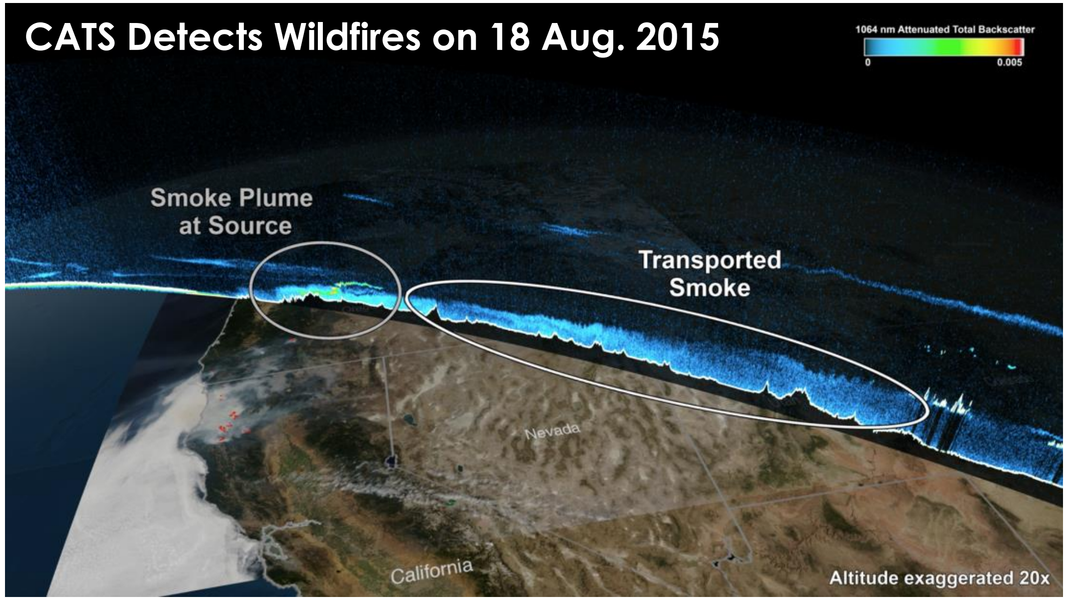
CATS

The **C**loud-**A**erosol **T**ransport **S**ystem (CATS) was designed as a tech demo (6-month lifetime) utilizing the **I**nternational **S**pace **S**tation (ISS) low inclination orbit:

- Complemented CALIPSO data record with cloud/aerosol vertical profiles at different times of day
- Was the first spaceborne LiDAR to provide data products in near real-time (within 6 hours)
- Primarily operated at 1064 nm but with some 532 nm measurements as well

CATS operated on the ISS for 33 months and fired 200+ billion laser shots.

