Use of the Density Dimension Algorithm to Identify Tenuous Cloud, Aerosol, Smoke, Dust, and Blowing Snow Layers in Lidar Data from ICESat-2 and CALIPSO Satellites

Camden Opfer[1], Ute Herzfeld[1], Mark Vaughan[1], Stephen Palm[1], Kathleen Powell[1], Thomas Trantow[1], Adam Hayes[1], and Huilin Han [1]

[1]Affiliation not available

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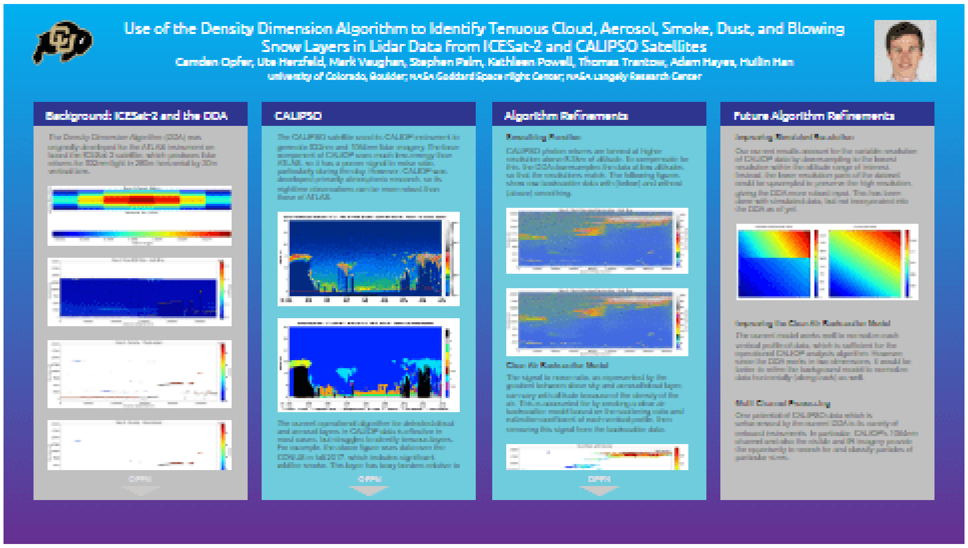

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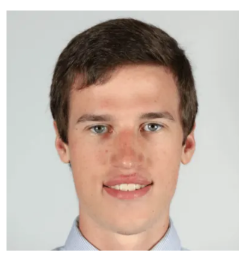
University of Colorado, Boulder; NASA Goddard Space Flight Center; NASA Langely Research Center



