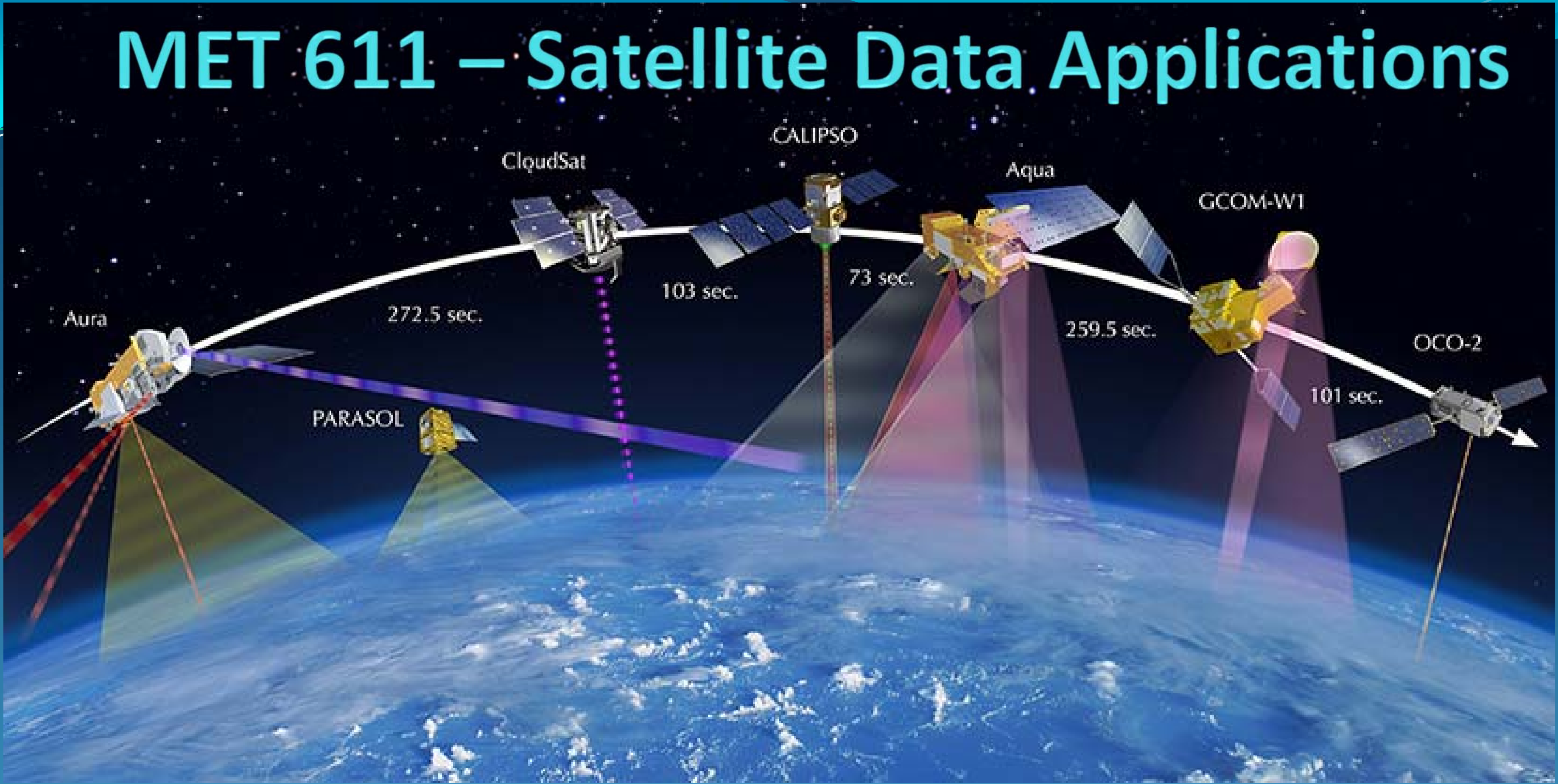
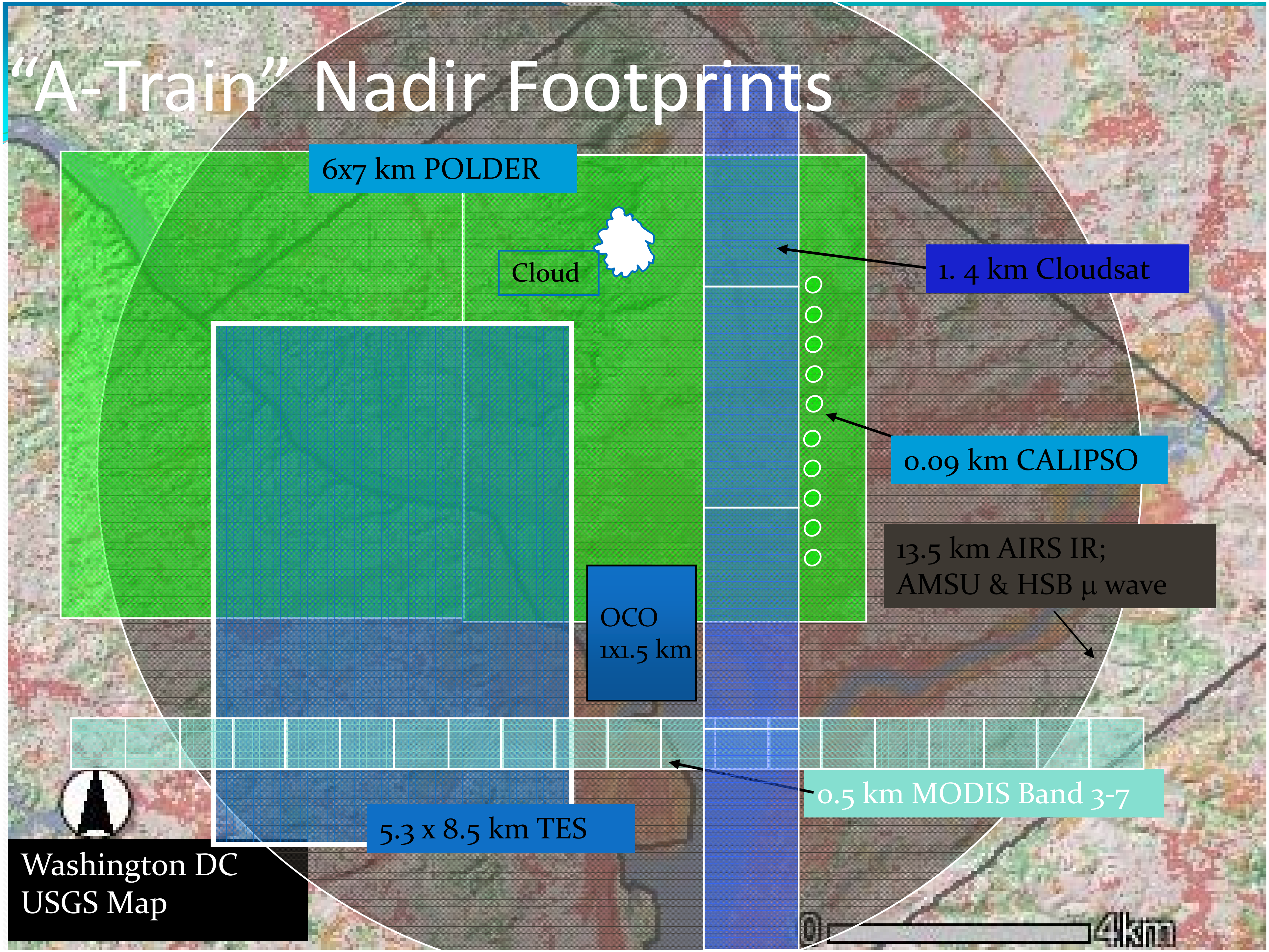
MET 611 – Satellite Data Applications



