The CALIPSO Lidar

Brian Getzewich, Dave Winker, Mark Vaughan, Jason Tackett, Chip Trepte, Ron Verhappen, Sharon Rodier, Bill Hunt

31st ILRC – Lidar Tutorial

23 June 2024

- Mission Overview
- Instrument
- Calibration
- Data Products & Algorithms

Mission Overview

- **C**loud-**A**erosol **L**idar and **I**nfrared **P**athfinder **S**atellite **O**bservations (CALIPSO) was a partnership between NASA and the French Space Agency (CNES)
- Satellite comprised of three instruments
  - **C**loud-**A**erosol **LI**dar with **O**rthogonal **P**olarization (CALIOP)
  - **I**maging **I**nfrared **R**adiometer (IIR); 8.65, 10.6, and 12.05 µm
  - **W**ide **F**ield **C**amera (WFC); 645 nm
- Mission Science Objectives
  - Provide a new ability to assess cloud feedback in the climate system, including the effects of thin cirrus, polar clouds, and multilayered cloud systems, all of which are poorly determined by passive sensors alone.
  - Provide a global suite of measurements from which the first *observationally-based* estimates of direct aerosol forcing, and its uncertainty, can be made.
  - Provide a dramatically improved empirical basis for global and regional assessments of indirect aerosol radiative forcing.
  - Improve the accuracy of satellite estimates of long-wave (LW) radiative fluxes at the surface of the Earth and within the atmosphere by a factor of 2.

Mission Milestones

April 28, 2006

- Launch, manifested along-side CloudSat, from Vandenberg, AFB in California.

June 13, 2006

- Start of Science Mission as part of Afternoon Train (A-Train) international satellite constellation

November 2007

- Off-nadir angle change from 0.3 to 3.0 degrees

February/March 2009

- Switch from primary to backup laser

September 2018

- A-Train exit, satellite lowered to its disposal orbit (AKA C-Train)

June 2023

- Primary laser re-activation

July 1, 2023

- Satellite Safe Hold Mode, end of science data collection

August 1, 2023

- End of Science Mission

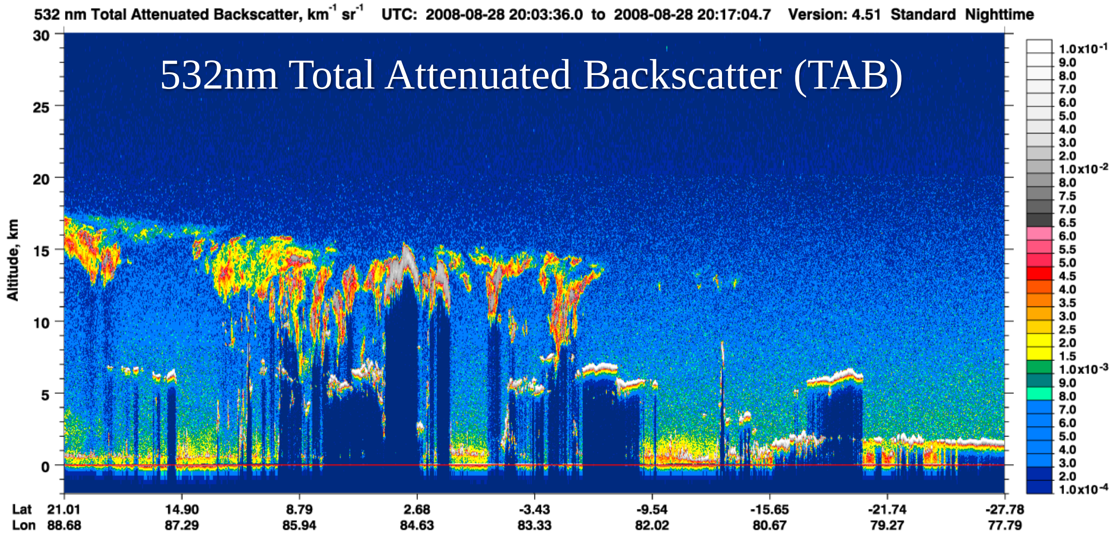
December 2023

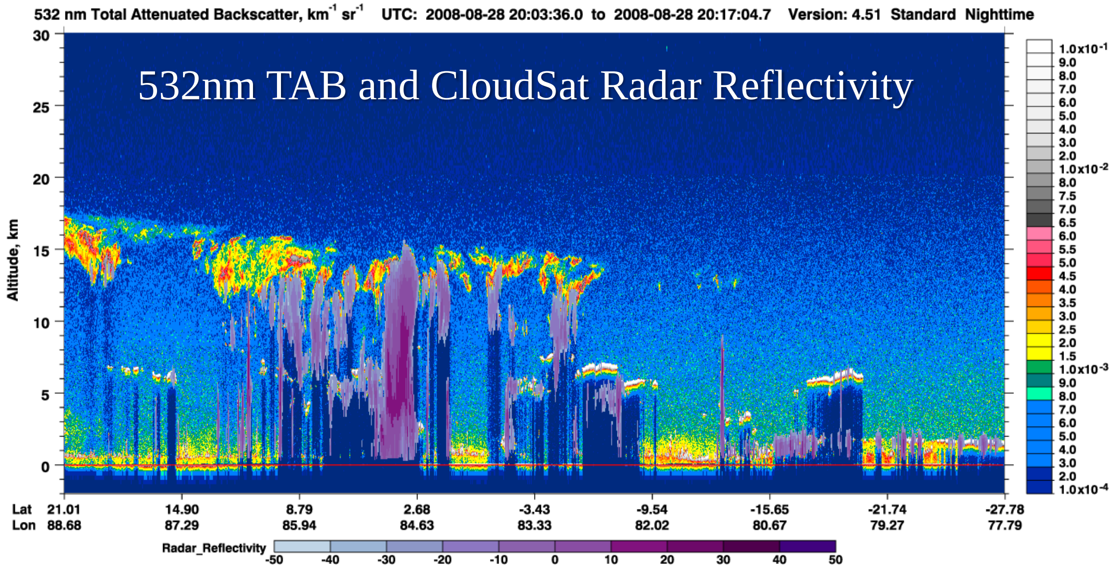
- Satellite/instrument pacification

Launch of CALIPSO and CloudSat aboard a Delta-2 rocket from Vandenberg Air Force Base

A-Train Formation Flying

- CALIPSO flew in the international Afternoon Train (A-Train) constellation, acquiring coincident measurements with other satellites
  - Sun-synchronous orbit with equatorial crossing time of 1:30 PM, altitude of 705 km, and speed of ~7 km/s
  - Yields multi-sensor synthesis with measure-ments from CloudSat, PARASOL, Aqua, Aura
- Lowered orbit from 705 km to 688 km starting on September 13, 2018, to resume formation flying with CloudSat as part of the ‘C-Train’
  - Satellite disposal orbit

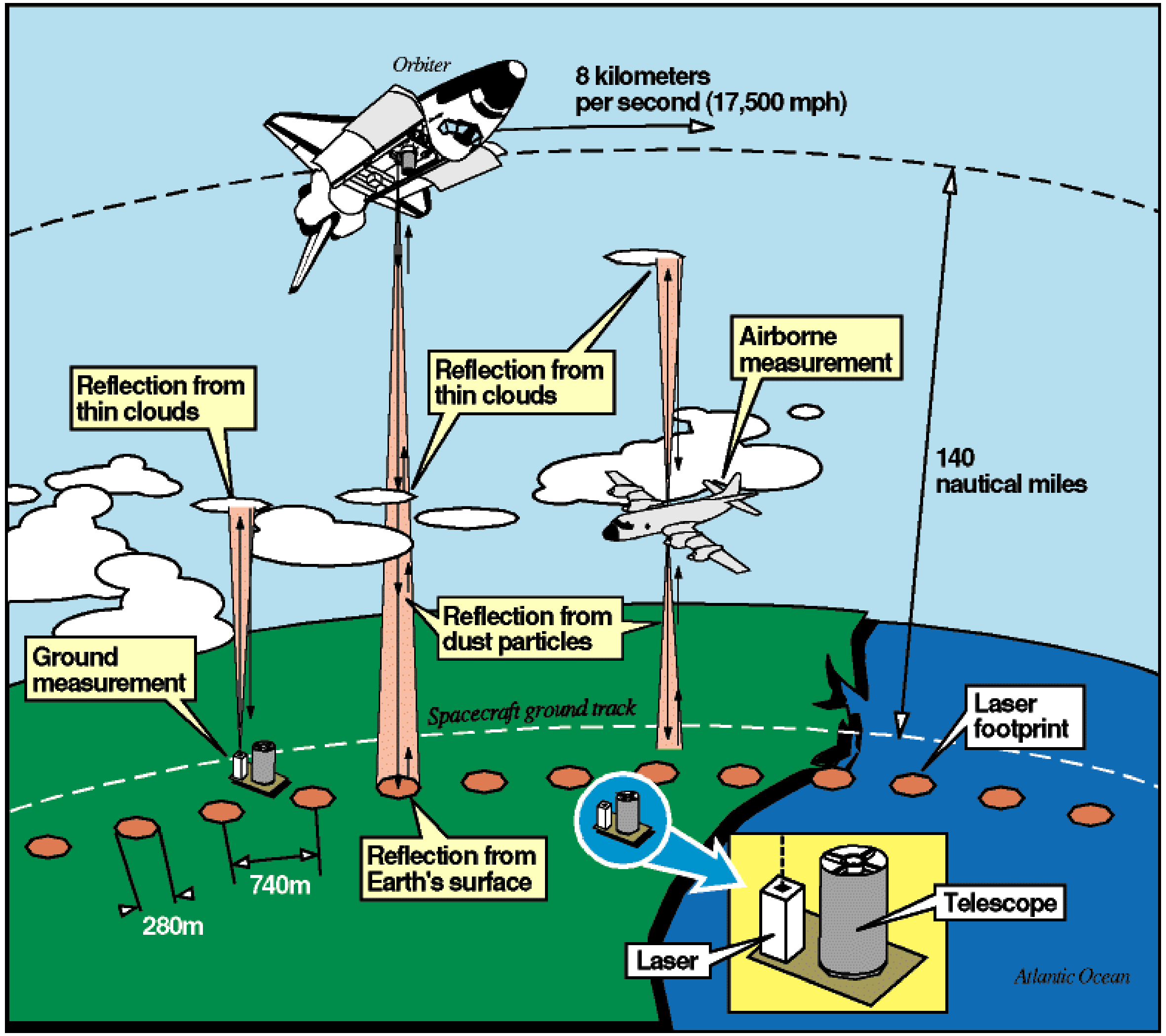




Images posted on CALIPSO Science Website; https://www-calipso.larc.nasa.gov/

Heritage: The Lidar In-Space Technology Experiment (LITE)

- CALIOP relied on the experience gained from the Lidar In-Space Technology Experiment (LITE); Winker et al., 1996, doi:10.1109/5.482227
- Prime payload onboard Space Shuttle Discovery (STS-64) between September 9-20, 1994
- 3-channel elastic backscatter lidar operating at 355 nm, 532 nm, 1064 nm
- First operational Earth-observing lidar to fly in low Earth orbit (LEO)



Images and content provided from the NASA LaRC SD LITE Project Page: https://science-data.larc.nasa.gov/LITE/

CALIOP Design Considerations

- Spacecraft imposed mass and power constraints on the payload
- Cost and the state (late 90's) of technology
- Two wavelength, polarization sensitive elastic backscatter lidar
  - Transmit laser light at 532 nm and 1064 nm
  - Separately detect parallel and perpendicular polarization components of the backscattered light at 532 nm
  - No polarization sensitivity at 1064 nm
  - No 355 nm channel given potential risk to laser life
- Maximizing Signal-to-Noise Ratio (SNR) largely drove instrument requirements (next slide)
- Data Downlink
  - ~25-hour solid state recorder
  - 1 science contact (S-Band) and multiple engineering (X-Band) contacts per 24 hours
- Downlink constraints resolved using on-board signal processing and data averaging
  - Maximize dynamic range of the signal
  - Minimize the telemetry data volume by use of altitude-varying spatial averaging

CALIOP Design Requirements: Signal-to-Noise Ratio

Channel	Lighting	Target: Altitude (km)	Target: Backscatter Coefficient (km^{-1} sr^{-1})	Max Averaging Horizontal (km)	Max Averaging Vertical (km)	SNR Requirement
532 nm Parallel	Night	30	2.39×10^{-5} (Rayleigh)	1500	5	50
532 nm Parallel	Day, Albedo = 0.15	1	1.45×10^{-3} (Rayleigh)	33	1	10
532 nm Perpendicular	Must satisfy the same SNR requirements as the 532 Parallel channel when illuminated with the same signal and background					
1064 nm	Day, Albedo = 0.15	1	1.00×10^{-3} (boundary layer aerosol)	50	1	5

Requirements specify the **minimum** signal-to-noise ratios (SNR) needed to ensure all four of the CALIPSO mission science requirements are fully met