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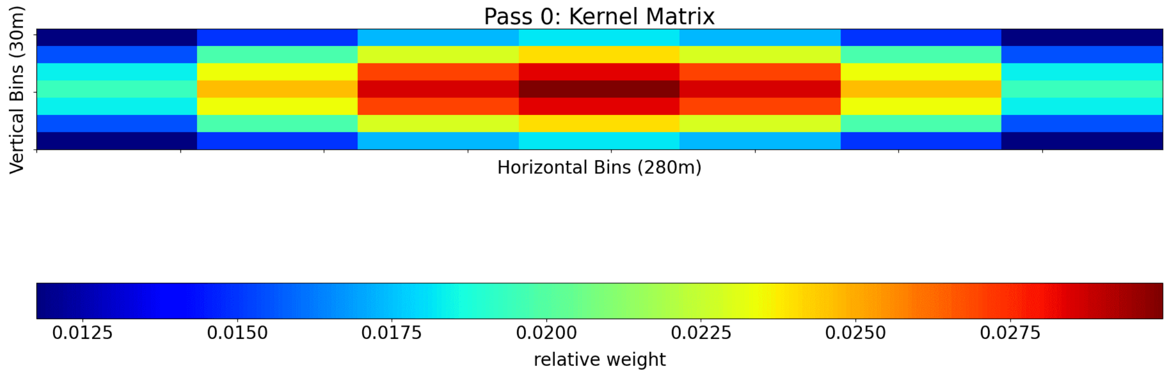
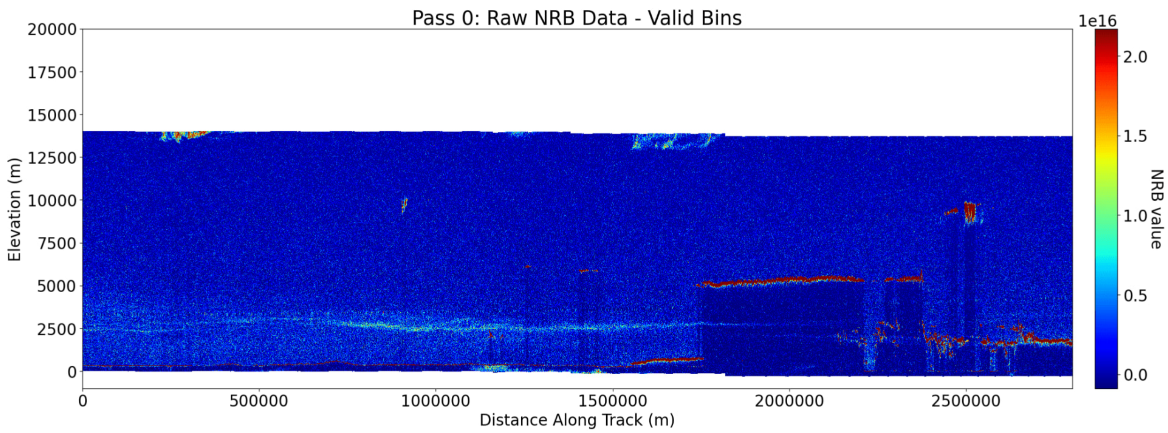
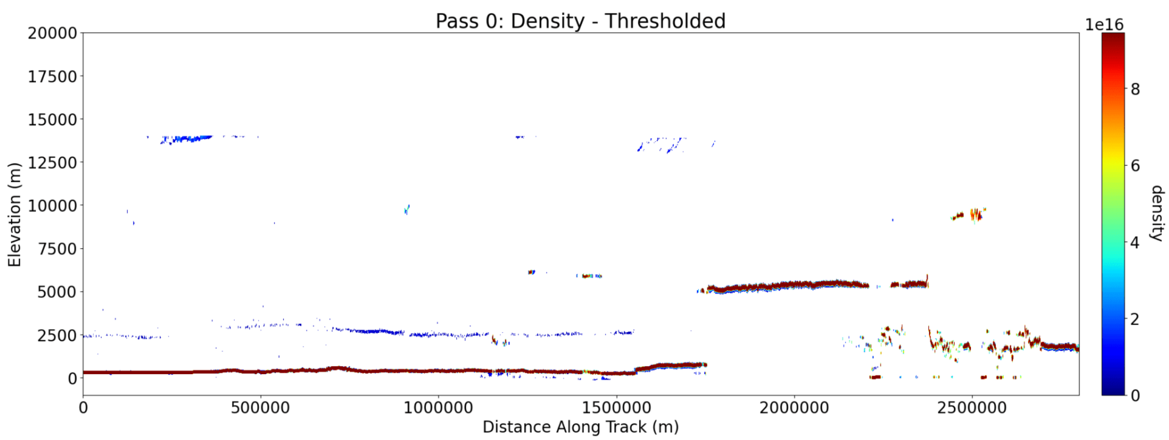
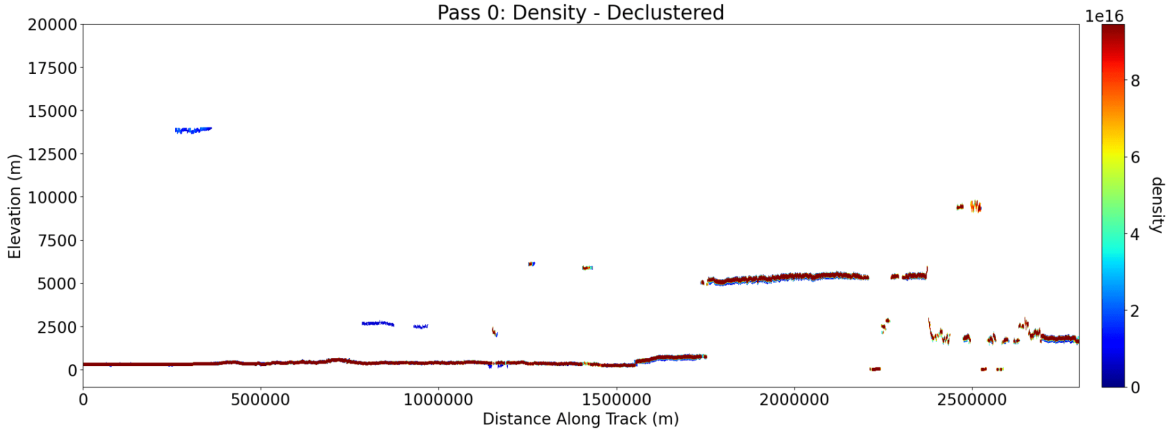
BACKGROUND: ICESAT-2 AND THE DDA