CALIOP Aerosol

Jennifer D. S. Griswold

“A-Train” Nadir Footprints


6x7 km POLDER

Cloud

1. 4 km Cloudsat

0.09 km CALIPSO

13.5 km AIRS IR;
AMSU & HSB µ wave

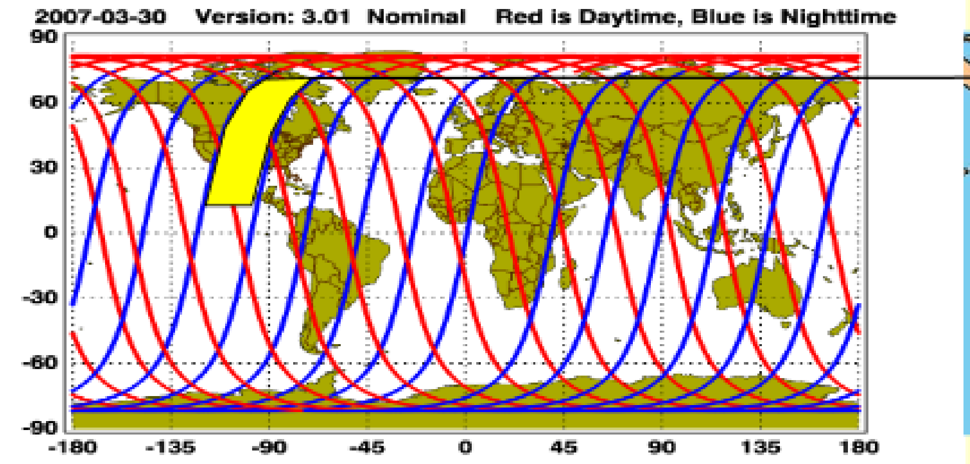
OCO
1x1.5 km

0.5 km MODIS Band 3-7

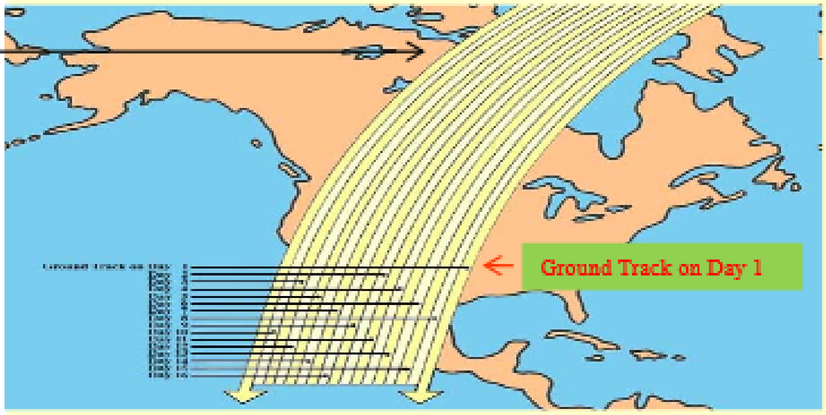
5.3 x 8.5 km TES

Washington DC
USGS Map

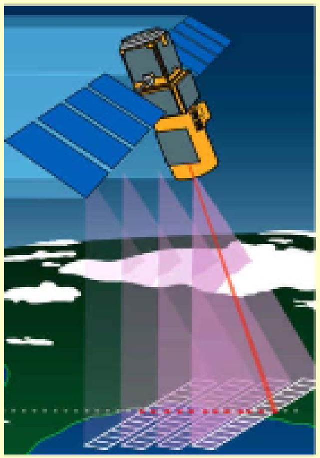