Block Diagram

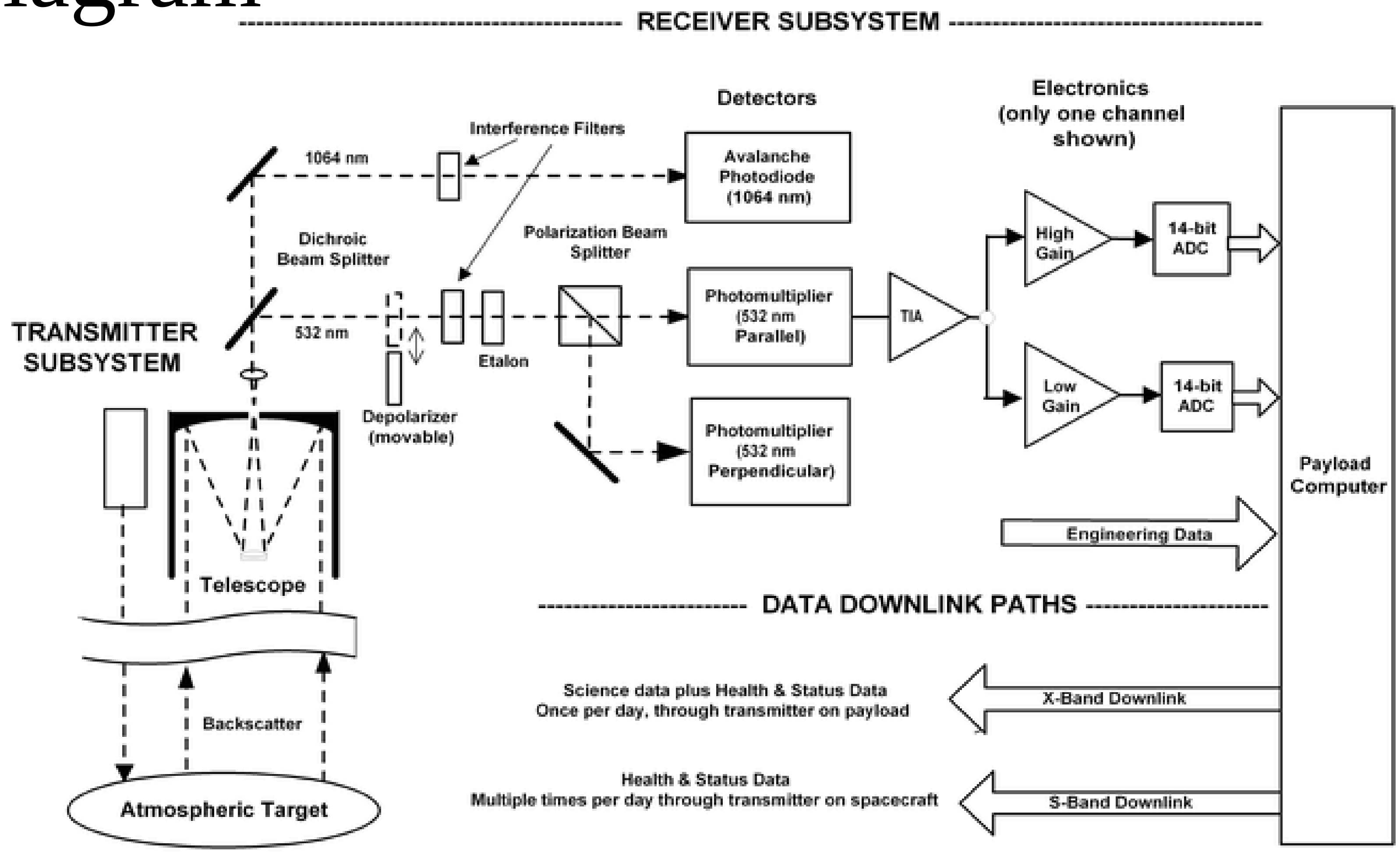
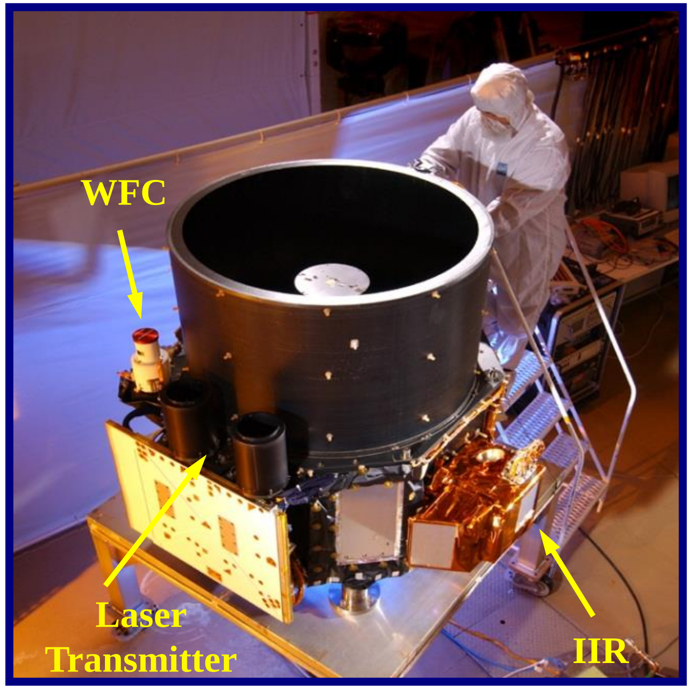


Figure 1 from Hunt et al, 2009. © American Meteorological Society. Used with permission.

Hunt, W. H, et al., 2009: "CALIPSO Lidar Description and Performance Assessment", *J. Atmos. Oceanic Technol.*, **26**, 1214-1228, https://doi.org/10.1175/2009JTECHA1223.1.

Transmitter Subsystem

Lasers	Diode-pumped Nd:YAG, 2x110 mJ
Pulse Energies	532 nm: 110 mJ 1064 nm: 110 mJ
Repetition Rate	20.25 Hz
Pulse Length	20 nsec
Boresight Range	+/- 1 degree, 1.6 µrad steps
Laser Canisters (2)	18 psia, nitrogen



CALIPSO payload in the clean room of Ball Aerospace Corporation in Boulder, Colorado

- Two Lasers (Primary & Backup) housed in separate pressured containers
- Laser pulse energy & repetition rate determined to maximize daytime SNR
- Available spacecraft power limited repetition rate to 20 Hz
- Bore-sighting capability to allow for routine alignment between the transmitter and receiver
  - Complete alignment achieved within a single nighttime orbit segment
  - On-orbit optimizations conducted every ~6 weeks

Receiver Subsystem

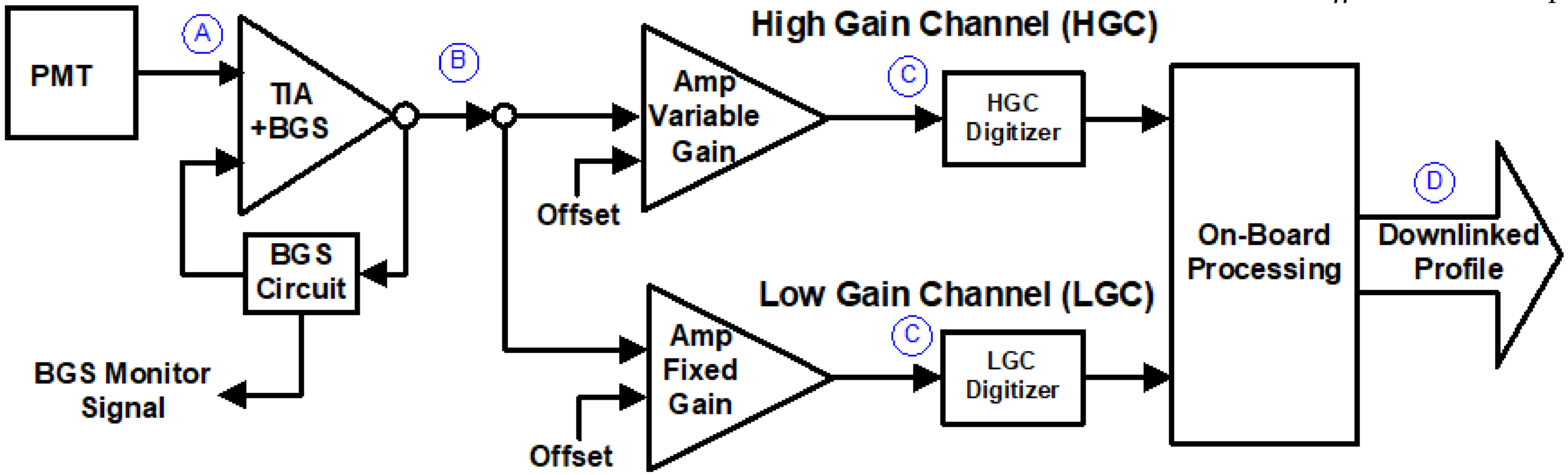
Parameter		Value	Notes
Telescope diameter		1 m	Due to payload mass constraints the telescope needed to be light. Beryllium selected due to cost, and the largest that could be built at the time was 1 meter.
Field of View (FOV)		130 µrad	FOV matched to laser divergence and optimized for daytime SNR. Small enough to reduce daytime background and large enough to capture laser footprint.
532 nm	Optical Filter Bandwidth	35 pm	Optical filters selected to reject as much solar background as possible and include as much laser return energy. Larger dark noise at 1064nm allowed for a wider filter.
	Detector Effective Quantum Efficiency	0.11	
	Detector Dark Count Rate	2.3×10^3	
1064 nm	Optical Filter Bandwidth	400 pm	
	Detector Effective Quantum Efficiency	0.40	
	Detector Dark Count Rate	2.0×10^7	
Digitizer sample rate		10 MHz	Fastest space-qualified ADCs at the time
Vertical sample spacing		15 m	Vertical sampling to enable cloud-aerosol separation with maximum retention of aerosol signals
Electronic bandwidth		2.0 MHz	Vertical resolution (30m) determined by electronic bandwidth and laser rep rate
Vertical resolution determined by bandwidth		30 m	
Single digitizer resolution		14 bits	
Merged digitizer dynamic range		2.5×10^6 (>21 bits)	Very large dynamic range needed for high altitude calibration while still measuring dense clouds without saturation; LITE ~ 1.0×10^6

Receiver Subsystem

- Moveable pseudo-depolarizer
  - Used to derive the polarization gain ratio (PGR); when inserted into the optical path, this device completely depolarizes the incident light, causing equal optical intensities to be directed onto both the 532 nm parallel and 532 nm perpendicular detectors
  - Commanded instrument mode – not part of normal science data acquisition mode (DAQ)
- Filters
  - Additional filtering for 532nm required narrow etalon filter, matched to the laser linewidth. Determined to not be as advantageous (and more cost) to use etalon for the 1064nm channel.
- Detectors
  - Limited to the space-qualified options available in the previous millennium
  - Photomultiplier Tubes (PMTs) at 532 nm
    - Chosen due to low dark noise and large dynamic range
  - Linear Avalanche Photodiodes (APDs) at 1064 nm
    - Chosen because PMT quantum efficiencies at 1064 nm were too low
  - Analog detectors used because photon counting devices could not provide the required dynamic range on the high end

Single Channel Signal Detection Electronics

TIA = Trans-Impendence Amplifiers (current to voltages)
BGS = Background Subtraction
Offset = Ensures positive signal after BGS



	Point A	Point B	Point C	Point D
Background Signal	Yes	No	No	No
Dark Current Signal	Yes	No	No	No
Backscatter Signal	Yes	Yes	Yes	Yes
Offset	No	No	Yes	No

<u>Backscatter Signals</u>

$P_{532,\parallel}(r)$
$P_{532,\perp}(r)$
$P_{1064}(r)$

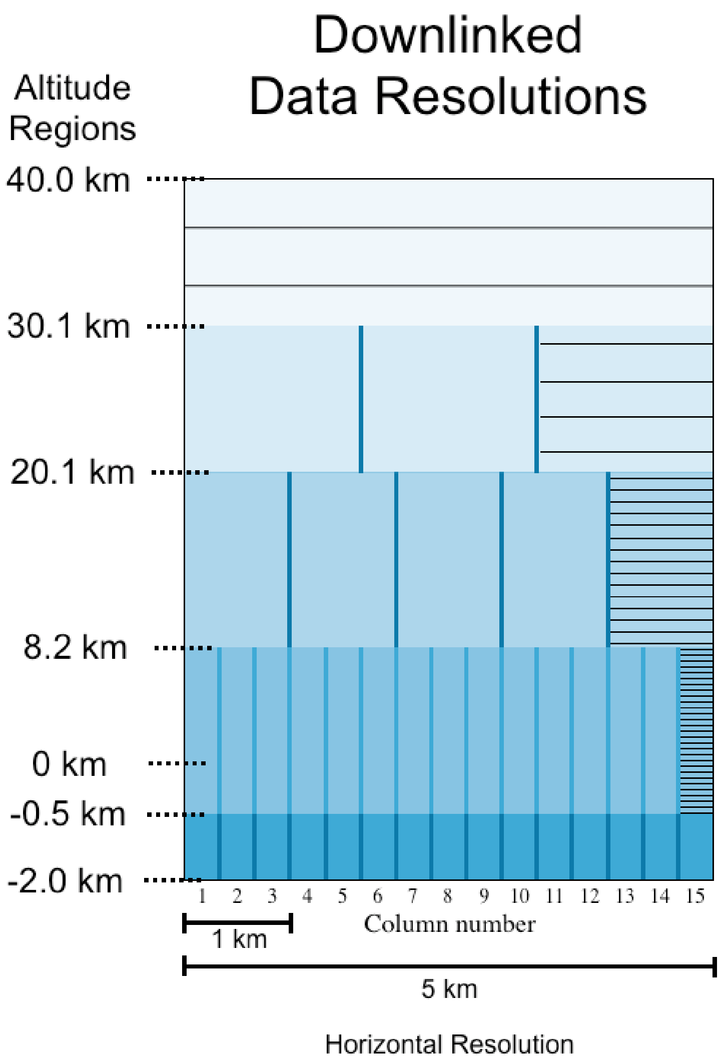
Creating CALIOP Backscatter Signal Profiles

- Range determination
  - Uses on-board geoid model with GPS and orbital propagator to adjust laser pulse initiation and maintain accurate ranging to mean sea level at the laser footprint locations
- Sampling
  - Digitizers sample backscatter at 10 MHz (15 m bin resolution), from 115 km above mean sea level to -18.5 km
- Background subtraction
  - Mean background signal calculated between 112 and 97 km, where backscatter is negligible
  - Background removed electronically from signal prior to digitization
- Amplifiers and Digitizers
  - Full dynamic range achieved by splitting each channel into high gain and low gain channels (each 14-bit)
- Onboard Signal Merging and Scaling
  - For each laser pulse, ***high gain and low gain measurements are merged onboard*** to create a single combined profile (~22-bit dynamic range, resolution = 30 m vertical × 333 m horizontal)
- Averaging
  - Horizontal and vertical averaging of merged profiles reduces overall data volume downlink

On-Board Averaging

Altitude Range (km)	Bin #	Horizontal Ave (km)	532nm Vertical Ave (m)	1064 nm Vertical Ave (m)	Rationale
30.1 to 40.0	1-33	5	300	N/A	532 nm nighttime calibration regime. Aerosol scattering ratios assumed to be 1.01 ± 0.01 above 36 km.
20.2 to 30.1	34-88	5/3	180	180	More spatial homogeneity of atmospheric targets in mid-latitude and equatorial regions; sufficient resolution for characterizing polar stratospheric clouds
8.3 to 20.2	89-288	1	60	60	Resolution commensurate with the expected spatial variability of multiple targets in the upper troposphere, including thin cirrus and volcanic aerosol injections.
-0.5 to 8.3	289-578	1/3	30	60	Single shot resolution at 532 nm enables high resolution feature detection and cloud-clearing of aerosols in the planetary bound layer.
-2.0 to -0.5	579-583	1/3	300	300	Allow for monitoring of subsurface signal returns.