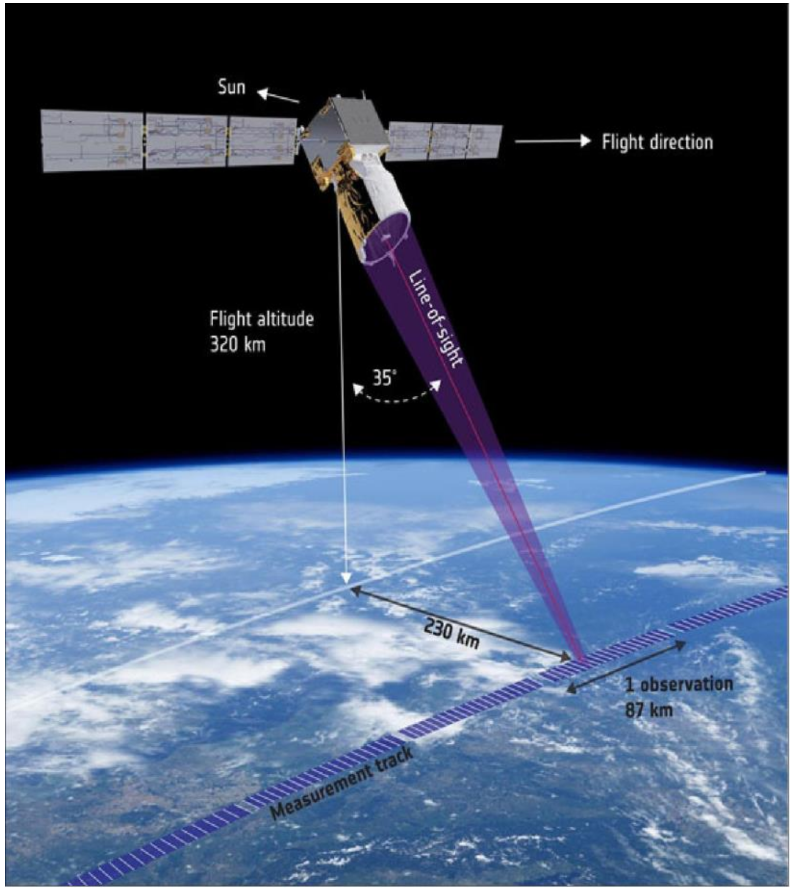


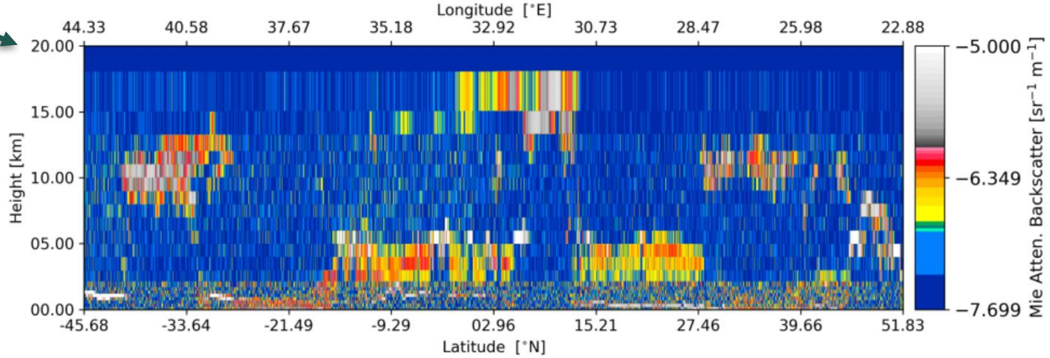


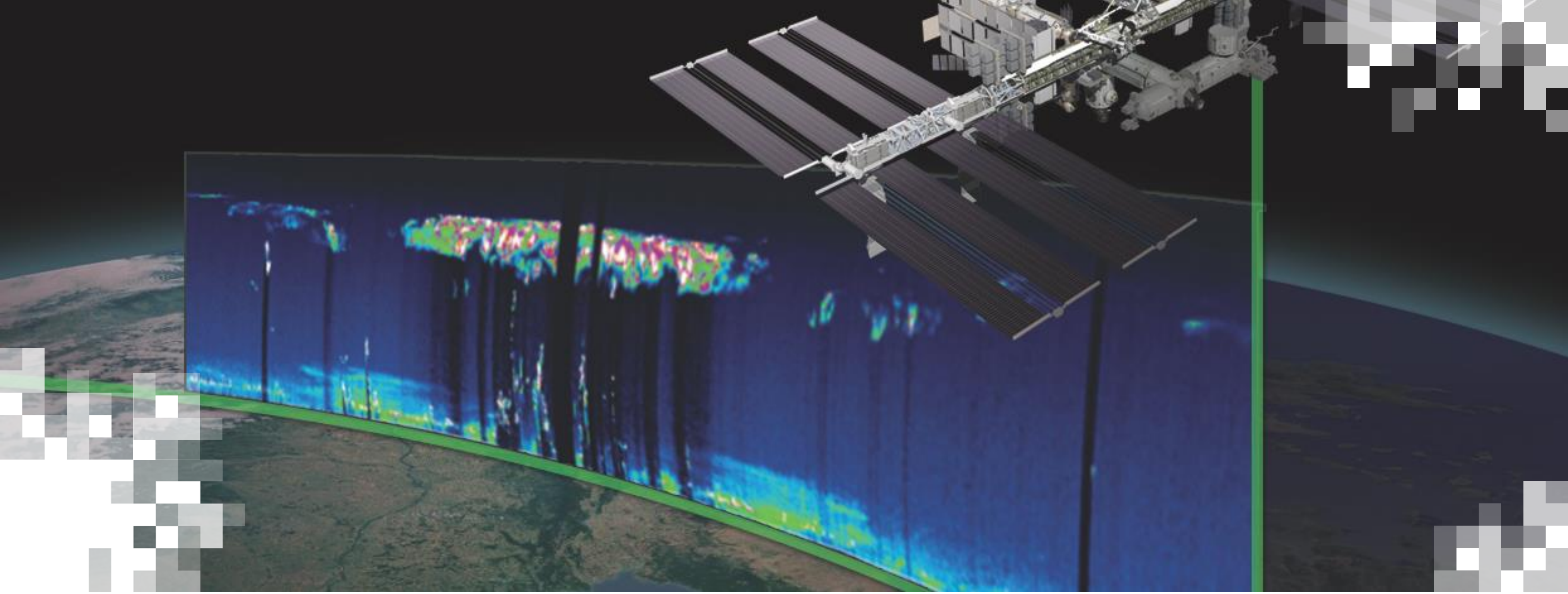
https://cats.gsfc.nasa.gov/

Aeolus

- In 2018, the European Space Agency (ESA) launched Aeolus as the first space-based Doppler wind lidar
- The instrument relied on measuring profiles of both Mie (aerosols & clouds) and Rayleigh (molecular) to derive wind speed and direction.
- Unlike previous NASA spaceborne lidar missions, Aeolus provided measurements in the UV at 355 nm with ~ 100m horizontal and ~ 500m vertical
- Ceased operations in 2023 but with a planned follow-on to launch in the early 2030's