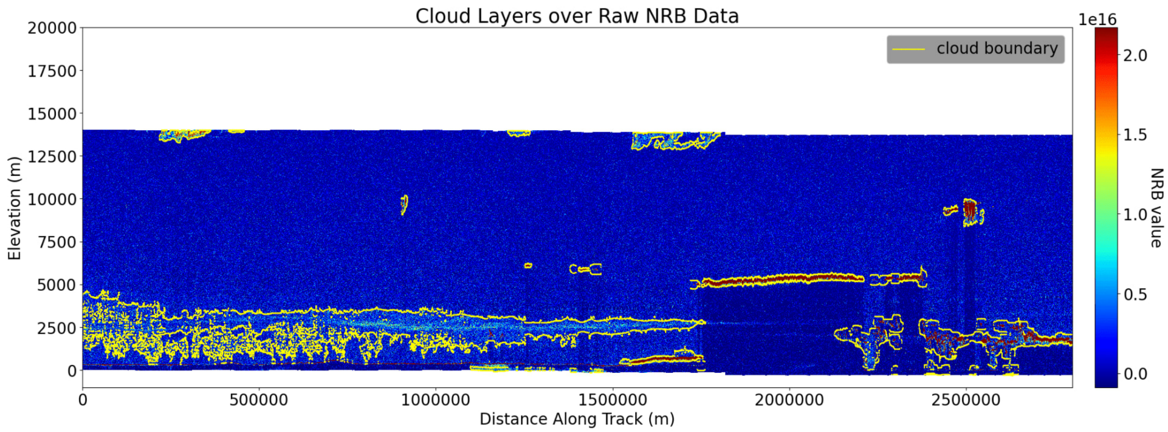
The Density-Dimension Algorithm (DDA) was originally developed for the ATLAS instrument on board the ICESat-2 satellite, which produces lidar returns for 532nm light in 280m horizontal by 30m vertical bins.











DDA-atmos uses an anisotropic Gaussian radial basis function (described by equation below) to calculate weighted photon density. Then a gradient in density represents a change in atmospheric composition.

$$\Phi(x, c) = \Phi(||x - c||_a)$$

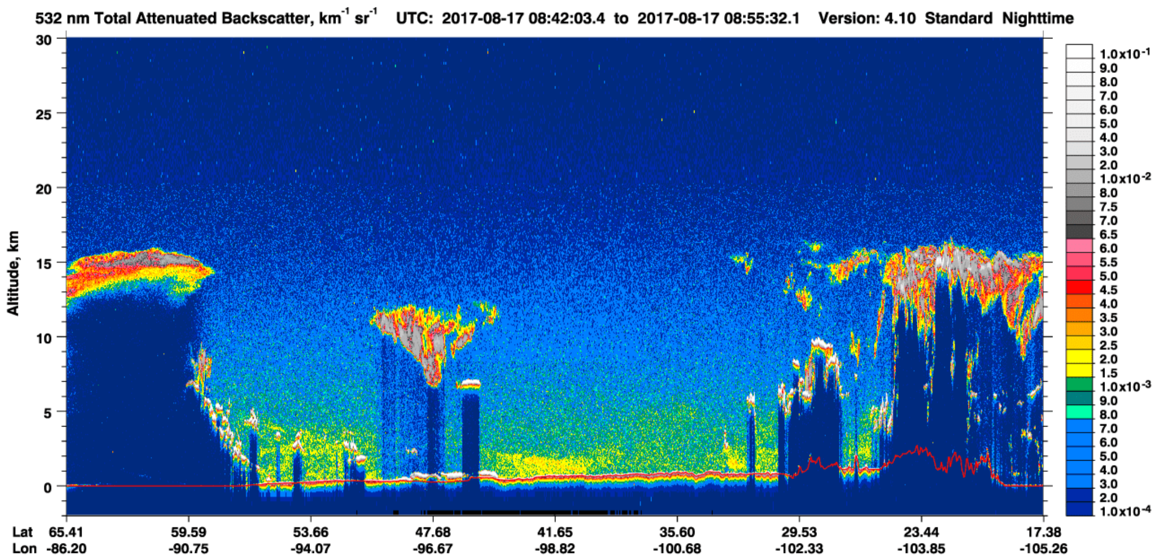
$$\Phi(r) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\left(\frac{||Ar||}{\sqrt{2}\sigma}\right)\right]$$