On-Board Averaging: Data Implications



Vertical Resolution	Horizontal Resolution	Profiles per 5 km	Bins per Profile Region
300 m	5000 m	1	33
180 m	1667 m	3	55
60 m	1000 m	5	200
30 m	333 m	15	290
300 m	333 m	15	5

L1 processing transfers to uniform horizontal grid. 15 x 583 (w x h)

Downlinked vertical resolution remains unchanged

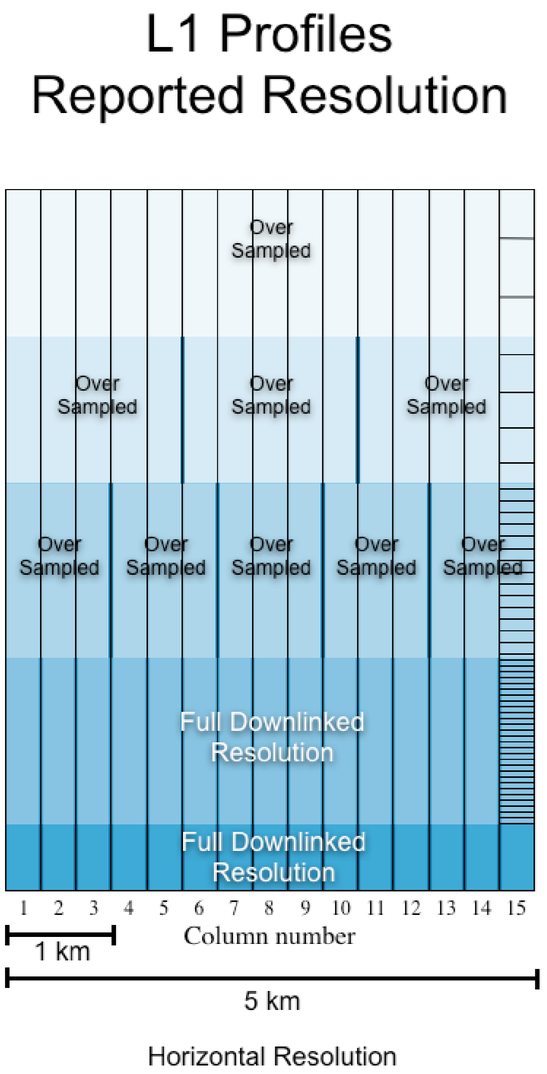


image source : https://www-calipso.larc.nasa.gov/resources/calipso_users_guide/essential_reading/index.php#altitude_array

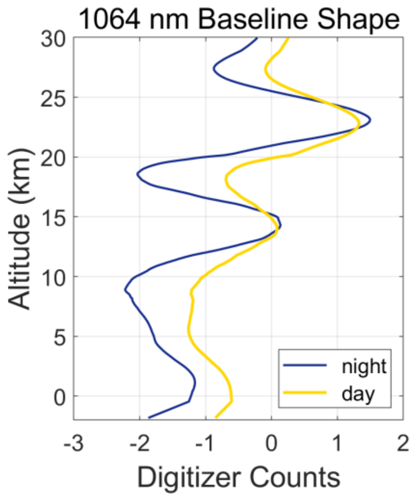
Science Data Product Definitions

- **Level 0**
  - Unprocessed instrument data (counts, voltages, etc.) at full downlinked resolutions
- **Level 1B**
  - Calibrated, geolocated, time-referenced lidar, altitude registered profiles
- **Level 2**
  - Derived Geophysical Variables (GVs; e.g., layer heights and optical depths) at multiple spatial resolutions

- **Expedited**
  - Expedited data products were created to support operational forecasting activities and have a latency of 12–24 hours from data downlink. This quick turnaround was achieved by using approximate geolocation information and meteorological data. CALIPSO expedited products should NEVER be used for rigorous science studies.
- **Standard**
  - Research quality data products having a longer time latency (e.g., several weeks). Standard products are derived using post-processed, highly accurate ephemeris and temporally matched MERRA2 meteorological data.

L0-L2 definitions taken from https://www.earthdata.nasa.gov/eosdis/science-system-description/eosdis-standard-products

Converting Level 0 to Level 1



Baseline (shape/slope) corrections eliminate low level electronic artifacts

1. Convert raw engineering data from digitizer counts to engineering units

2. Apply instrument and signal corrections (e.g., baseline shape, baseline slope, day-night gain ratios, etc.)

3. For each altitude bin(z) and profile (k), apply range squared correction (r^2) to the raw signals (P(z,k)) and normalize for electronic gain (G) and laser energy (E)

$$X(z,k) = \frac{r^2(z)\, P(z,k)}{G(k)\, E(k)}$$

4. Apply geolocation and altitude registration

5. Apply calibration coefficients

$$\beta'_{532,\parallel}(z,k) = \left(\frac{X_{532,\parallel}(z,k)}{C_{532,\parallel}}\right) \qquad \beta'_{532,\perp}(z,k) = \left(\frac{X_{532,\perp}(z,k)}{PGR \times C_{532,\parallel}}\right)$$

$$\beta'_{1064}(z,k) = \left(\frac{X_{1064}(z,k)}{C_{1064}}\right)$$

Radiometric Calibration

532 nm nighttime uses molecular normalization between 36-39 km to minimize stratospheric aerosol loading; calibration coefficients calculated by ratioing the measured signals to the expected signals derived using an atmospheric model; requires temporal averaging over 11 consecutive nighttime orbit segments. All other radio-metric calibrations are derived from the 532 nm nighttime calibration.

532 nm daytime assumes diurnally invariant aerosol loading in the lower stratosphere; calibration coefficients calculated by ratioing uncalibrated daytime "clear air" scattering ratios to calibrated nighttime "clear air" scattering ratios measured at the same latitude and altitude; requires temporal averaging over 165 consecutive daytime orbit segments

1064 nm (nighttime and daytime) assumes that both backscatter and extinction are spectrally invariant within dense cirrus clouds at 532 nm and 1064 nm; uses the calibrated 532 nm signals and the uncalibrated 1064 nm signals from "calibration quality" cirrus to compute 532-to-1064 calibration scale factors; requires temporal averaging over 165 consecutive orbit segments

CALIOP Radiometric Calibration References

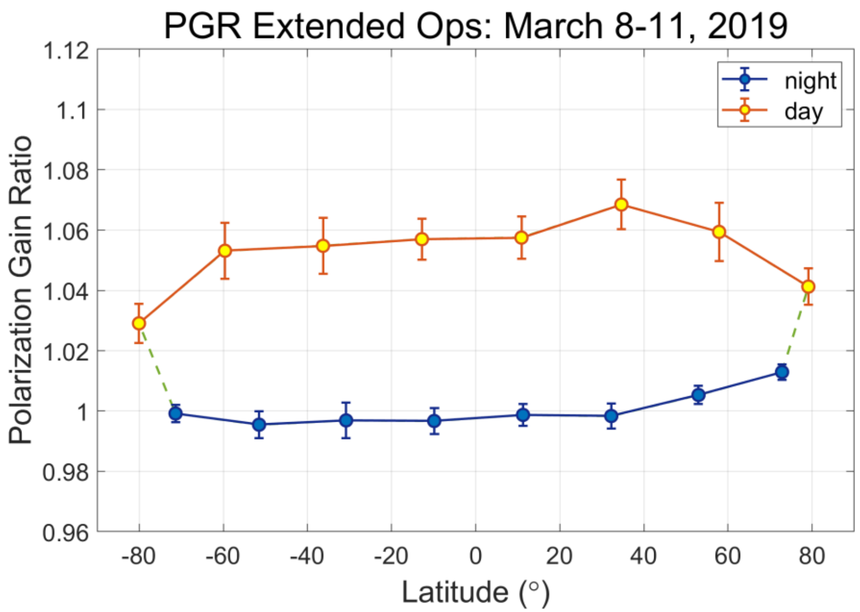
- Kar et al., 2018: CALIPSO Lidar Calibration at 532 nm: Version 4 Nighttime Algorithm, https://doi.org/10.5194/amt-11-1459-2018
- Getzewich et al., 2018: CALIPSO Lidar Calibration at 532-nm: Version 4 Daytime Algorithm, https://doi.org/10.5194/amt-11-6309-2018
- Vaughan et al., 2019: CALIPSO Lidar Calibration at 1064 nm: Version 4 Algorithm, https://doi.org/10.5194/amt-12-51-2019

Polarimetric Calibration

The polarization gain ratio (PGR) is an essential calibration coefficient required for computing both the total attenuated backscatter coefficients and the volume depolarization ratios.

Nighttime PGR measurements are obtained by inserting a pseudo-depolarizer into the 532 nm optical path. This device completely depolarizes the incident light, causing equal optical intensities to be directed on both the 532 nm parallel and 532 nm perpendicular detectors

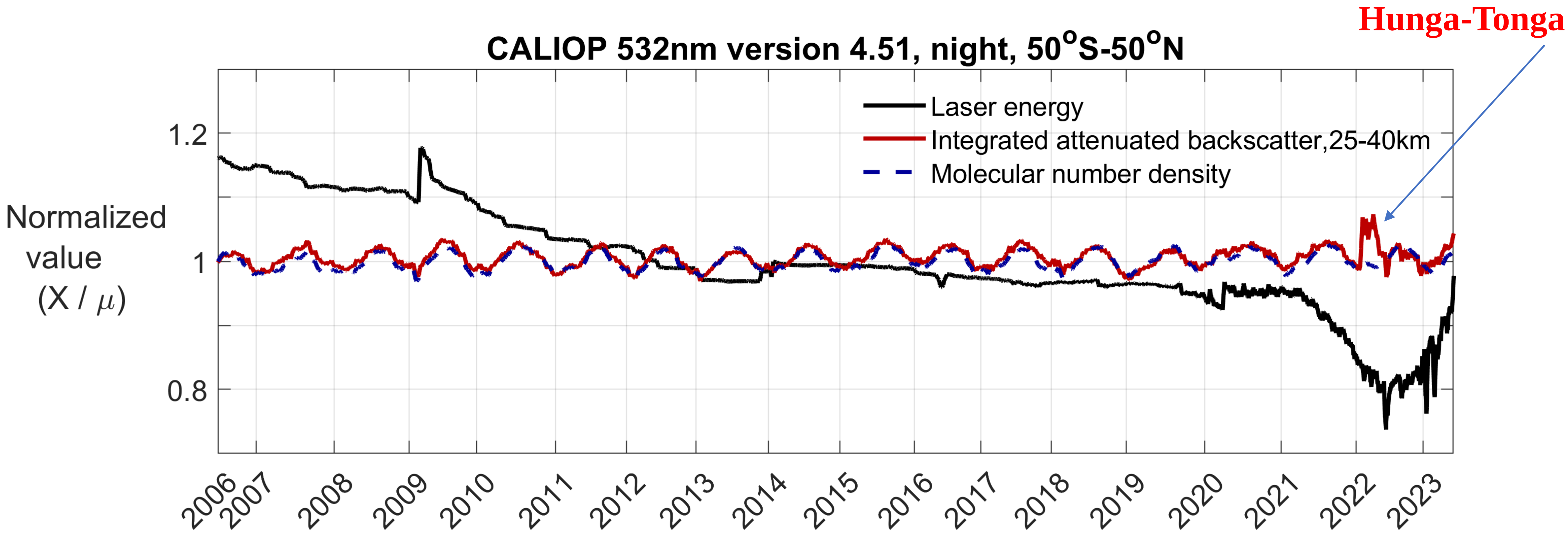
Because extended dwell time requirements prohibit routine use of the pseudo-depolarizer during daytime operations, daytime PGR measurements are estimated using solar background measurements acquired above opaque ice clouds.



CALIOP Polarimetric Calibration References

- Liu et al., 2004: Validating lidar depolarization calibration using solar radiation scattered by ice clouds, https://doi.org/10.1109/LGRS.2004.829613
- Powell et al., 2009: CALIPSO Lidar Calibration Algorithms: Part I - Nighttime 532 nm Parallel Channel and 532 nm Perpendicular Channel, https://doi.org/10.1175/2009JTECHA1242.1
- Vaughan et al., 2023: Correcting CALIOP Polarization Gain Ratios for Diurnal Variations, https://doi.org/10.1007/978-3-031-37818-8_89

Calibration Stability

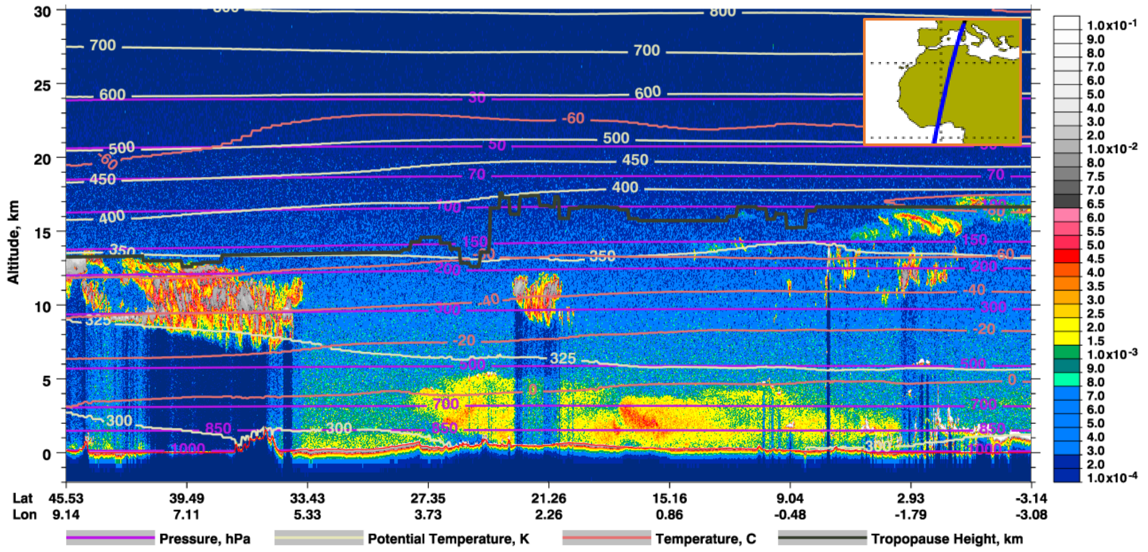


The stability of CALIOP measurements and robustness of calibration procedures is evidenced by the time series of global 532 nm integrated attenuated backscatter (IAB) from 25-40 km over the course of the mission. In this largely aerosol-free region of the atmosphere, the seasonal trend in IAB tracks that of molecular number density as expected. Despite the reduction in 532 nm laser energy and increased occurrence of low energy shots within the South Atlantic Anomaly (SAA) since 2017, the IAB remains well behaved.

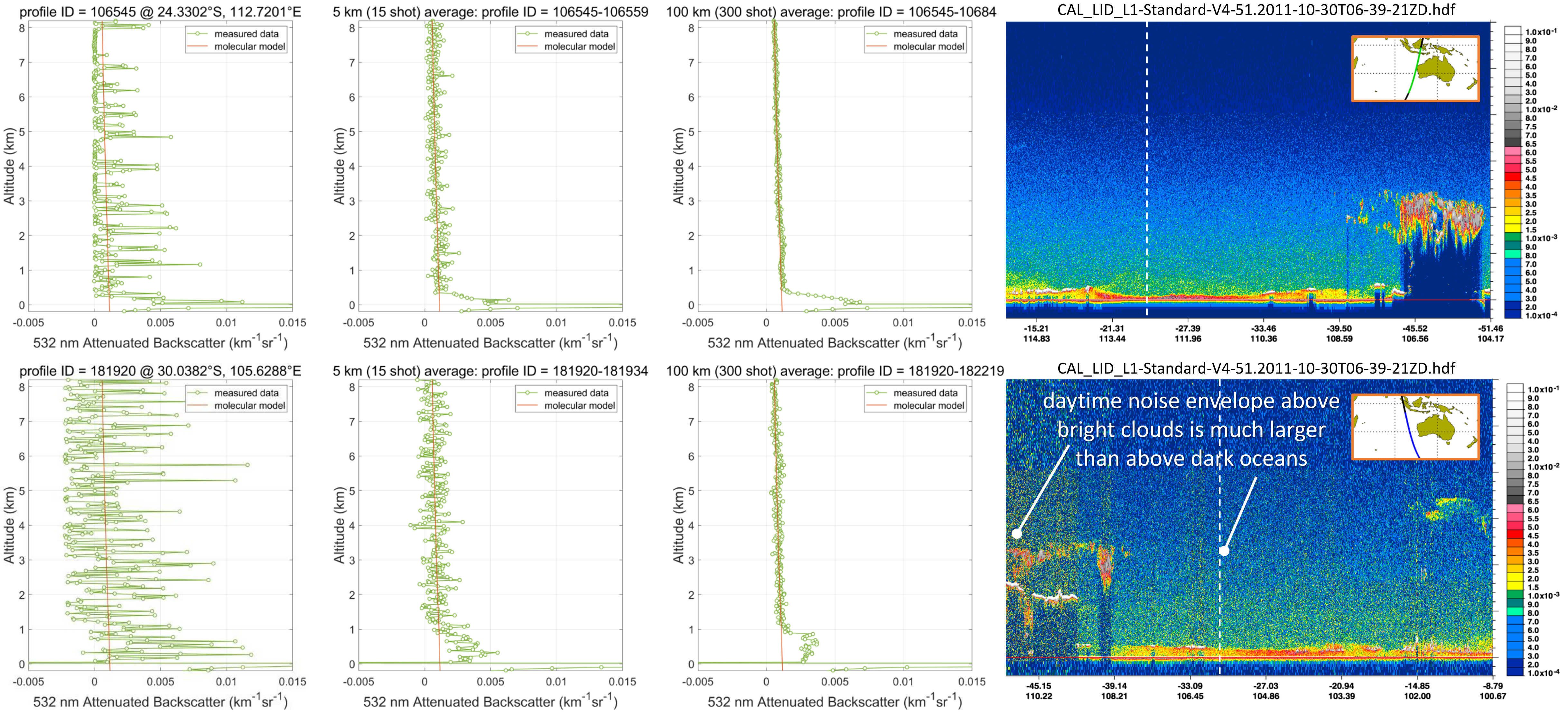
Primary Level 1 Output Parameters

- 532 nm Total Attenuated Backscatter – $\beta'_{532,total}(z) = \beta'_{532,\parallel}(z) + \beta'_{532,\perp}(z)$
- 532 nm Perpendicular Attenuated Backscatter – $\beta'_{532,\perp}(z)$
- 1064 nm Total Attenuated Backscatter – $\beta'_{1064}(z)$
- 532 nm Polarization Gain Ratio
- Calibration Coefficients and Uncertainties
- Laser Energy and Instrument Characterization Parameters
- Quality Flags
- Ancillary Meteorological Data