Current LiDAR Missions

Advanced Topographic Laser Altimeter System (ATLAS) aboard ICESat-2

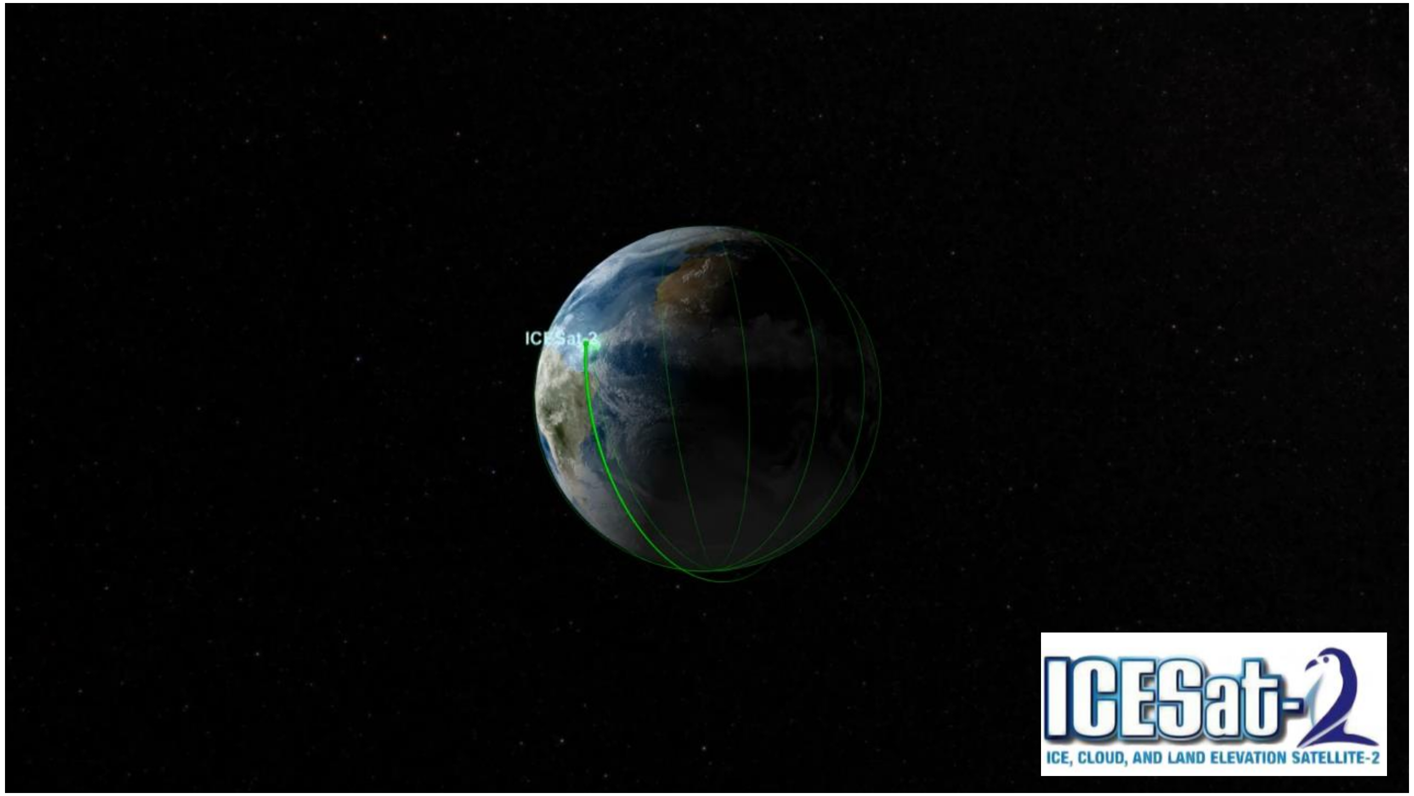
Primary Science Goal: Measure changes in the height, thickness, and extent of polar ice sheets and sea ice.

Orbit: 91-day repeat, 92° precessing orbit, ~475 km altitude

Launch: 15 Sep. 2018, 3-5 year planned mission

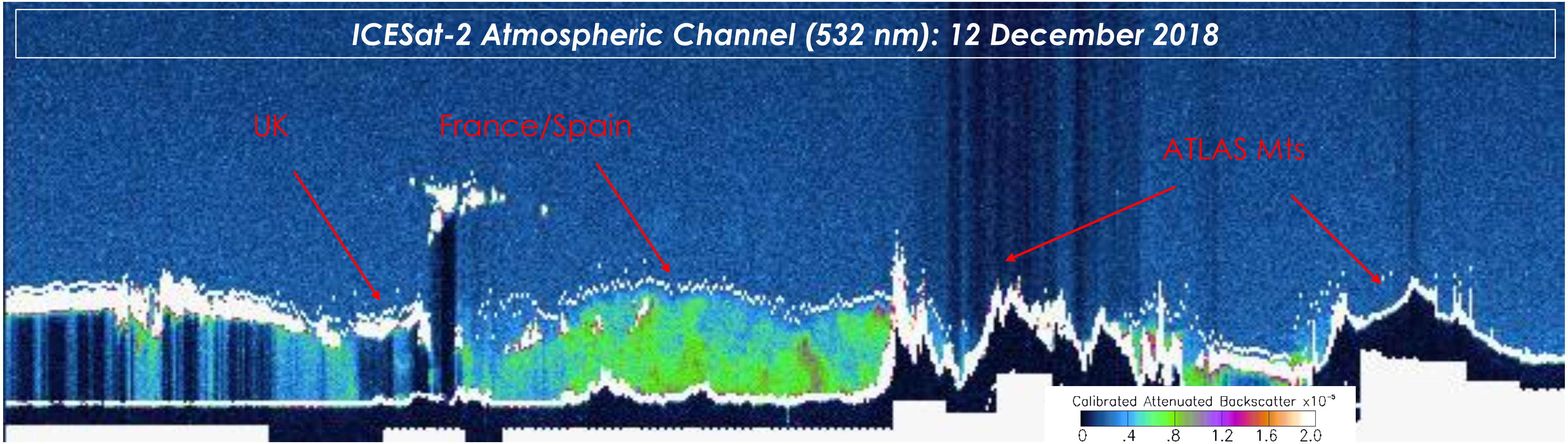
Secondary Science Goal: Measure layer heights and optical properties of clouds and aerosols, especially in the polar regions.

Atmospheric Channel: Provides 532 nm backscatter profiles from 0-14 km altitude at 280 m horizontal and 30 m vertical resolution using the 3 strong laser beams (532 nm), each 3 km apart. *Palm et al. 2021 [ESS]*



https://svs.gsfc.nasa.gov/4373/

Atmospheric Aerosol and Cloud Data from ATLAS



EarthCARE – Mission Objective

How do aerosols and clouds, heat or cool the Earth?

Systematic provision of vertical profiles of clouds and aerosols, collated with measurements of solar and emitted thermal radiation.

Direct verification of impact of clouds and aerosols on atmospheric heating rates and radiative fluxes.