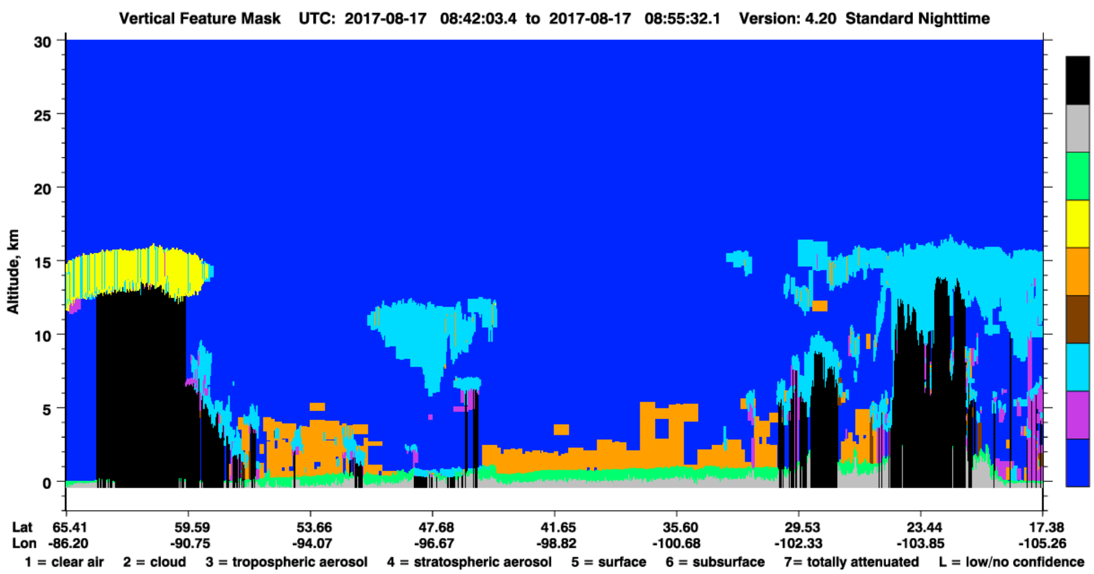
$$A = \begin{bmatrix} \frac{1}{a} & 0 \\ 0 & 1 \end{bmatrix}$$

Aerosol and cloud layers are then identified as regions where the photon density is above a quantile value given as a parameter when running the algorithm. A declustering function removes isolated patches which are too small to physically represent a cloud or aerosol layer. This process is repeated 2 or more times according to user-specified parameters.

CALIPSO

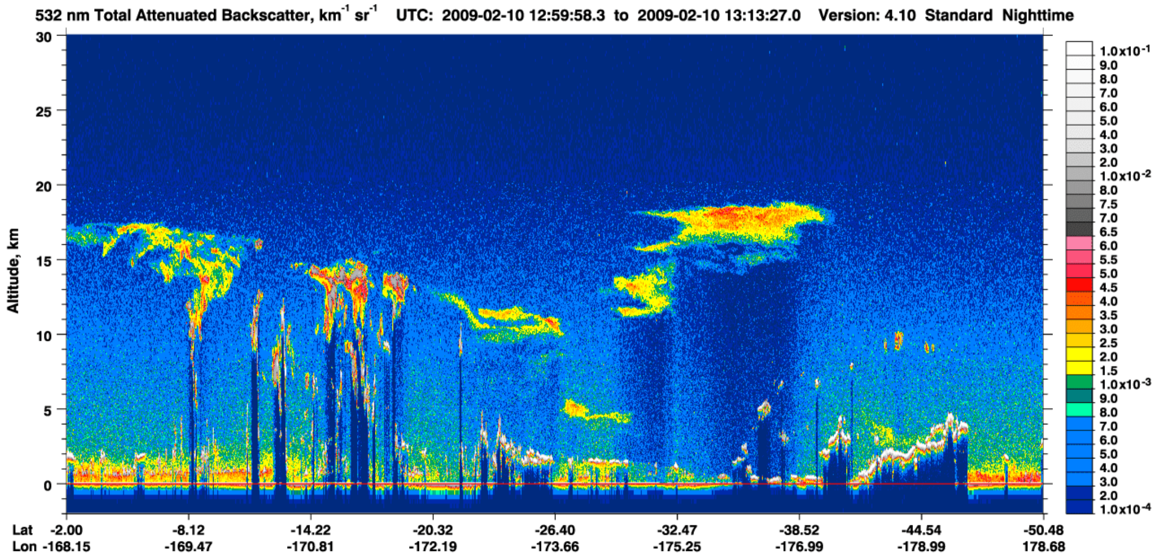
The CALIPSO satellite used its CALIOP instrument to generate 532nm and 1064nm lidar imagery. The laser component of CALIOP uses much less energy than ATLAS, so it has a poorer signal to noise ratio, particularly during the day. However, CALIOP was developed primarily atmospheric research, so its nighttime observations can be more robust than those of ATLAS.