CALIPSO Spatial and Temporal Coverage

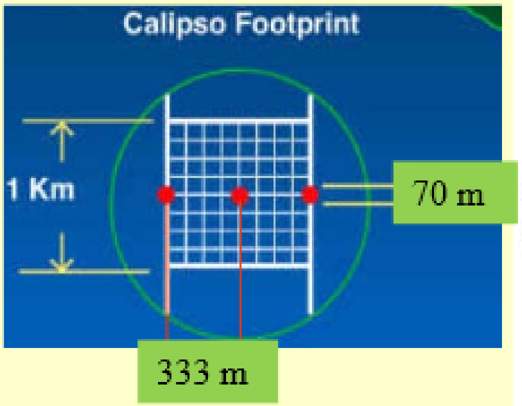


- 1 day coverage area, Cover whole area: 16 days

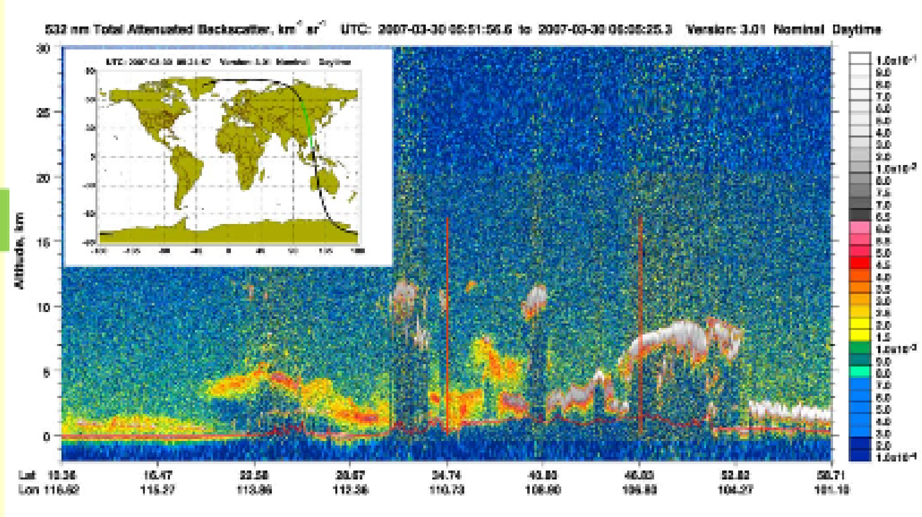


- Cover whole area: 16 days



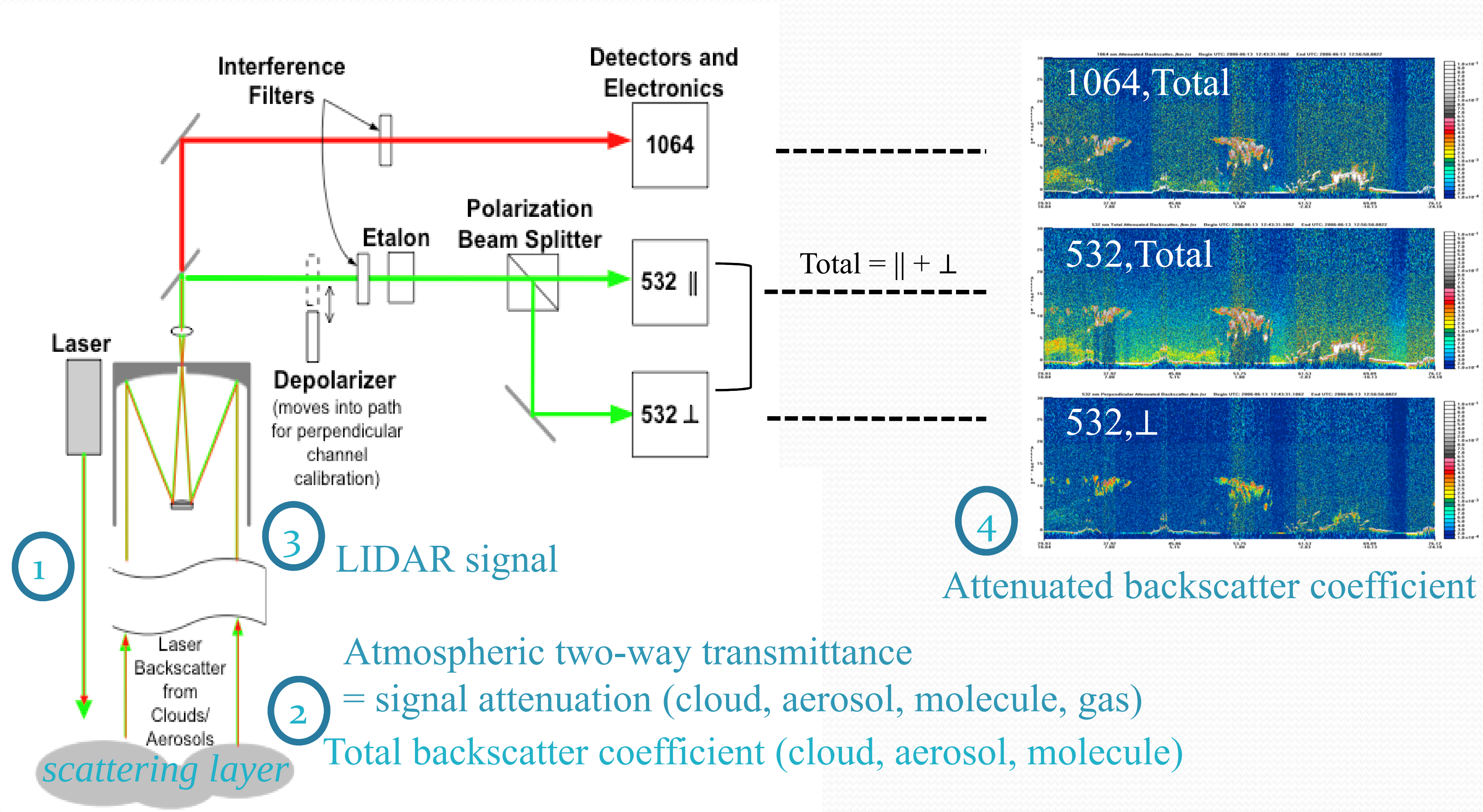


- Footprint (70m) spacing: 333 m (1 km~3 points)



- 532 nm total attenuated backscatter, km^{-1} sr^{-1} (Level 1B data)

How does CALIOP work?