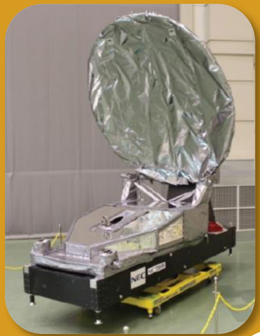
Courtesy of Fabien Marnas and Thorsten Fehr at ESA

EarthCARE – Space Segment

Cloud Profiling Radar CPR (JAXA)

High Power 94GHz Doppler Radar

- *Cloud profiles, rain estimates, particle vertical velocity*



Atmospheric LIDAR ATLID (Airbus TLS)

High spectral resolution 355nm LIDAR

- *Vertical profiles of aerosol and (thin) clouds*

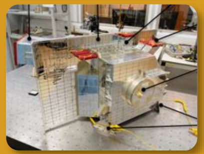
Multi Spectral Imager MSI (SSTL)

- *Context information*
- *Creating 3D cloud-aerosol scenes*
- *VIS, Near IR, SWIR Camera (VNS)*
- *Thermal IR Camera (TIR)*
- *4 solar and 3 TIR channels*

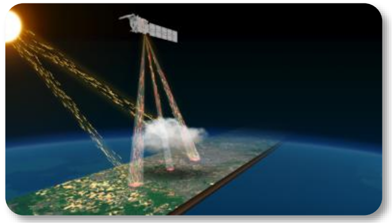
Courtesy of Fabien Marnas and Thorsten Fehr at ESA

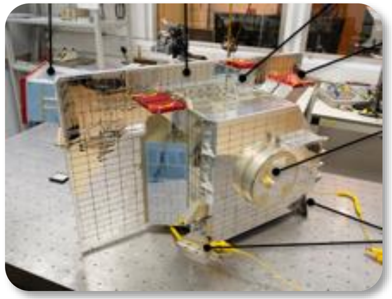
BroadBand Radiometer BBR (TAS-UK)

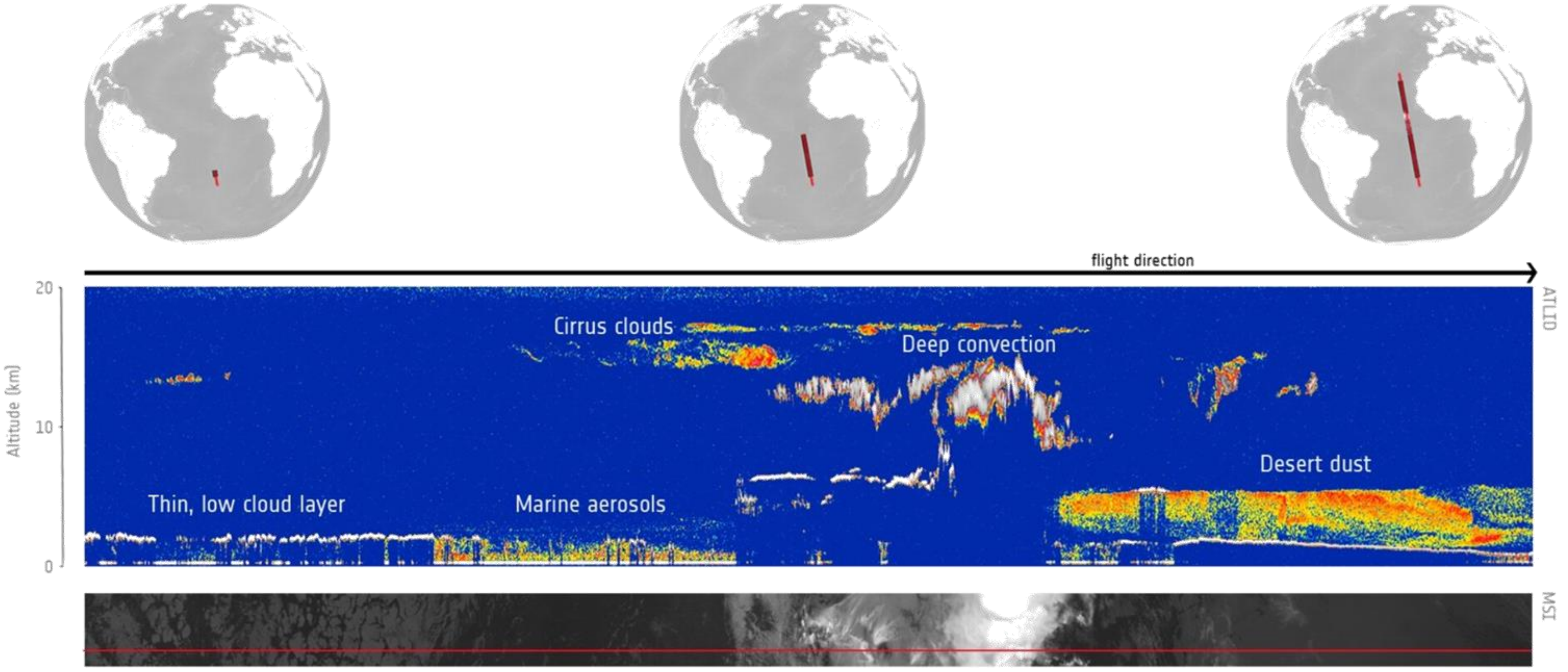
- *Measurements of reflected solar and emitted thermal radiation*