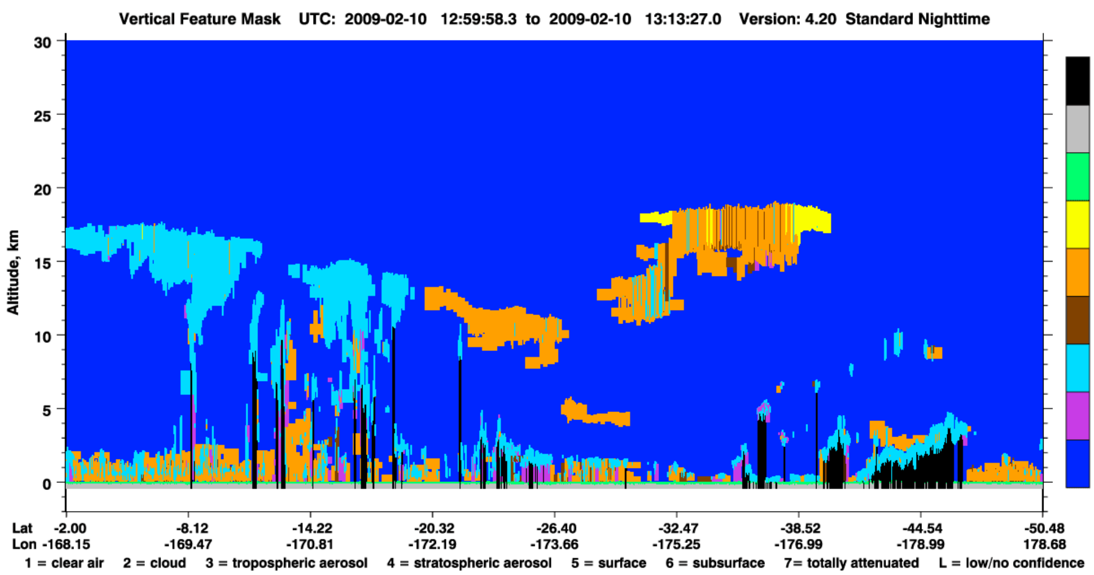




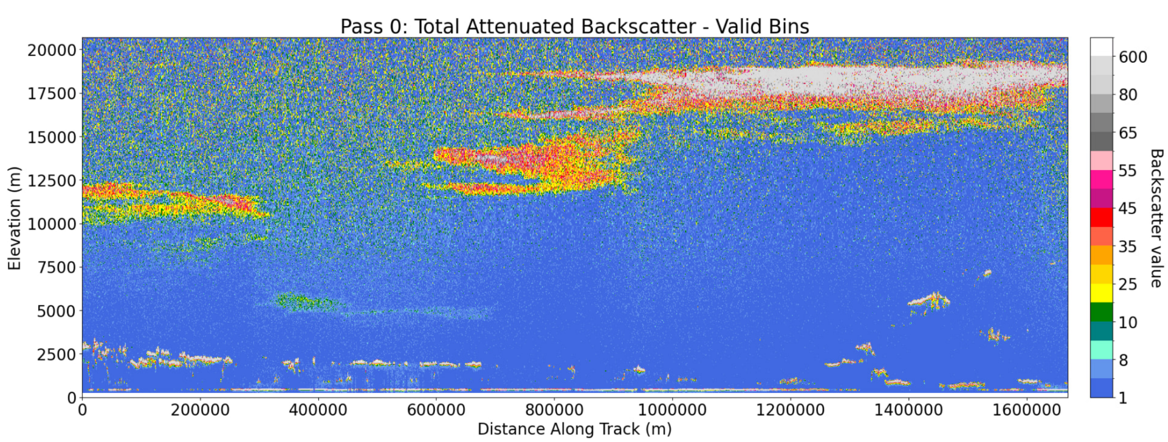
The current operational algorithm for detected cloud and aerosol layers in CALIOP data is effective in most cases, but struggles to identify tenuous layers. For example, the above figure uses data over the CONUS in fall 2017, which includes significant wildfire smoke. This layer has boxy borders relative to the thicker clouds aloft.

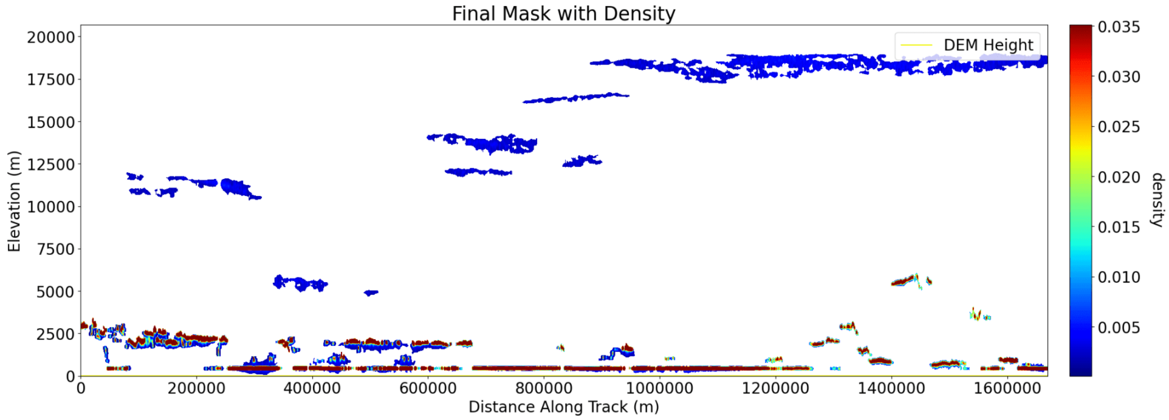
The following example with smoke from the 2009 Black Sunday fires in Australia shows CALIPSO performing slightly better. However, there are still choppy estimates of the near-surface smoke layer on the left-hand side of the figure.