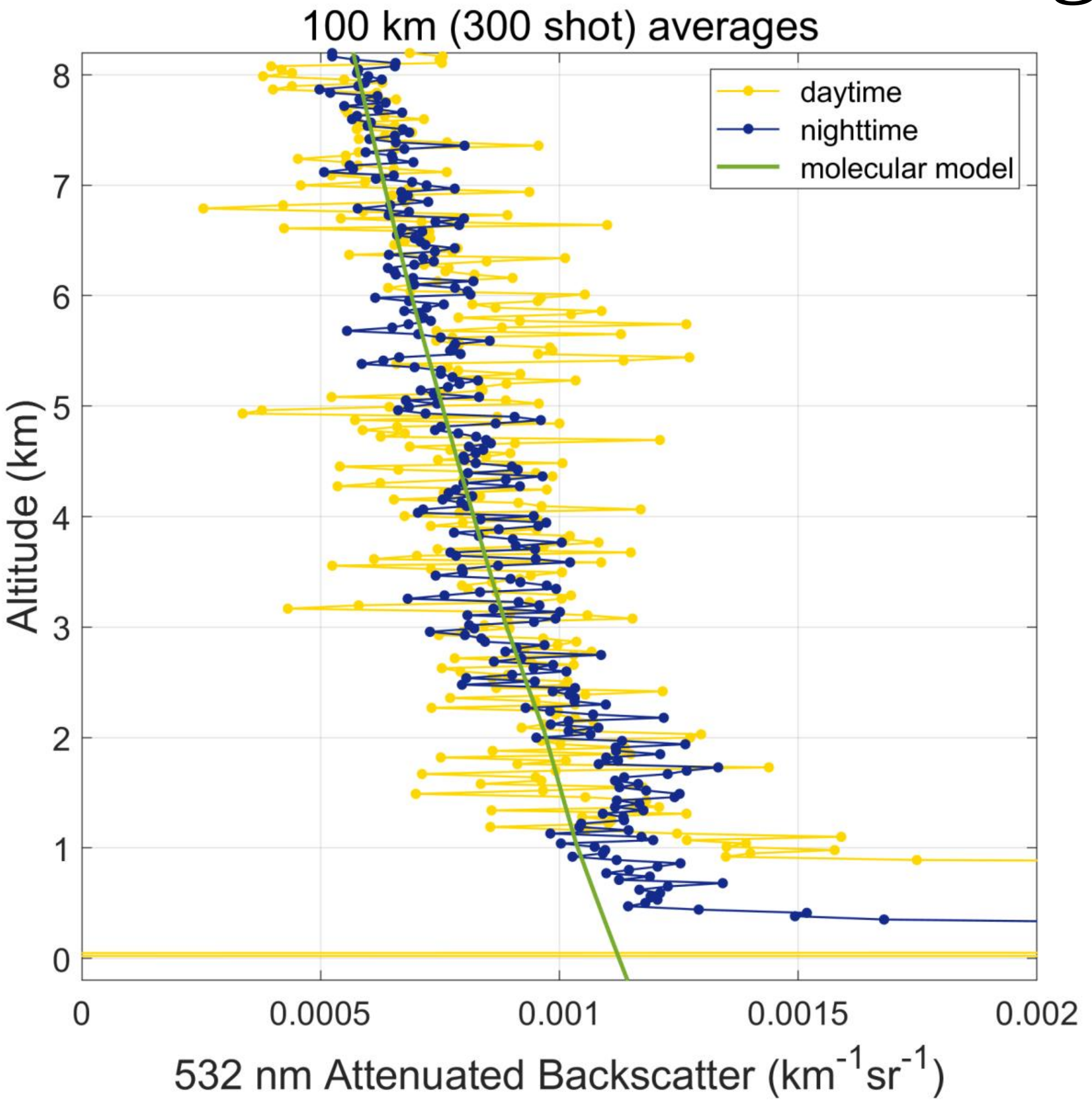
532 nm Total Attenuated Backscatter (km^{-1} sr^{-1}), 2010-10-30 @ 01:41:41 UTC

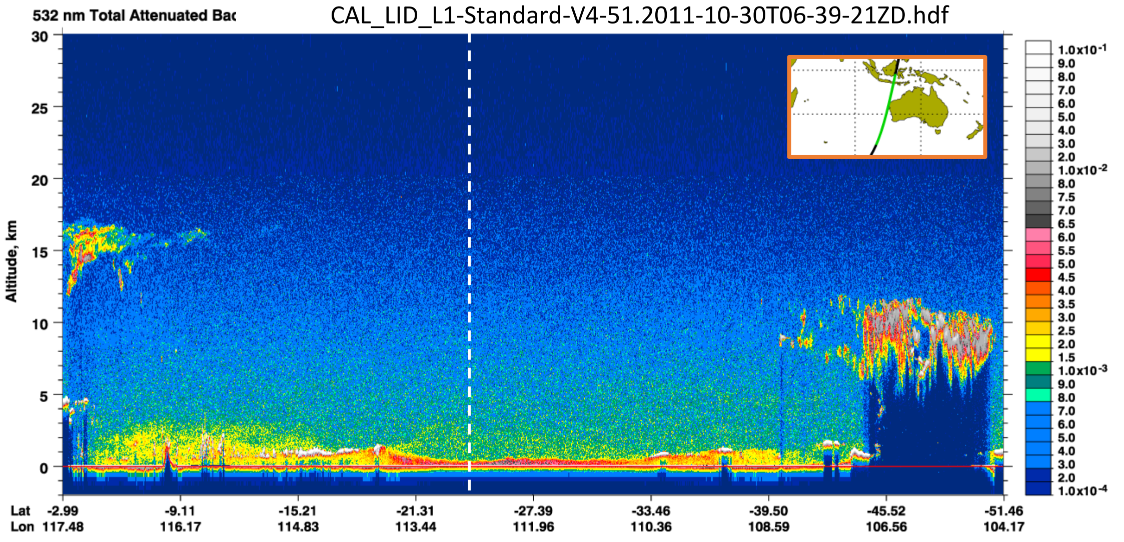


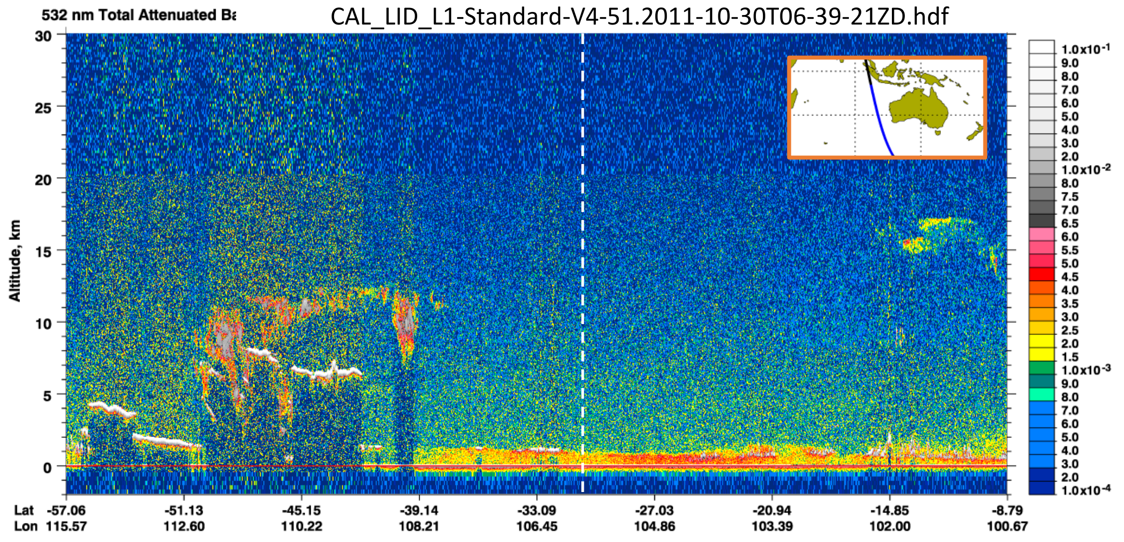
Random Noise: CALIOP Nighttime vs. Daytime



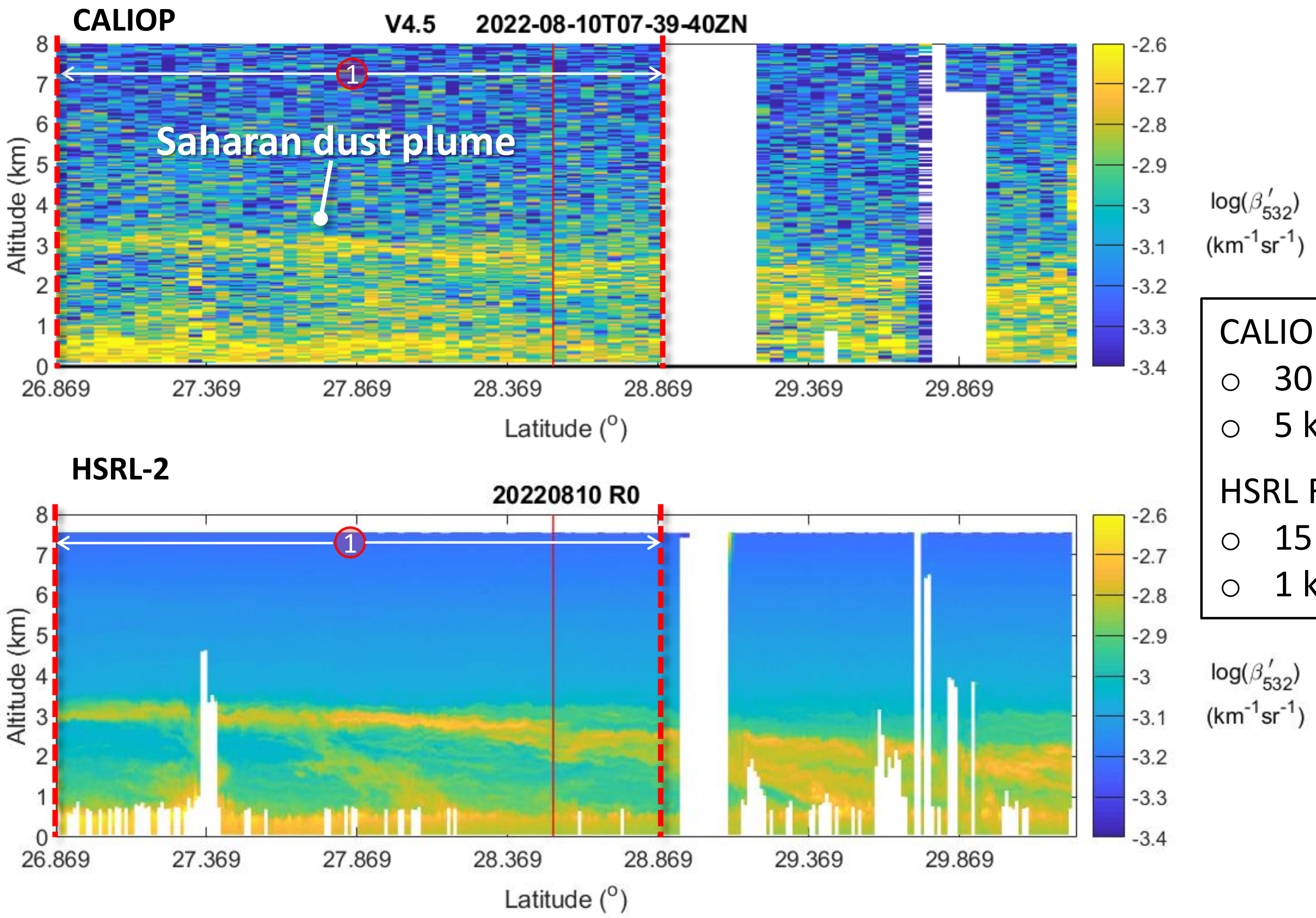
Random Noise: CALIOP Nighttime vs. Daytime