EarthCARE ATLID *First Images*: Tropical Atlantic

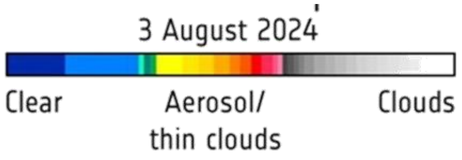


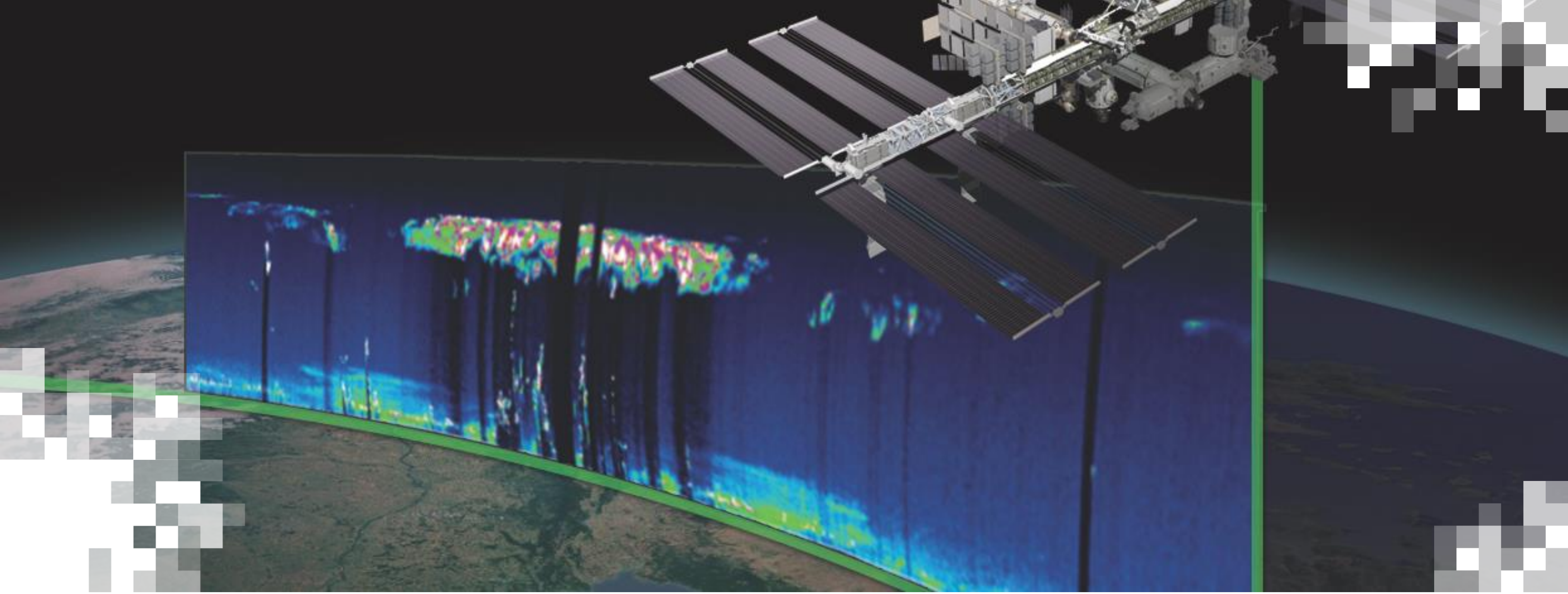




Clouds and aerosols measured by the EarthCARE atmospheric lidar

Courtesy of Fabien Marnas and Thorsten Fehr at ESA



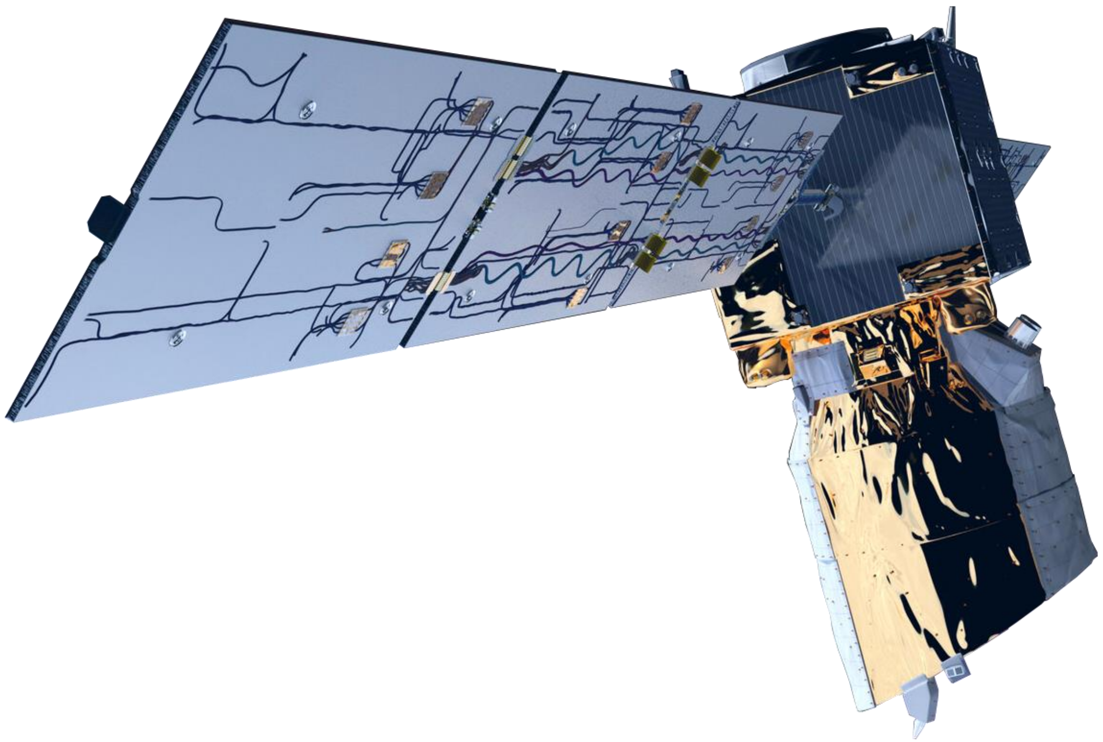


Future LiDAR Missions

EPS - Aeolus

- EUMETSAT and ESA have partnered to launch an operational version of Aeolus, known as EPS-Aeolus, in the early 2030's

- Modifications to the first Aeolus design include improved:
  - Horizontal and vertical resolution
  - Signal-to-noise ratio
  - Data Latency (within 2 hours)
  - Sensitivity to better discriminate aerosols types and cloud phase
  - Lifetime: 3 years vs. 5.5 years