Our lab is working to improve on the weaknesses of the current operational algorithm by employing the DDA on CALIPSO data.



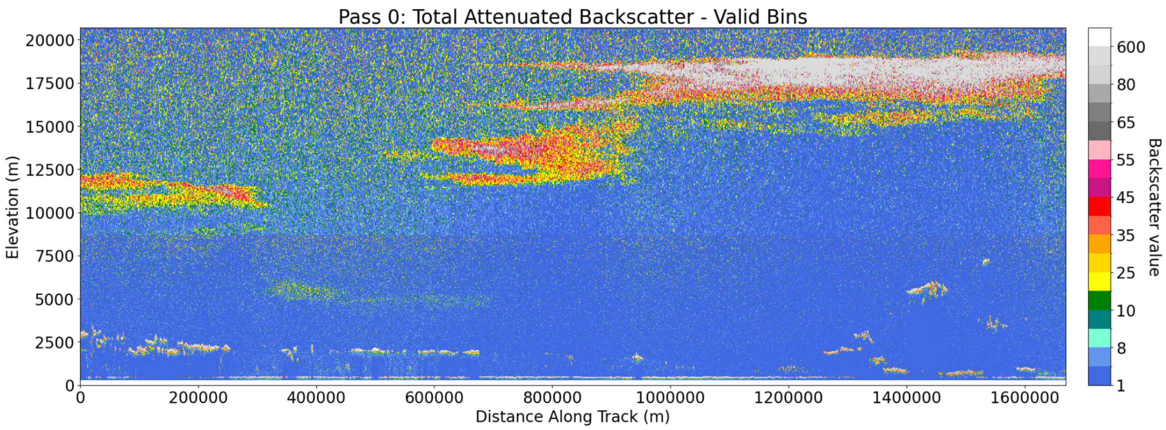


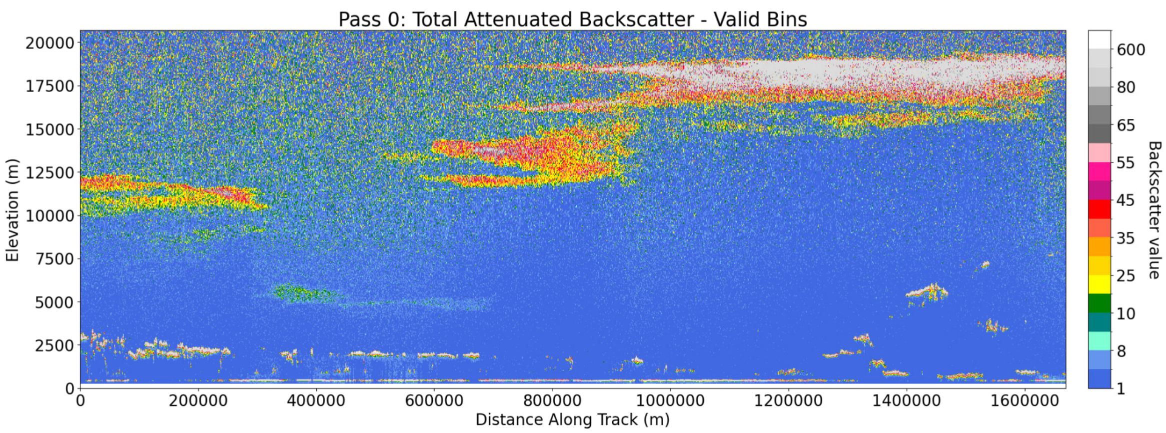
Because of the differences between satellites, simply employing the DDA built for ICESat-2 data does not yield desired results in CALIPSO data, as seen in the figure above, which misses a significant portion of the smoke layer.