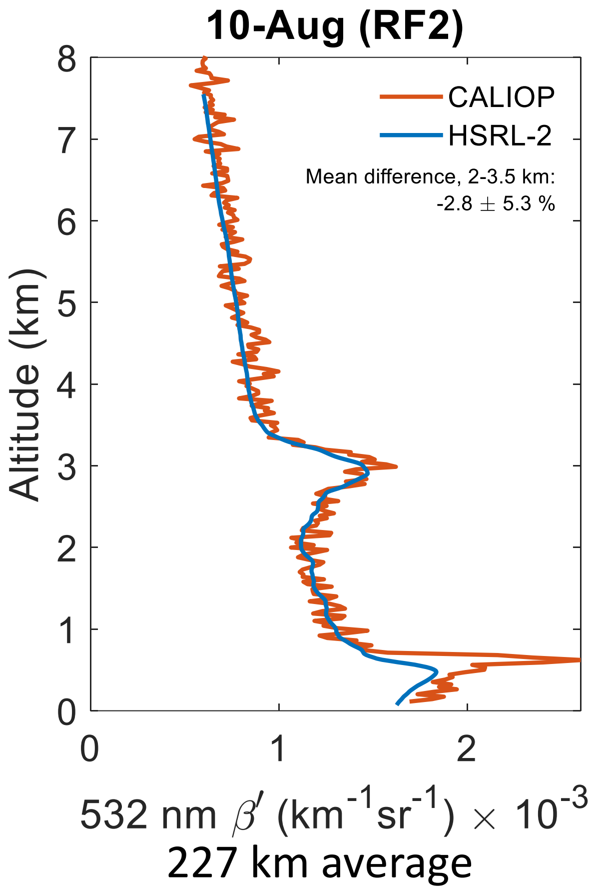


Random Noise: CALIOP vs. HSRL-2



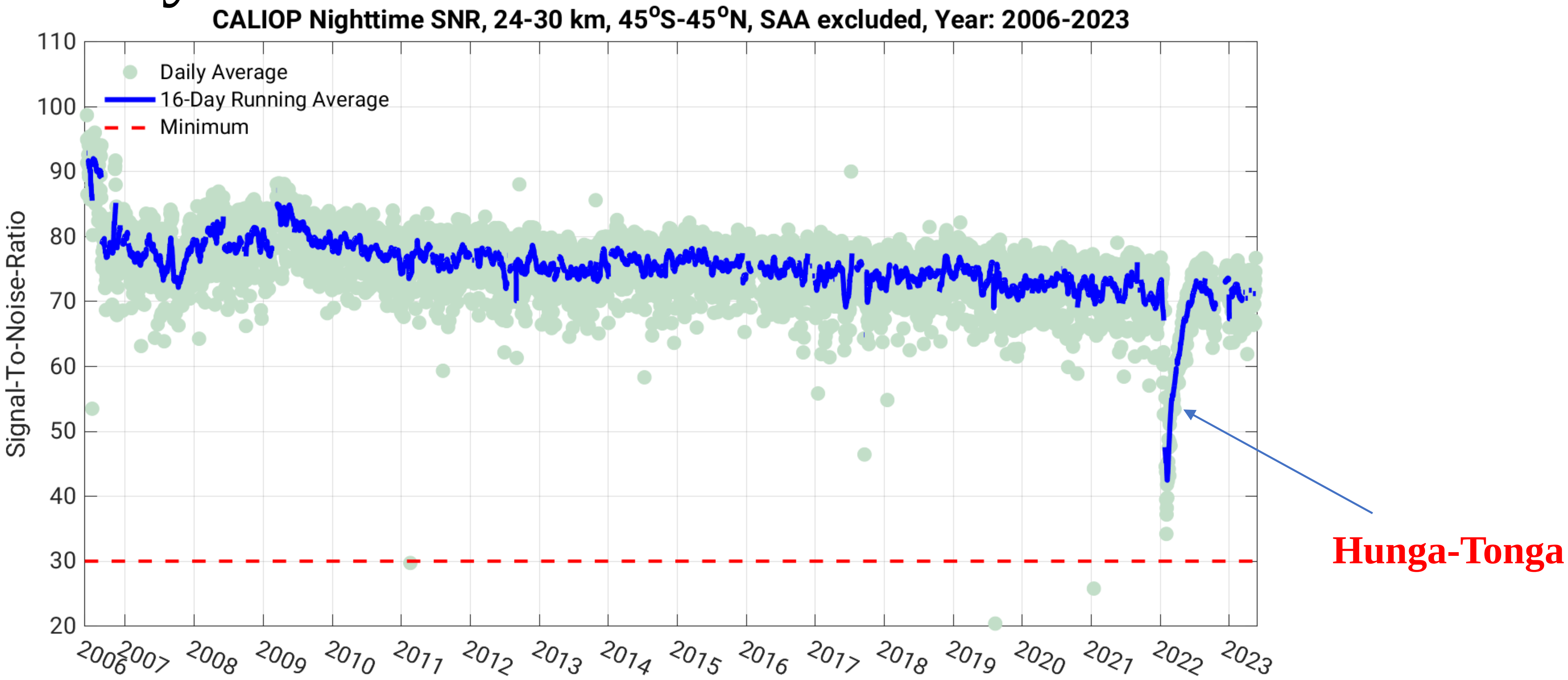
CALIOP Resolution
- 30 m vertical
- 5 km horizontal

HSRL Resolution
- 15 m vertical
- 1 km horizontal



Campaign Data Available at https://asdc.larc.nasa.gov/project/CALIPSO-NVF/CALIPSO-NVF_HSRL2_KingAir_Data_1

SNR Stability



Measured 532 nm channel nighttime signal-to-noise (SNR) computed from the nighttime total attenuated backscatter coefficients between 24 km and 30 km and 45º N to 45º S with a horizontal averaging of 1500 km along track. No noise filtering is applied to the data, meaning that radiation-induced noise and low energy laser shots are included in the SNR calculations.

Level 2 Data Products

<u>Lidar Level 2 Profile Products</u>

CAL_LID_L2_05kmCPro; Cloud

CAL_LID_L2_05kmAPro; Aerosol

Profile products report profiles of extinction, backscatter and depolarization (*derived/built from level 2 extinction algorithm*) at a uniform vertical and horizontal spatial resolution.

Profile Products
Particulate Backscatter Coefficients Profiles; β_{532}, β_{1064}
Particulate Extinction Coefficient Profiles; σ_{532}, σ_{1064}
Particulate Depolarization Profiles; δ_p
Column Optical Properties; τ

<u>Lidar Level 2 Layer Products</u>

CAL_LID_L2_333mMLay; 333m Merged

CAL_LID_L2_01kmCLay; 1km Cloud

CAL_LID_L2_05kmCLay; 5km Cloud

CAL_LID_L2_05kmALay; 5km Aerosol

CAL_LID_L2_05kmMLay; 5km Merged

Layer products report vertical locations of layer boundaries and the integrated optical properties of each layer.

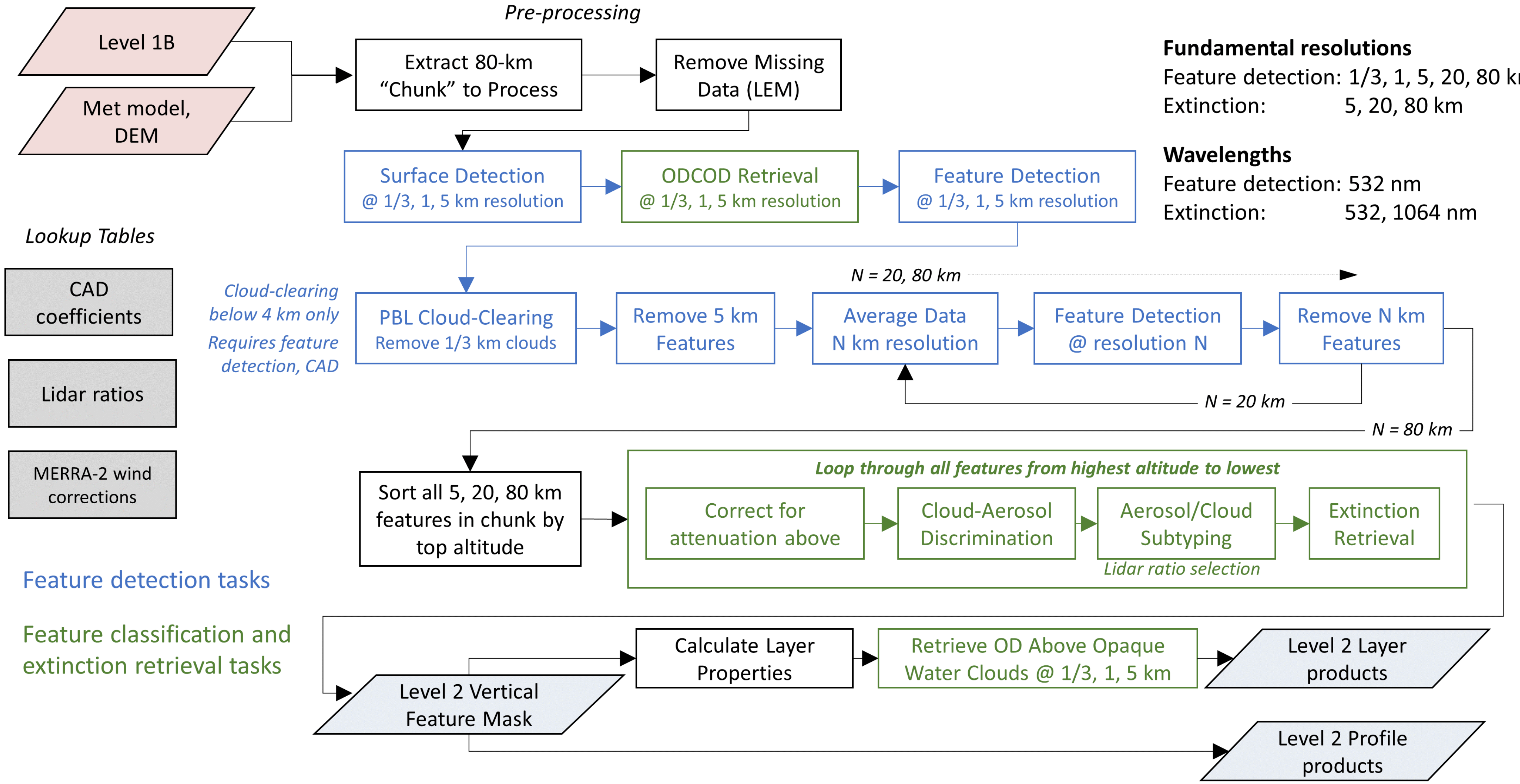
Layer Products
Layer Spatial Properties; Top, Base, Type and Subtype
Layer Measured Optical Properties; γ'_{532}, γ'_{1064}, δ_v, χ'
Layer Derived Optical Properties; τ, δ_p, χ_p

<u>Lidar Level 2 Vertical Feature Mask Product</u>

CAL_LID_L2_VFM

Vertical Feature Mask product describes the vertical and horizontal distribution of cloud and aerosol layers observed. Bit-mapped values report feature type, subtype, phase(cloud) or type(aerosol), horizontal averaging, and associated quality assessment (QA) flags.

Level 2 Algorithm Overview

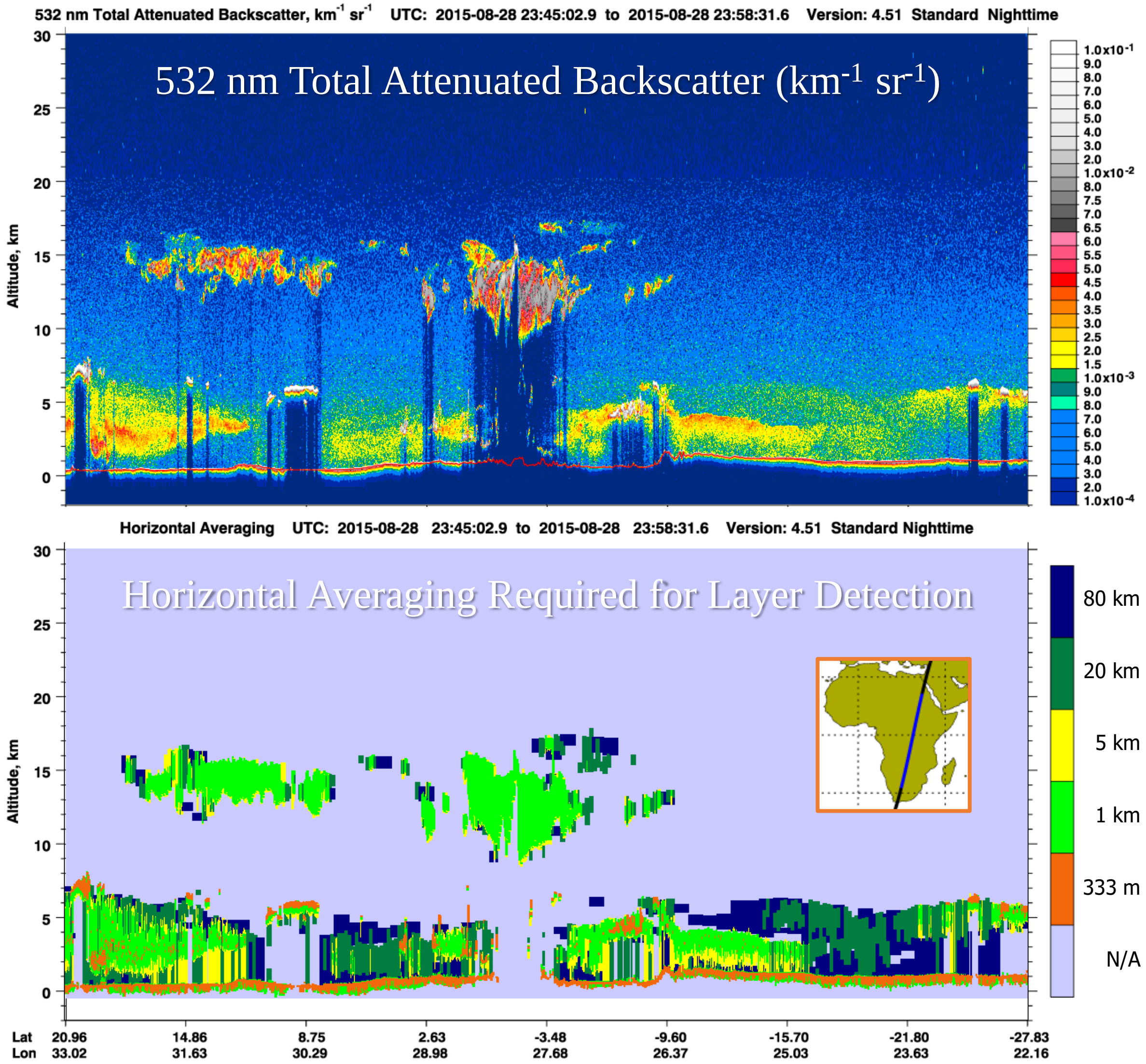


Fundamental resolutions
Feature detection: 1/3, 1, 5, 20, 80 km
Extinction: 5, 20, 80 km

Wavelengths
Feature detection: 532 nm
Extinction: 532, 1064 nm

Level 2 Algorithm - Feature Detection

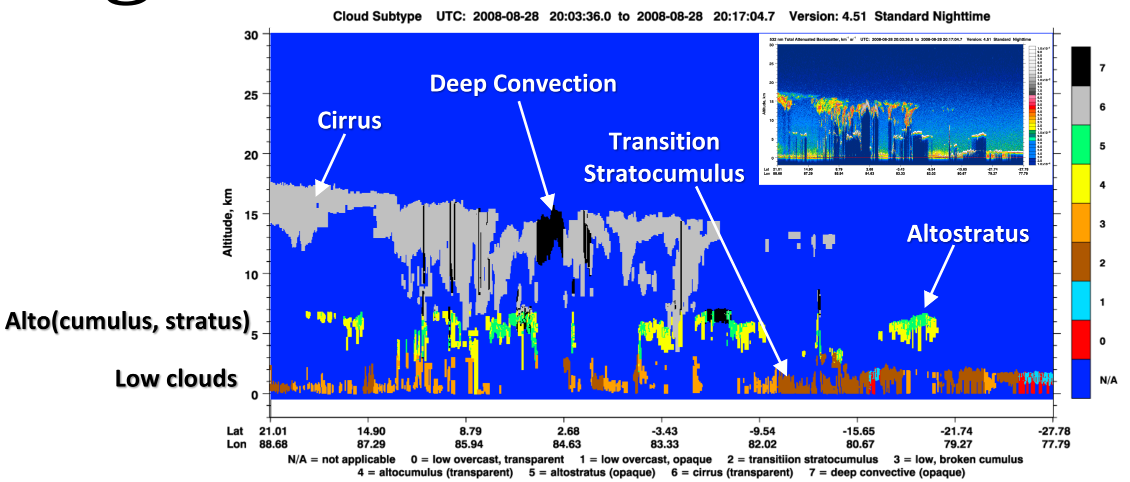
- A data-aware profile scanning algorithm is fused with an iterated, multi-resolution data averaging engine to detect atmospheric features at horizontal resolutions of 333 m, 1 km, 5 km, 20 km, and 80 km
- The profile scanner uses MERRA2 meteorological data and CALIOP measurements of background noise to construct altitude-dependent thresholds that account for the CALIOP onboard averaging scheme
- An integrated cloud-aerosol discrimination algorithm identifies clouds detected in the boundary layer at single shot resolution. These clouds are removed, and the surrounding data is reaveraged to coarser spatial resolutions to search for boundary layer aerosols.