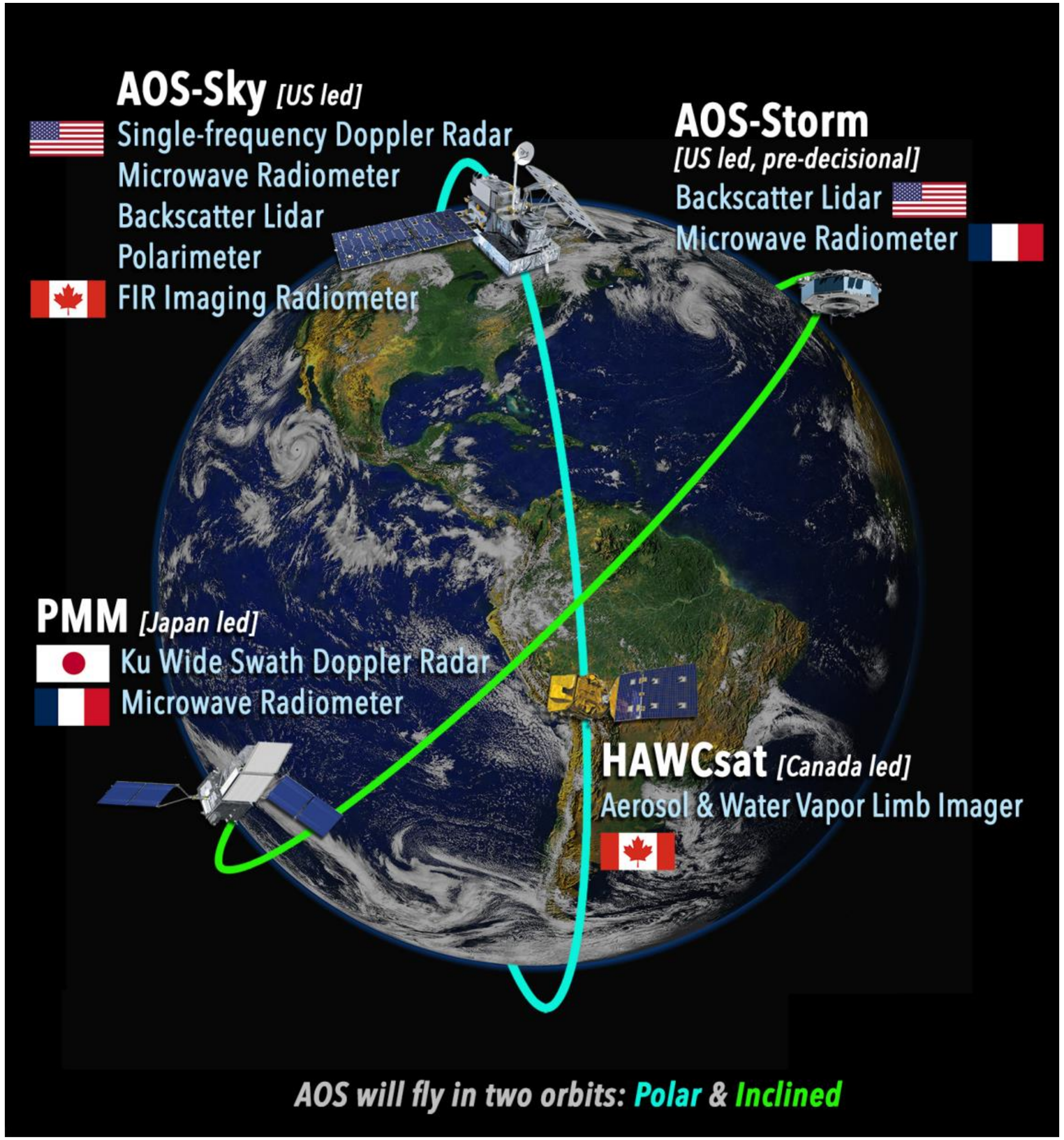


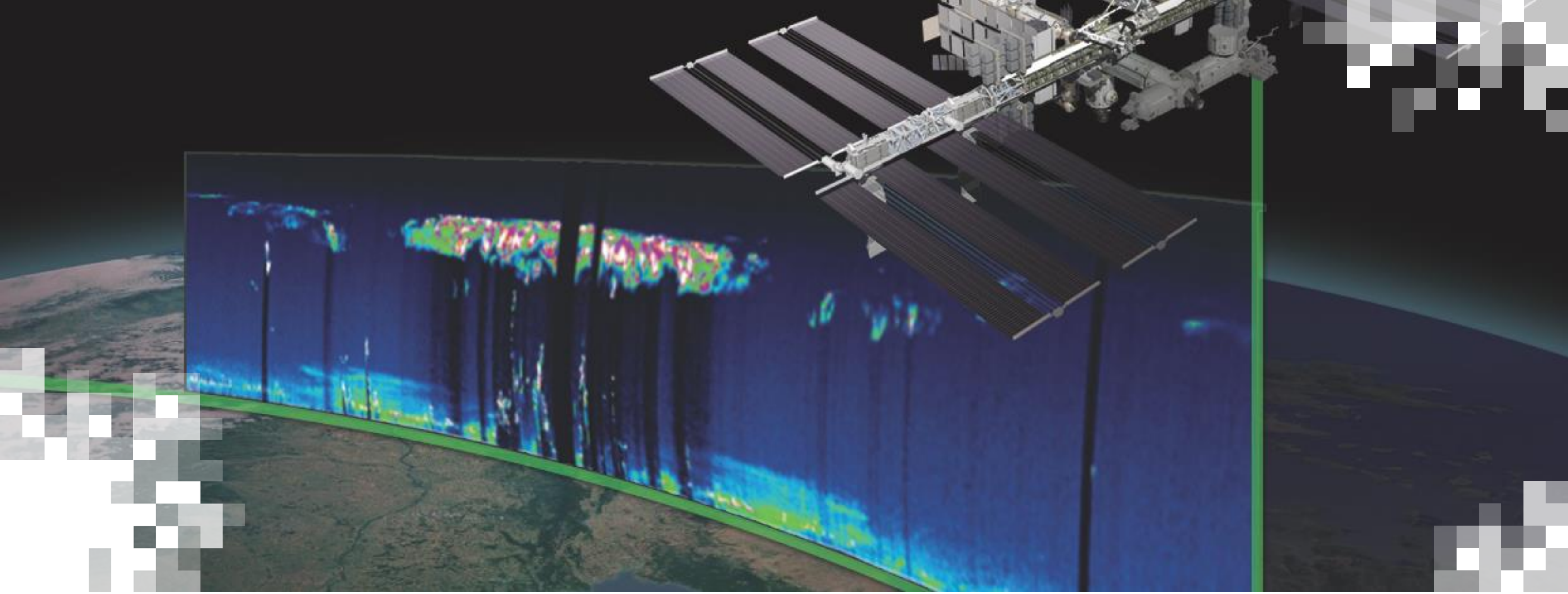
AOS/LUCE

In the early 2030's, NASA, in partnership with international space agencies, will launch the **A**tmosphere **O**bserving **S**ystem (AOS), comprised of a polar-orbiting Sun-synchronous orbit (AOS-Sky) and prescessing low-inclination orbit (AOS-Storm).