ALGORITHM REFINEMENTS

Smoothing Function

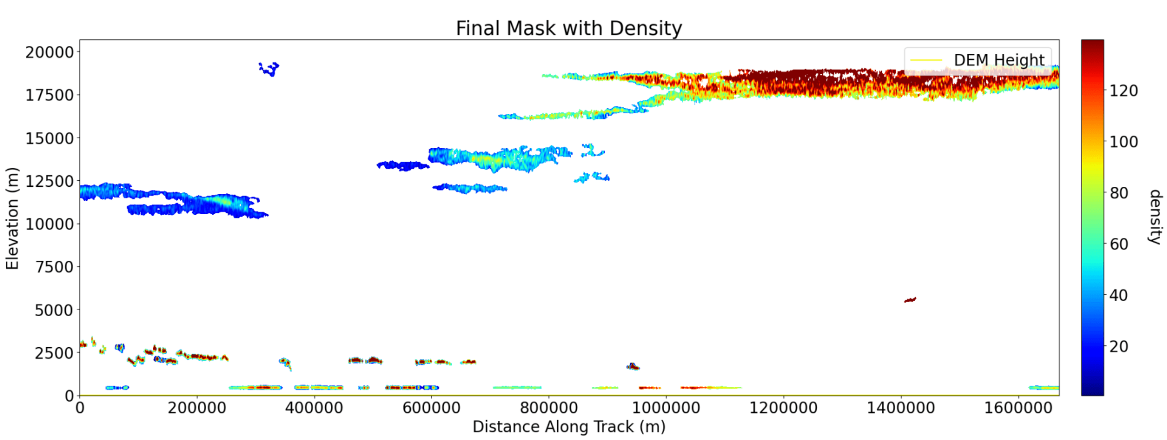
CALIPSO photon returns are binned at higher resolution above 8.3km of altitude. To compensate for this, the DDA downsamples the data at low altitudes so that the resolutions match. The following figures show raw backscatter data with (below) and without (above) smoothing.





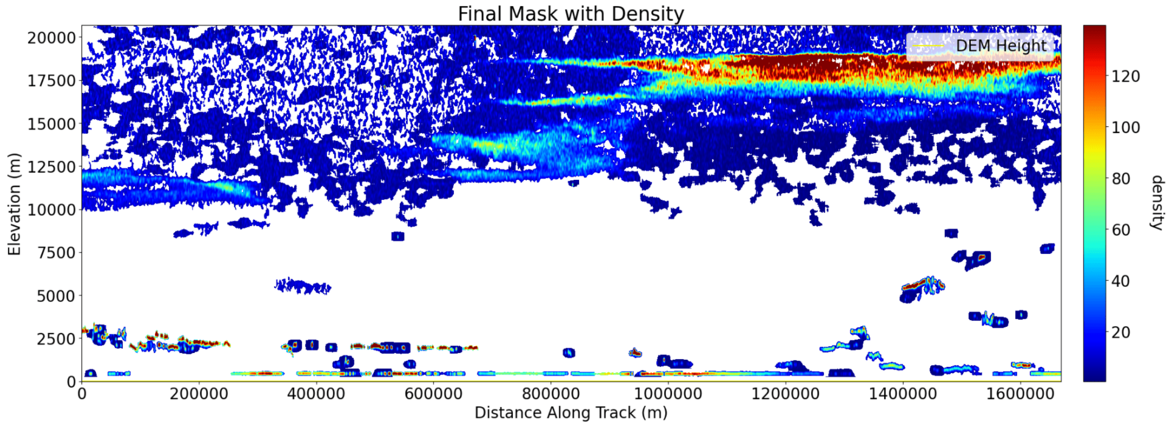
Clear Air Backscatter Model

The signal to noise ratio, as represented by the gradient between clean sky and aerosol/cloud layer, can vary with altitude because of the density of the air. This is accounted for by creating a clear air backscatter model based on the scattering ratio and extinction coefficient of each vertical profile, then removing this signal from the backscatter data.



Density-n

Besides the clean air backscatter model, one strategy expected to increase the accuracy of the DDA is running it for more than two passes. This has been done in the ATL09 product to more effectively resolve tenuous cloud and aerosol layers. However, with CALIPSO observations, noise is added to the aerosol layer before any real improvements can be made.