Vaughan et al, 2009: Fully Automated Detection of Cloud and Aerosol Layers in the CALIPSO Lidar Measurements, *J. Atmos. Oceanic Technol*., **26**, 2034–2050, https://doi.org/10.1175/2009JTECHA1228.1.

Level 2 Algorithm – Cloud Typing & Phase

- Cloud type based on meteorological cloud definitions developed by the International Satellite Cloud Climatology Project (ISCCP)
  - Layer top pressure, Cloud opacity, and cloud cover fraction
- Cloud phase (Water, HOI, and ROI) and QA confidence are derived based <u>primarily</u> on the relationship between layer integrated volume depolarization ratio (δ_v) and 532 nm integrated attenuated backscatter (γ'_{532}) (Hu et al., 2009).



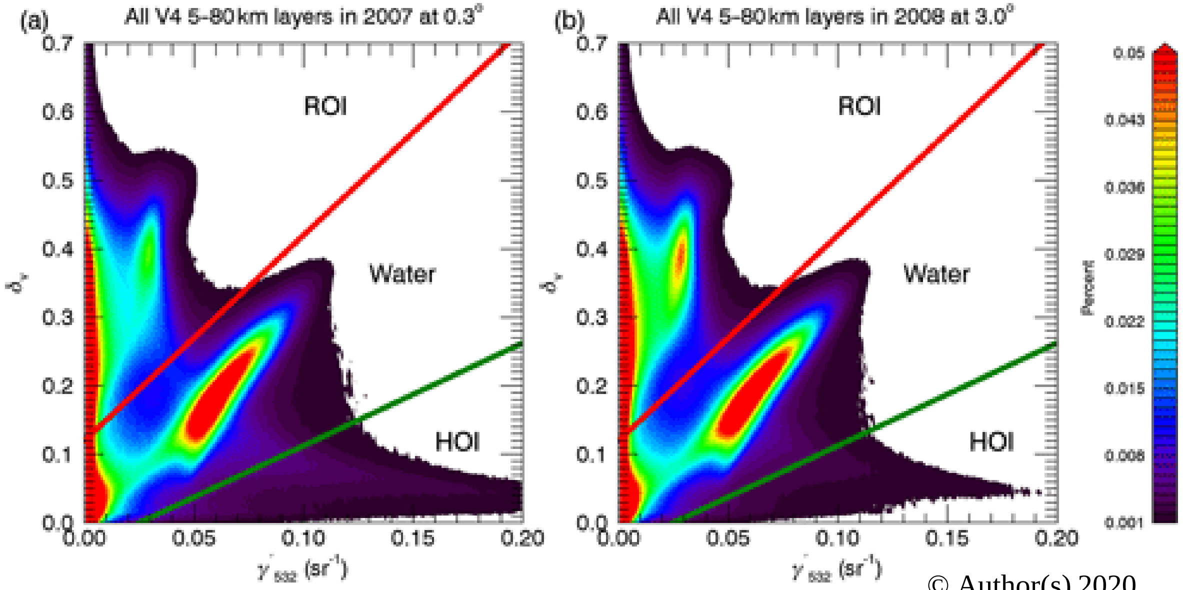
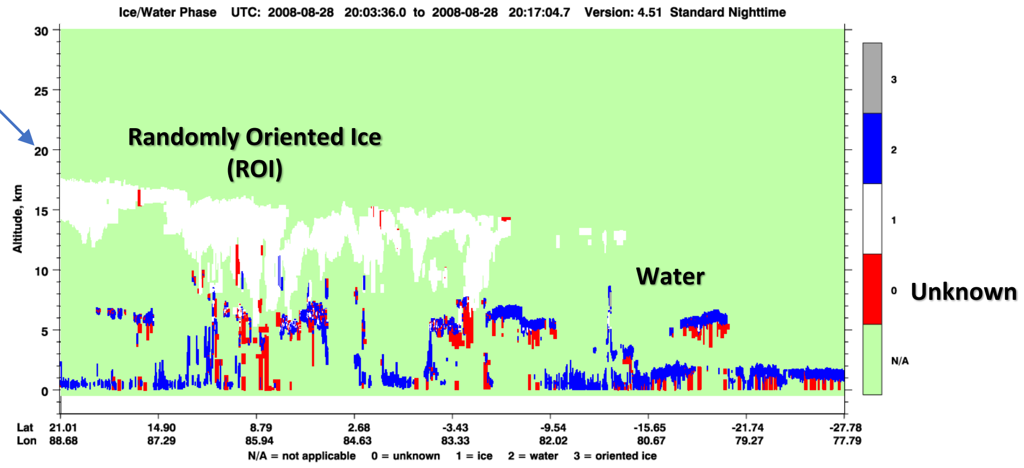


Figure 1 from Avery et al., 2020

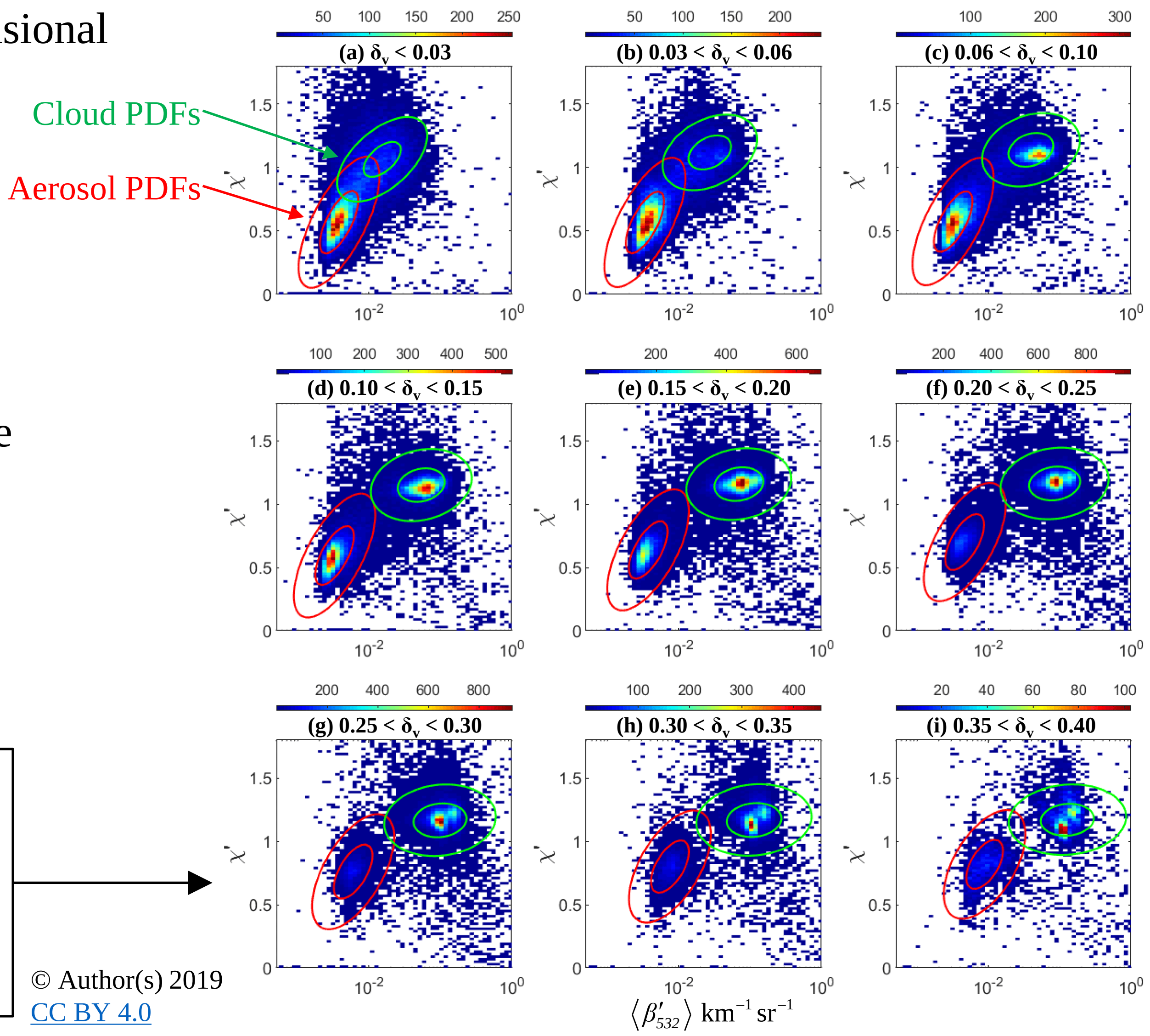


Avery et al., 2020: CALIOP V4 cloud thermodynamic phase assignment and the impact of near-nadir viewing angles, *Atmos. Meas. Tech.*, **13**, 4539–4563, https://doi.org/10.5194/amt-13-4539-2020

Level 2 Algorithm – Cloud-Aerosol Discrimination

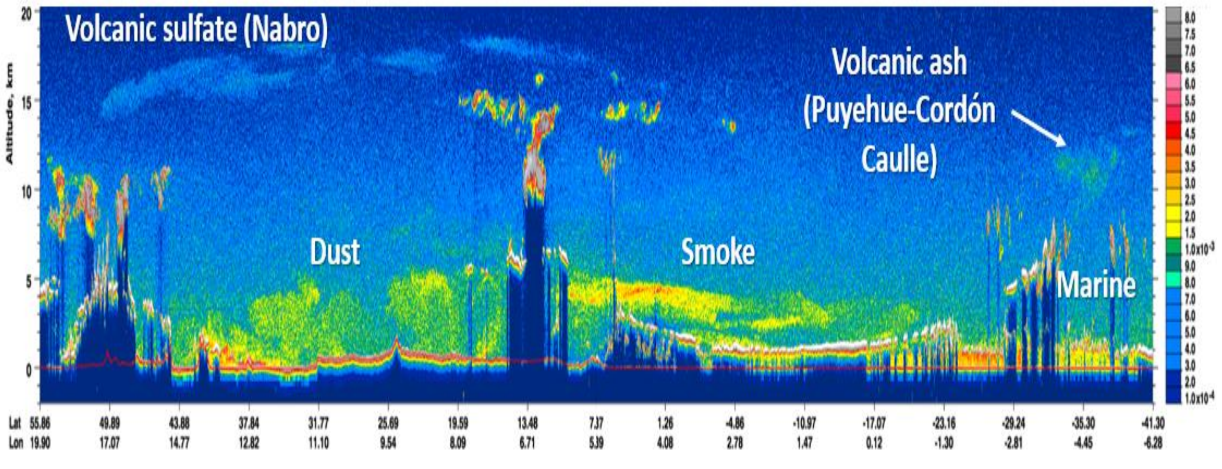
- Cloud-Aerosol Discrimination (CAD) based on five-dimensional probability density function (PDF)
  - Layer mean 532 nm attenuated backscatter ($<\beta'_{532}>$)
  - Layer averaged attenuated color ratio (χ')
  - Layer integrated volume depolarization ratio (δ_v)
  - Mid-layer altitude
  - Latitude
- CAD scores reported in the data products provide both type identification and a discrimination confidence estimate
  - Cloud: $0 \leq$ CAD Score ≤ 100
  - Aerosol: $-100 \leq$ CAD Score < 0
  - Classification confidence = | CAD Score |
  - CAD scores outside for ±100 for 'special' cases

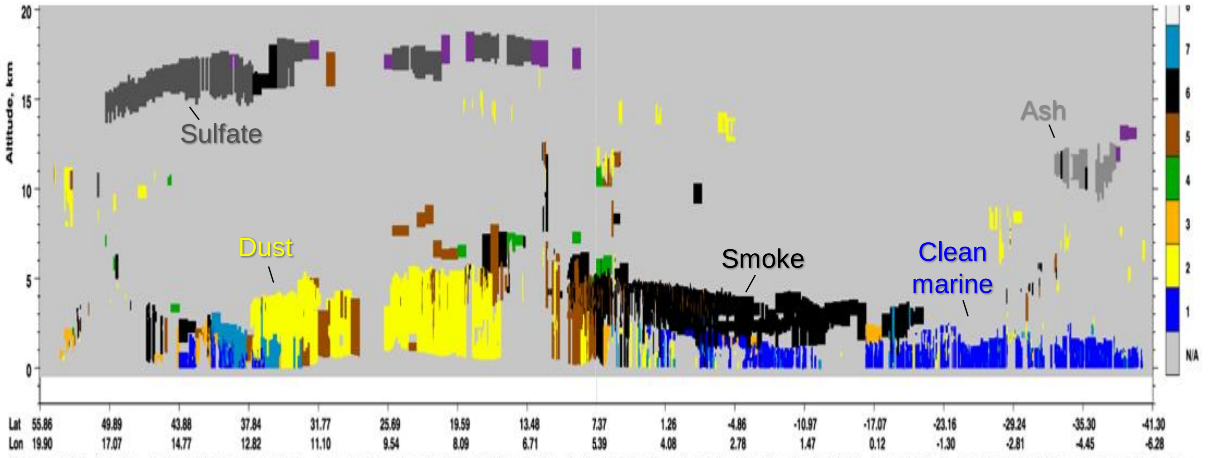
Image adapted from figure 2 (a – i) in Liu et al., 2019: Discriminating between clouds and aerosols in the CALIOP version 4.1 data products, https://doi.org/10.5194/amt-12-703-2019; individual panels show cloud and aerosol PDFs for features having mid-layer altitudes between 1 km and 2 km detected between 20° N and 30° N for 9 different ranges of layer-integrated volume depolarization ratios.