A LiDAR is planned to launch as part of AOS-Storm, called LUCE, that will include a 3-wavelength Raman LiDAR at 355, 532, and 1064 nm.

Current efforts are being made to finalize science and, consequently, design requirements for the LiDAR.





Part 1

Summary

Conclusion: Part 1

Thank you for attending Part 1 of LiDAR Profiling Satellite Observations for Air Quality Applications!

Topics Covered Today:

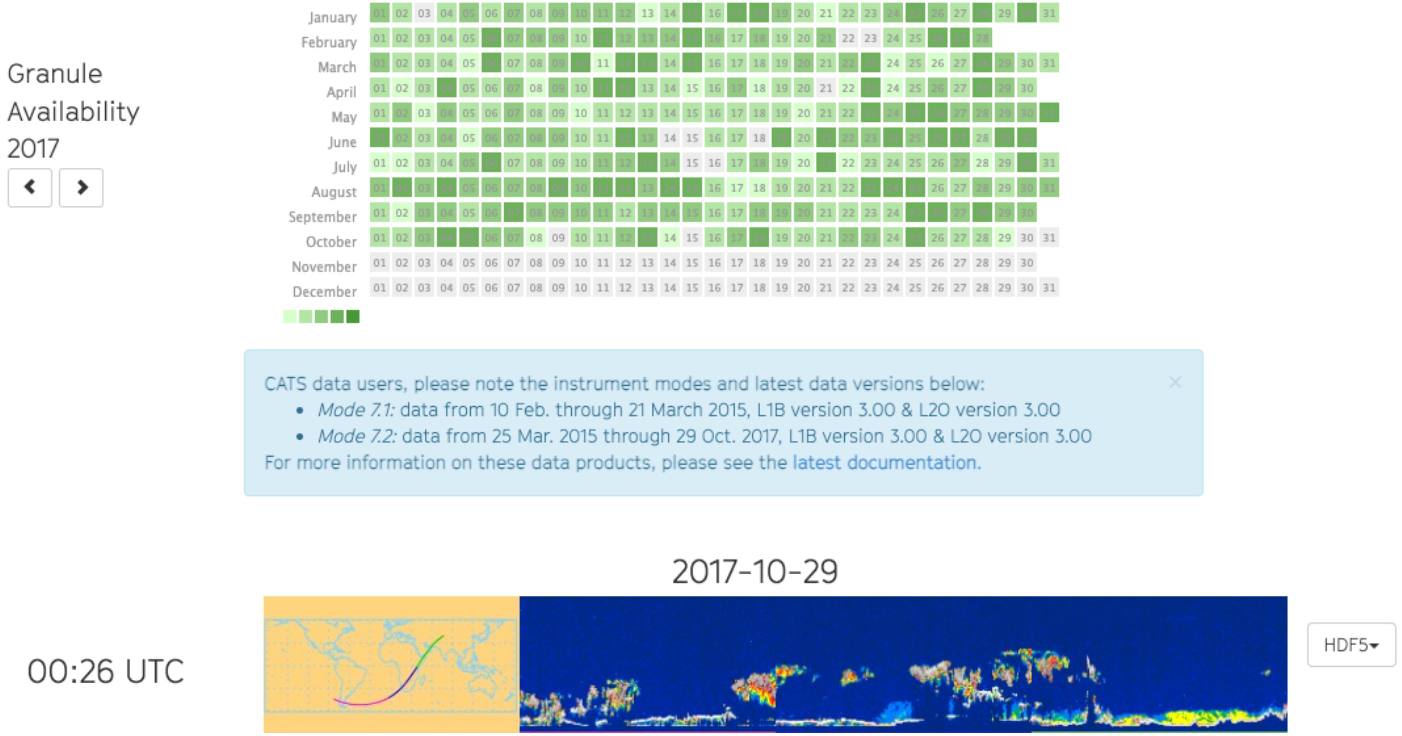
1. Identify past and currently available lidar missions and their characteristics ✓

2. Recognize the capabilities of LiDAR active remote sensing in measuring vertical profiles of aerosols and clouds for informing air quality applications ✓
   - The power of active remote sensing for vertical profiling for air quality applications
   - Basic understanding of how lidar systems work
   - Various implementations of lidar (ground, airborne, space)
   - Past, current, and future spaceborne lidar missions

3. Recognize the strengths and limitations of LiDAR observations ✓
   - Strengths:
     - High-resolutions vertical resolution not possible from passive sensors
     - Near-surface observations
   - Limitations:
     - Swath
     - Signal attenuation; daytime SNR

Looking Ahead to Part 2

1. Interpret information within lidar curtains to discern cloud phase, aerosol type, and aerosol plume altitude for a given scene
2. Find lidar images and data for a particular time period and location using NASA Earthdata and mission websites



Homework and Certificates

- **Homework:**
  - One homework assignment
  - Opens on June 11, 2025
  - Access from the training webpage
  - Answers must be submitted via Google Forms
  - **Due by June 25, 2025**

- **Certificate of Completion:**
  - Attend all both live webinars (attendance is recorded automatically)
  - Complete the homework assignment by the deadline
  - You will receive a certificate via email approximately two months after completion of the course.