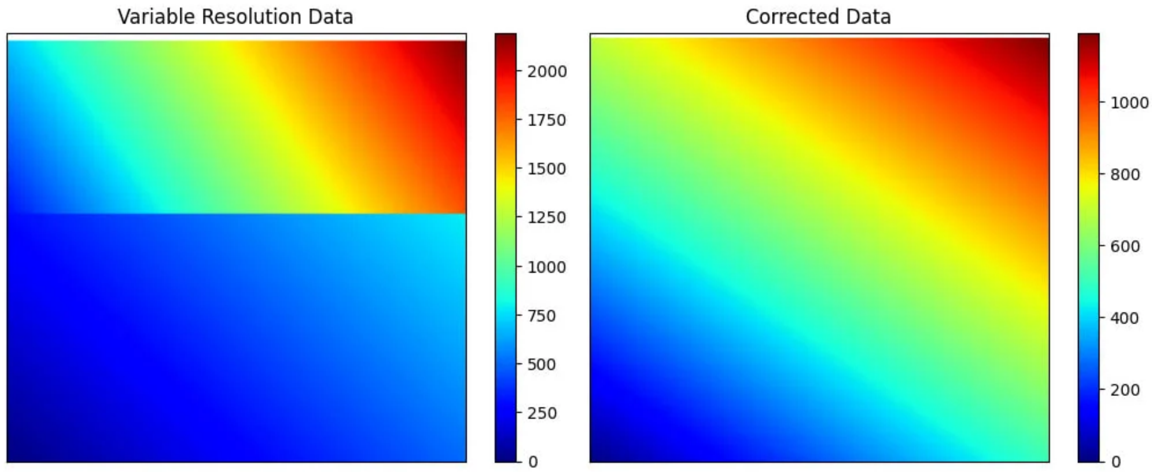
Parameter Combinations

The DDA uses a set of user-defined parameters to determine the size and anisotropy of the kernel used in the RBF, the quantile values used to identify layers, and other properties of the algorithm. Sensitivity studies have been performed to identify optimized parameter sets which can identify both optically thick layers, like this smoke plume, and thinner layers like sparse cirrus clouds.

FUTURE ALGORITHM REFINEMENTS

Improving Simulated Resolution

Our current results account for the variable resolution of CALIOP data by downsampling to the lowest resolution within the altitude range of interest. Instead, the lower resolution parts of the dataset could be upsampled to preserve the high resolution, giving the DDA more robust input. This has been done with simulated data, but not incorporated into the DDA as of yet.



Improving the Clear Air Backscatter Model

The current model works well to normalize each vertical profile of data, which is sufficient for the operational CALIOP analysis algorithm. However, since the DDA works in two dimensions, it would be better to refine the background model to normalize data horizontally (along track) as well.

Multi-Channel Processing

One potential of CALIPSO data which is unharnessed by the current DDA is its variety of onboard instruments. In particular, CALIOP's 1064nm channel and also the visible and IR imagery provide the opportunity to search for and classify particles of particular sizes.

TRANSCRIPT

ABSTRACT

Thin particulate layers vary widely in composition and in their impacts. From low smoke layers impacting human health to Saharan dust aloft influencing Atlantic hurricane growth, these layers warrant high quality, consistent detection through remote sensing methods. However, many algorithms applied to satellite lidar observations are unable to identify such layers.

This presentation will introduce the Density-Dimension Algorithm for Atmospheric Lidar Data (DDA-Atmos) as a means of delineating the location of tenuous layers, especially cirrus clouds, smoke plumes, Asian and Saharan dust, blowing snow, and diamond dust. The DDA-Atmos uses the radial basis function, in combination with auto-adaptive thresholding, to quantify and interpret the spatial density of photon returns. This approach was originally developed for the ICESat-2 ATLAS instrument, and algorithm improvements continue to be made in order to more universally detect thin, spatially dispersed, atmospheric layers.

The DDA-Atmos is also being modified to analyze data from the CALIPSO satellite's CALIOP sensor. This extension of the algorithm provides access to a rich dataset intended primarily for atmospheric analysis. The results produced by this adapted DDA-Atmos will be discussed.

REFERENCES

Herzfeld, U., Hayes, A., Palm, S., Hancock, D., Vaughan, M., and Barbieri, K. (2021a).
Detection and Height Measurement of Tenuous Clouds and Blowing Snow in ICESat-2 ATLAS Data.
Geophysical Research Letters, 48, DOI: 10.1029/2021GL093473.

Palm, S., Yang, Y., Herzfeld, U., and Hancock, D. (2022a).
ICESat-2 Algorithm Theoretical Basis Document for the Atmosphere, Part I: Level 2 and 3 Data Products,
Version 8.6, August 15, 2022.
NASA ICESat-2 Project, DOI: 10.5067/H975R4YYVIT6.

Vaughan, M., Pitts, M., Trepte, C., Winker, D., Detweiler, P., Garnier, A., Getzewich, B., Hunt, W.,
Lambeth, J., Lee, K., et al. (2020).
Cloud-aerosol lidar infrared pathfinder satellite observations (calipso) data management system data
products catalog, release 4.92, nasa langley research center document pc-sci-503.

Vaughan, M. A., Powell, K. A., Winker, D. M., Hostetler, C. A., Kuehn, R. E., Hunt, W. H., Getzewich,
B. J., Young, S. A., Liu, Z., and McGill, M. J. (2009).
Fully automated detection of cloud and aerosol layers in the calipso lidar measurements.
Journal of Atmospheric and Oceanic Technology, 26(10):2034–2050.