Level 2 Algorithm – Aerosol Typing

- Tropospheric and stratospheric aerosol typing reported in data products
  - Height of centroid of 532nm backscatter compared with location of tropopause
- Separate subtyping algorithms for the two aerosol types based on decision-based flow chart
- Tropospheric sub-typing scheme
  - Kim et al., 2018, doi: amt-11-6107-2018
  - Function of γ'_{532}, δ_p, Top, Base, Surface Type (land/ocean)
- Stratospheric sub-typing scheme
  - Tackett et al., 2023, doi: 10.5194/amt-16-745-2023
  - Function of γ'_{532}, δ_p, Mid-Layer Temperature, Season (latitude & month)
  - Thresholding algorithms determined by CALIPSO observations tuned to well documented stratospheric aerosol, volcanic, and smoke events



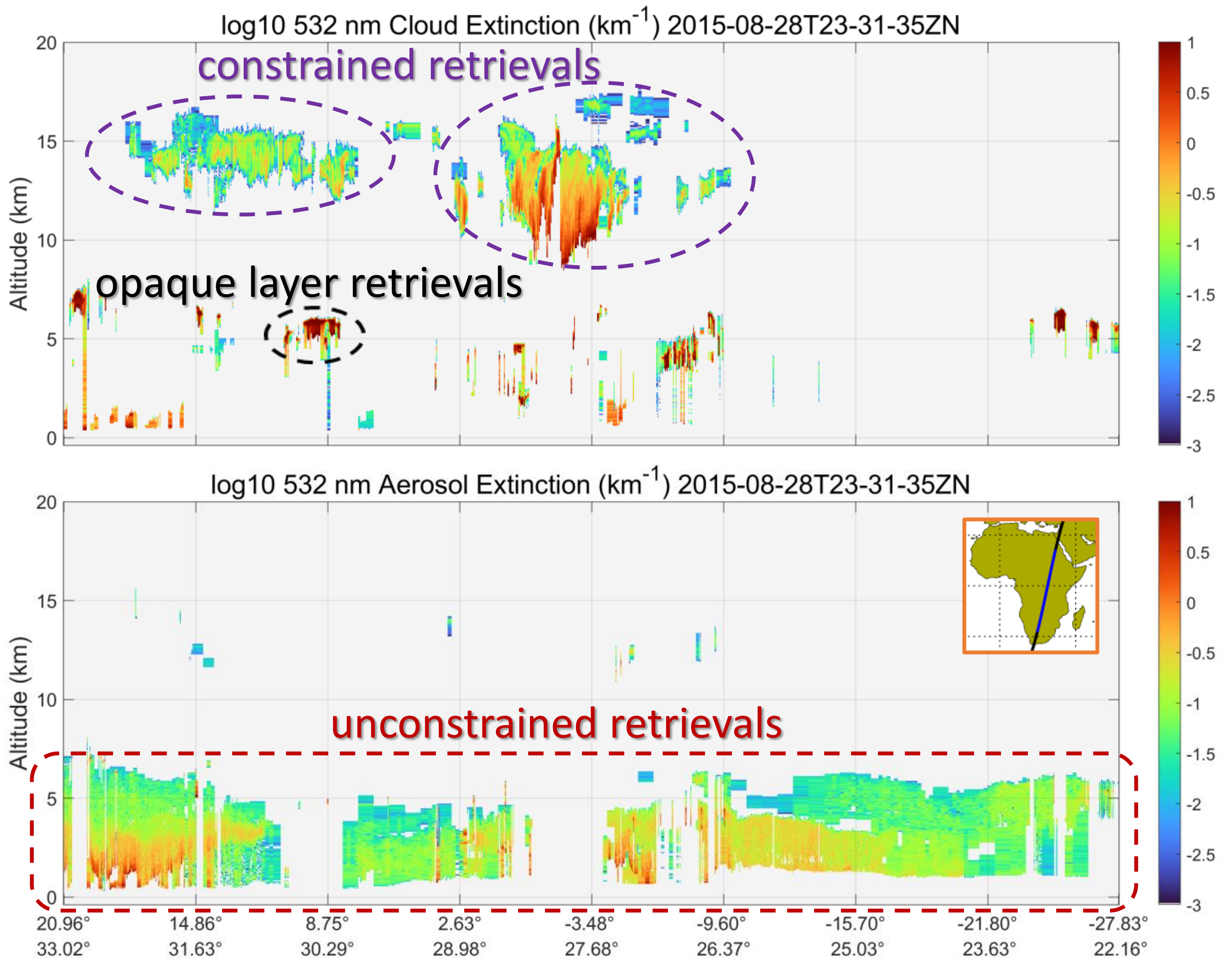


July 1, 2011 (2011-07-01T01-13-31ZN) orbit crossing continental Africa

Mediterranean → Southern Atlantic

Level 2 Algorithm – Extinction

- *constrained retrievals* use measurements of two-way transmittance derived from clear skies above and below a cloud or aerosol layer to compute a matching extinction profile and lidar ratio
- *unconstrained retrievals* derive extinction profiles using type-dependent initial estimates of the layer lidar ratio (S) and multiple scattering factor (η)
- *opaque layer retrievals* calculate extinction coefficients and lidar ratios constrained by Platt's equation: $\gamma' = (2\,\eta\,S)^{-1}$
- all retrievals report range-resolved uncertainty estimates and assign an extinction QC flag to characterize retrieval quality



Young et al, 2018: Extinction and Optical Depth Retrievals for CALIPSO's Version 4 Data Release, *Atmos. Meas. Tech.*, **11**, 5701–5727, https://doi.org/10.5194/amt-11-5701-2018.

Initial Lidar Ratios (S), CALIOP Version 4.51

Feature Type	**532 nm**	**1064 nm**	**References**
water cloud	day: 18.8 ± 2.8 sr night: 17.7 ± 2.7 sr	N/A	
ice cloud	$S_c = f(T_{centroid}) \pm 25\%$	N/A	1, 2
unknown phase cloud	22 ± 11 sr	N/A	
unknown tropospheric aerosol	35 ± 14 sr	35 ± 14 sr	
marine aerosol	23 ± 5 sr	23 ± 5 sr	3
desert dust aerosol	44 ± 9 sr	44 ± 13 sr	4, 5
polluted continental/smoke aerosol	70 ± 25 sr	30 ± 14 sr	6
clean continental aerosol	53 ± 24 sr	30 ± 17 sr	7
polluted dust aerosol	55 ± 22 sr	48 ± 24 sr	8
elevated smoke aerosol	70 ± 16 sr	30 ± 18 sr	4
dusty marine aerosol	37 ± 15 sr	37 ± 15 sr	9
undetermined stratospheric aerosol	50 ± 20 sr	50 ± 20 sr	
polar stratospheric aerosol	50 ± 20 sr	25 ± 10 sr	10
stratospheric volcanic ash	61 ± 17 sr	44 ± 13 sr	11
stratospheric sulfate	50 ± 18 sr	30 ± 14 sr	12
stratospheric smoke	70 ± 16 sr	30 ± 18 sr	4
unclassified stratospheric aerosol	50 ± 18 sr	30 ± 14 sr	13

References

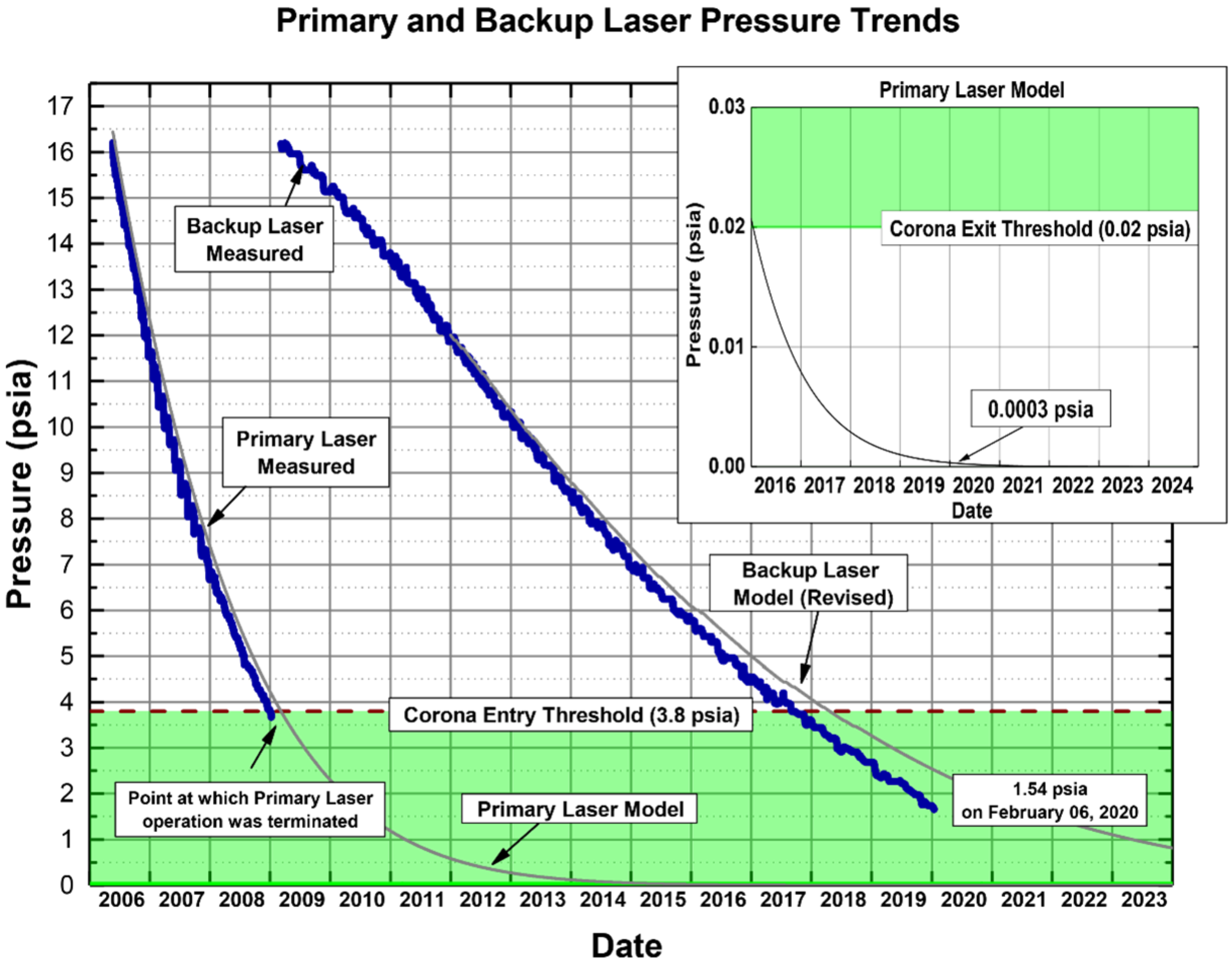
1. Young et al., 2018; https://doi.org/ 10.5194/amt-11-5701-2018
2. Garnier et al., 2016; https://doi.org/ 10.5194/amt-8-2759-2015
3. HSRL measurements in multiple field campaigns; e.g., Burton et al., 2012; https://doi.org/ 10.5194/amt-5-73-2012
4. Liu et al., 2014; https://doi.org/ 10.1007/s13351-014-3051-5
5. HRSL measurements of transported Saharan dust; e.g., Burton et al., 2014; https://doi.org/10.5194/amt-7-419-2014
6. Omar et al., 2010; https://doi.org/ 10.1029/2010JD014223
7. Rogers et al., 2014; https://doi.org/ 10.5194/amt-7-4317-2014
8. Omar et al., 2010; https://doi.org/ 10.1029/2010JD014223
9. Kim et al., 2018; https://doi.org/ 10.5194/amt-11-6107-2018
10. Kim et al., 2018; https://doi.org/ 10.5194/amt-11-6107-2018
11. Tackett et al., 2023; https://doi.org/ 10.5194/amt-16-745-2023
12. Kim et al., 2018; https://doi.org/ 10.5194/amt-11-6107-2018
13. Tackett et al., 2023; https://doi.org/ 10.5194/amt-16-745-2023

Resources & Tools

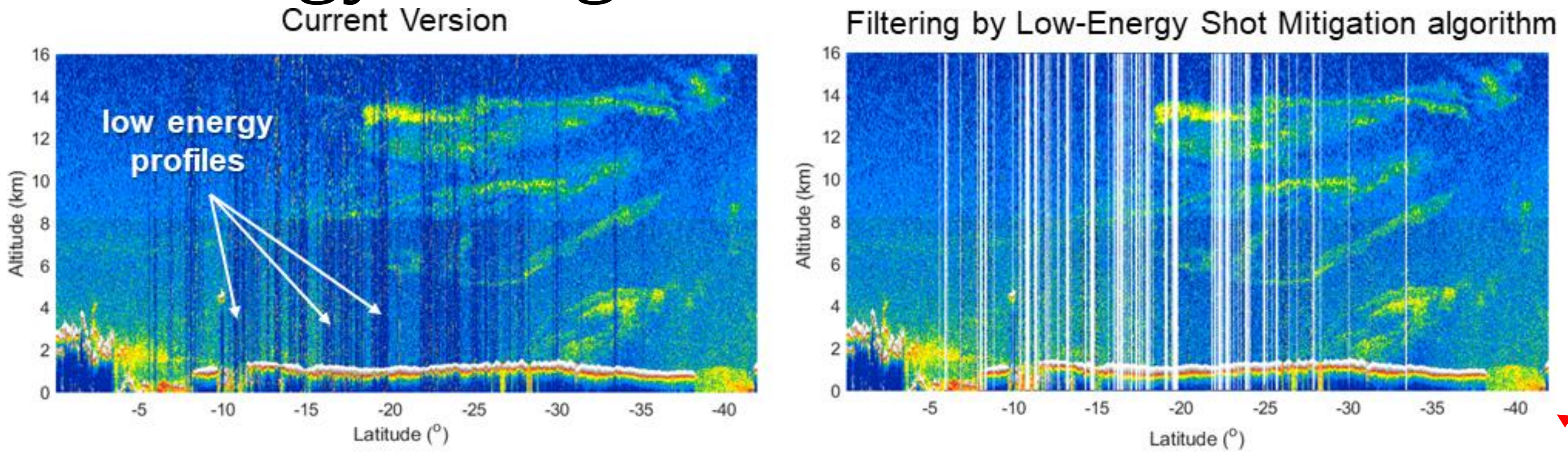
- CALIPSO Science Site
  - https://www-calipso.larc.nasa.gov
- NASA LaRC Atmospheric Science Data Center (ASDC)
  - Order Tool: https://asdc.larc.nasa.gov/project/CALIPSO
  - Data Pool (OpenDAP): https://opendap.larc.nasa.gov/opendap/hyrax/CALIPSO/
- Cloud-Aerosol-Water-Radiation-Interactions (ICARE) Data and Services Center
  - https://www.icare.univ-lille.fr/
- CALIPSO Search/Sub-setter Tool
  - https://subset.larc.nasa.gov/calipso
- CALIPSO Data Availability Tool
  - https://www-calipso.larc.nasa.gov/tools/data_avail/
- CALIPSO Browse Images
  - https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/

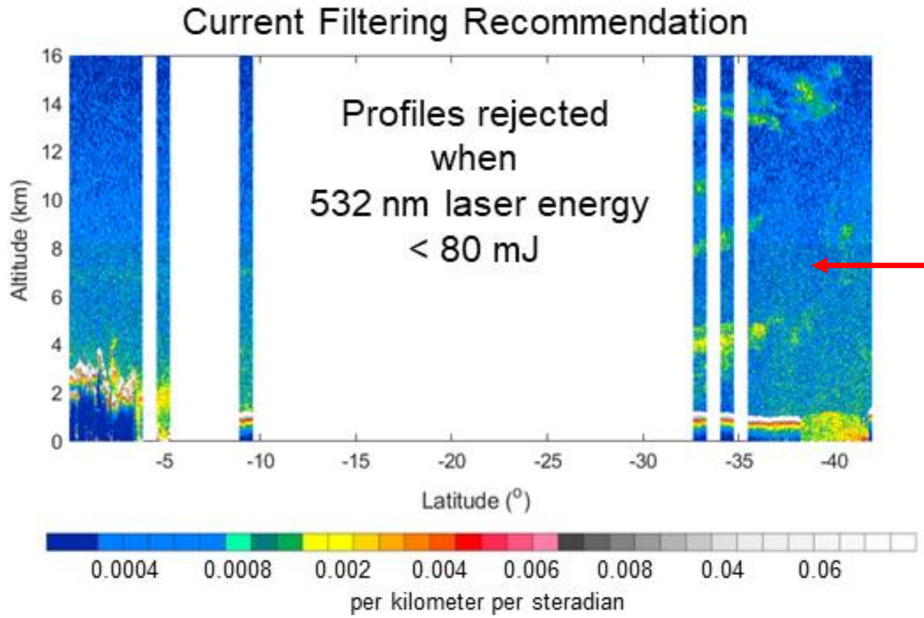
Questions?