Contact Information

Trainers:

- Ed Nowottnick
  - edward.p.nowottnick@nasa.gov

- ARSET Website
- ARSET YouTube

Visit our Sister Program:

- DEVELOP

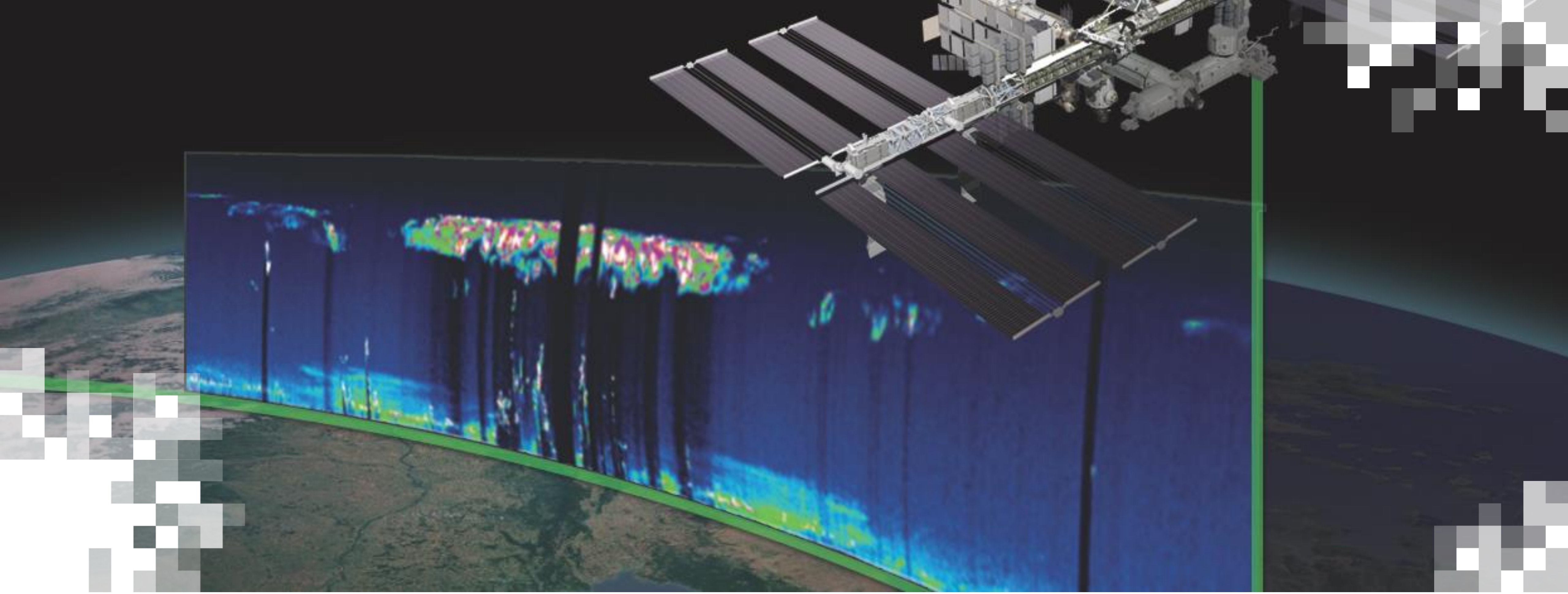
Resources

- Useful websites:
  - CALIPSO: https://www-calipso.larc.nasa.gov/
  - CATS: https://cats.gsfc.nasa.gov/
  - ICESat-2: https://icesat-2.gsfc.nasa.gov/
  - EarthCARE: https://earth.esa.int/eogateway/missions/earthcare
- References from this presentation:

  - Hsu, N.C., Gautam, R., Sayer, A.M., Bettenhausen, C., Li, C., Jeong, M.J., Tsay, S.C. and Holben, B.N., 2012. Global and regional trends of aerosol optical depth over land and ocean using SeaWiFS measurements from 1997 to 2010. *Atmospheric Chemistry and Physics*, *12*(17), pp.8037-8053.
  - Toth, T.D., Zhang, J., Reid, J.S. and Vaughan, M.A., 2019. A bulk-mass-modeling-based method for retrieving particulate matter pollution using CALIOP observations. *Atmospheric Measurement Techniques*, *12*(3), pp.1739-1754.
  - Colarco, P.R., Kahn, R.A., Remer, L.A. and Levy, R.C., 2014. Impact of satellite viewing-swath width on global and regional aerosol optical thickness statistics and trends. *Atmospheric Measurement Techniques*, *7*(7), pp.2313-2335.
  - McGill, M.J., 2003. Lidar–remote sensing. *Encyclopedia of Optical Engineering*, *2*, pp.1103-1113.

- Other useful references:

  - Winker, D.M., Vaughan, M.A., Omar, A., Hu, Y., Powell, K.A., Liu, Z., Hunt, W.H. and Young, S.A., 2009. Overview of the CALIPSO mission and CALIOP data processing algorithms. *Journal of Atmospheric and Oceanic Technology*, *26*(11), pp.2310-2323.
  - Yorks, J.E., McGill, M.J., Palm, S.P., Hlavka, D.L., Selmer, P.A., Nowottnick, E.P., Vaughan, M.A., Rodier, S.D. and Hart, W.D., 2016. An overview of the CATS level 1 processing algorithms and data products. *Geophysical Research Letters*, *43*(9), pp.4632-4639.
  - Wehr, T., Kubota, T., Tzeremes, G., Wallace, K., Nakatsuka, H., Ohno, Y., Koopman, R., Rusli, S., Kikuchi, M., Eisinger, M. and Tanaka, T., 2023. The EarthCARE mission–science and system overview. *Atmospheric Measurement Techniques*, *16*(15), pp.3581-3608.



Questions?

Thank You!