Laser Canister Pressure



Laser Energy Mitigation Effort

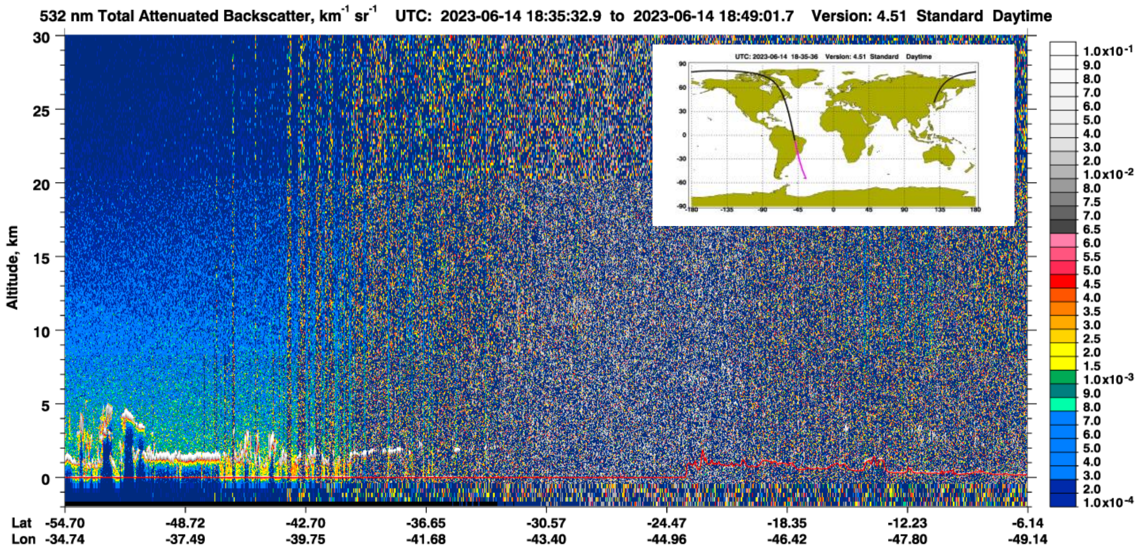


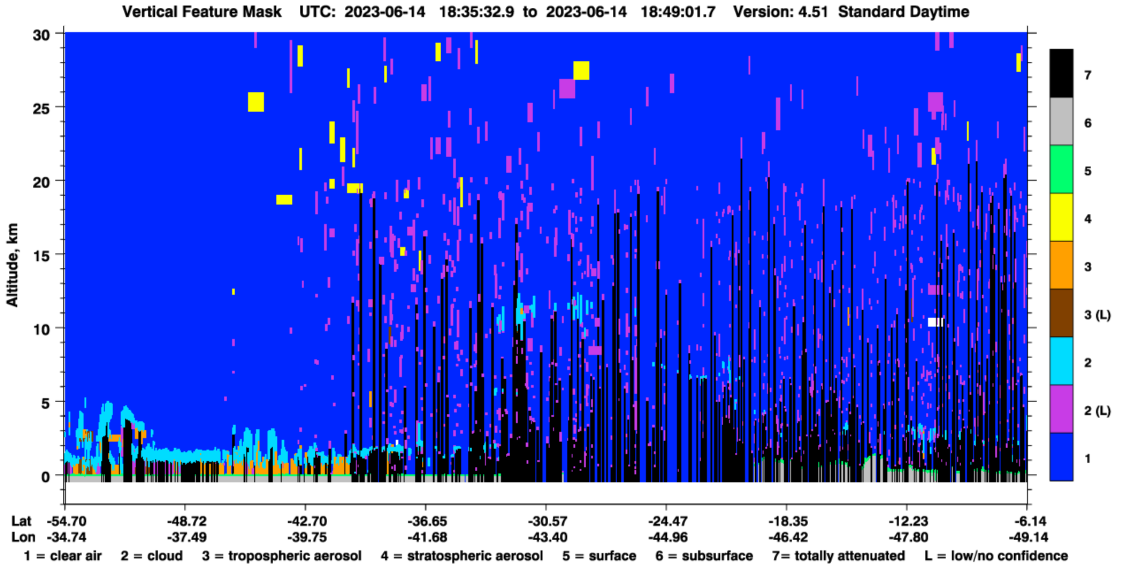


Suggested filtering provided to data users for older version of the data product (V4)

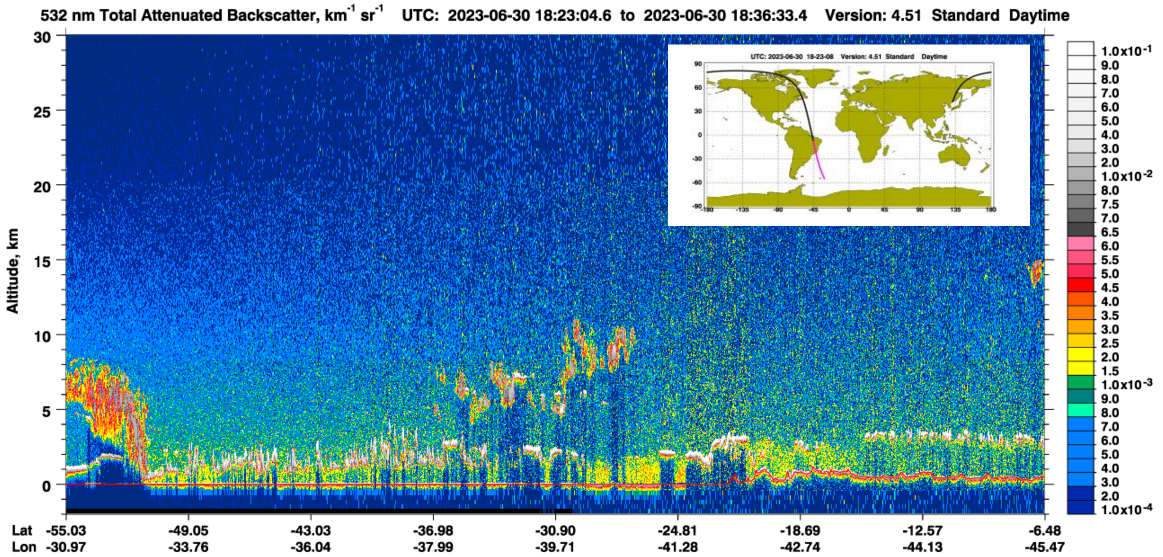
New Lidar Level 2 algorithm (LEM) to filter data based on on-board averaging considerations. Will be implemented for final release of the data product.

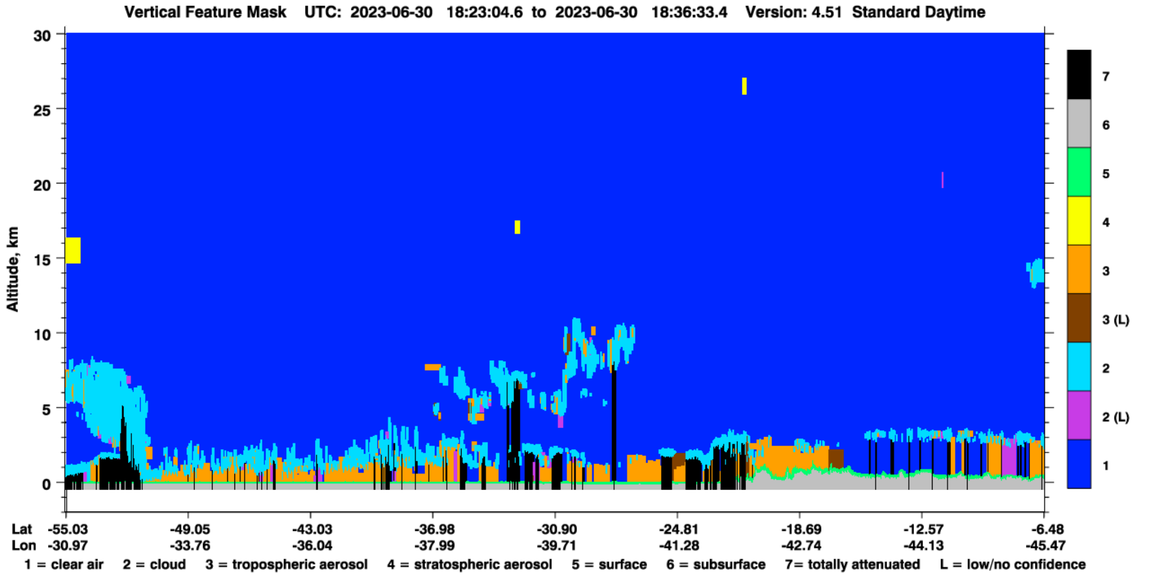
Backup Laser





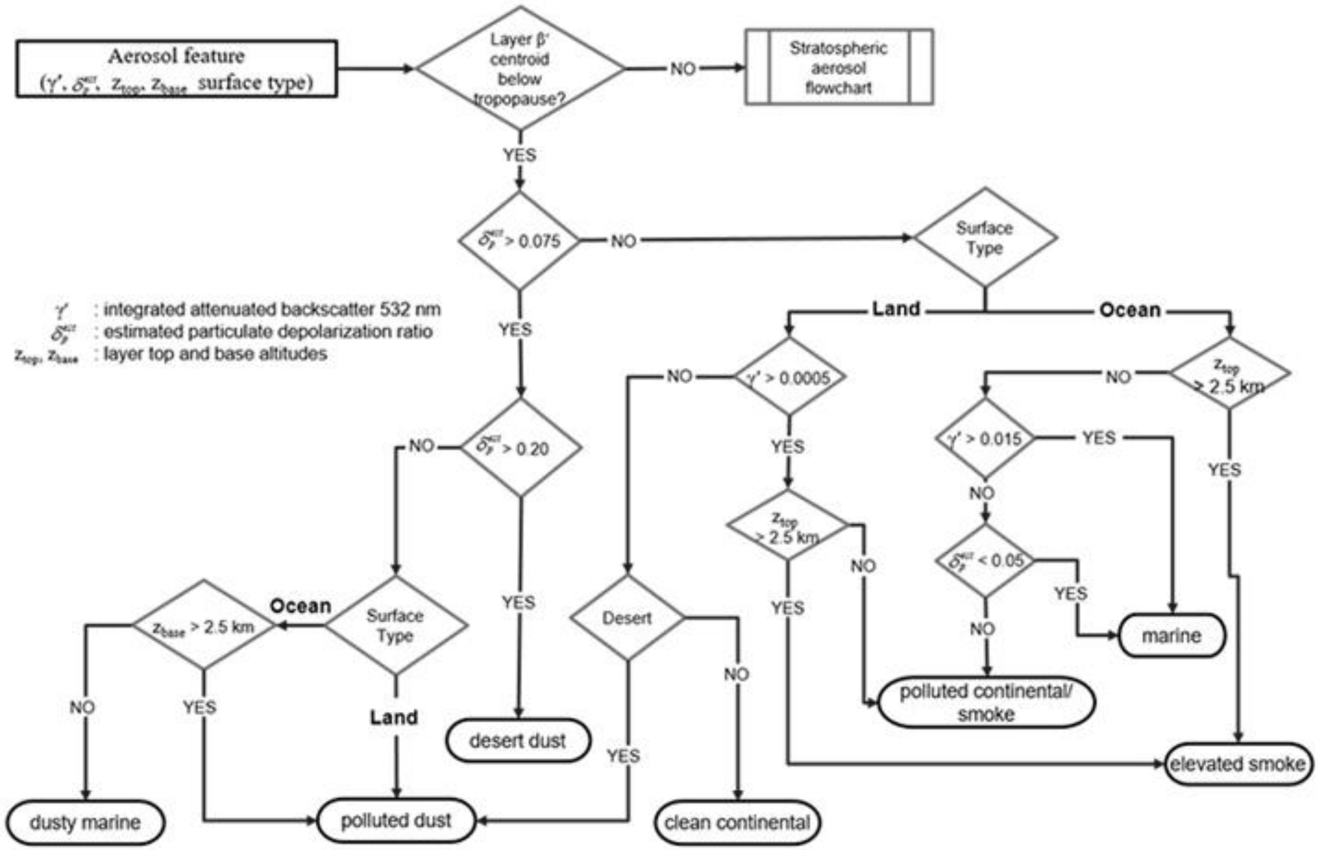
Primary Laser (after 172-month hibernation)



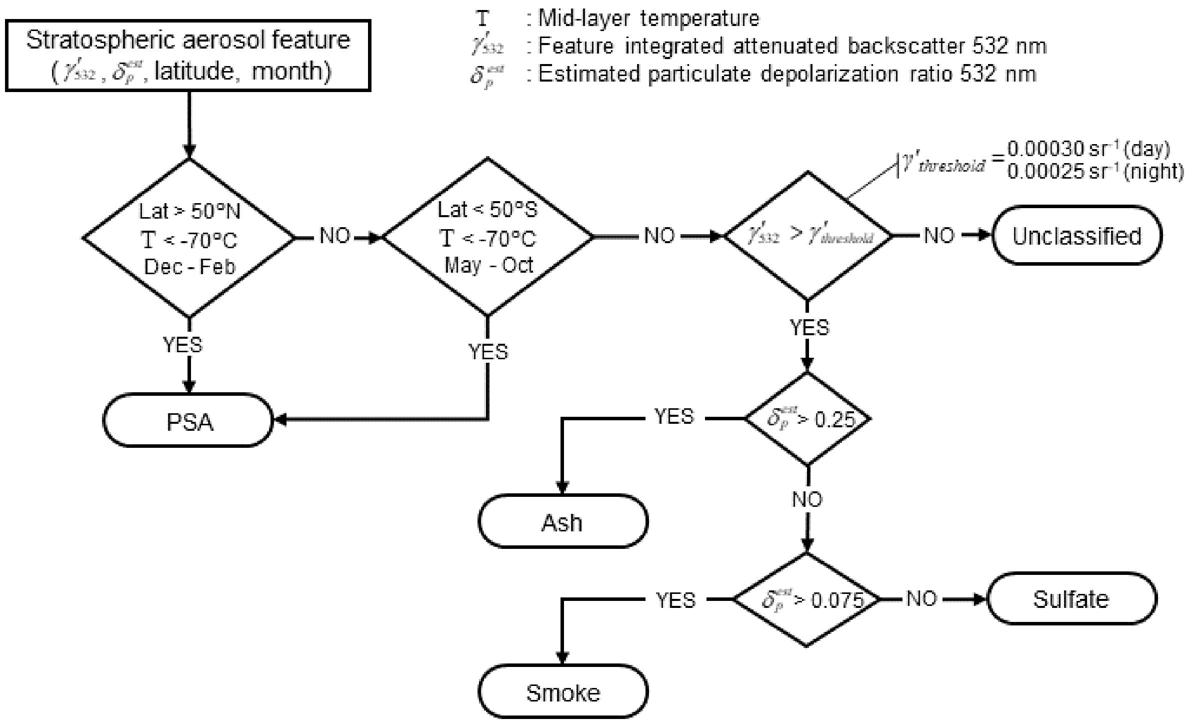


Level 2 Algorithm – Aerosol Subtyping

Tropospheric Algorithm



Stratospheric Algorithm



Flow charts posted on CALIPSO Science Website; https://www-calipso.larc.nasa.gov/