③ LIDAR signal

④ Attenuated backscatter coefficient

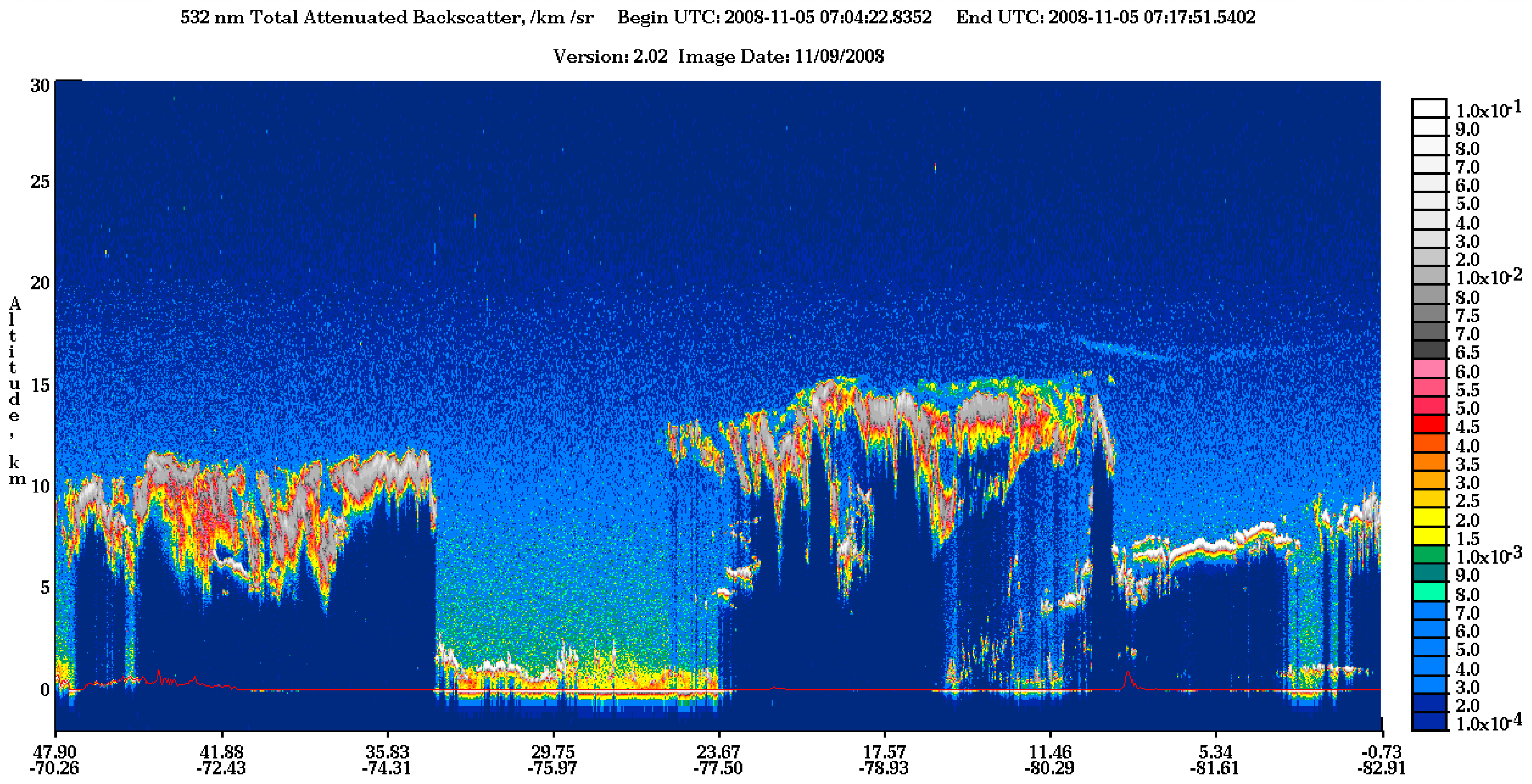
② Atmospheric two-way transmittance
= signal attenuation (cloud, aerosol, molecule, gas)
Total backscatter coefficient (cloud, aerosol, molecule)

Lidar Signal Interpretation

β'_{532}	$\beta'_{532\perp}$	β'_{1064}	Particle Type
Enhanced Signal	Enhanced Signal	Same intensity as 532	Non-Spherical Coarse
Enhanced Signal	Enhanced Signal	Lower intensity than 532	Non-Spherical Fine
Enhanced Signal	Non Enhanced Signal	Same intensity as 532	Spherical Coarse
Enhanced Signal	Non Enhanced Signal	Lower intensity than 532	Spherical Fine

CALIPSO

- **"Curtain"**



532 nm Total Attenuated Backscatter, /km /sr Begin UTC: 2008-11-05 07:04:22.8352 End UTC: 2008-11-05 07:17:51.5402

Version: 2.02 Image Date: 11/09/2008

CALIPSO products

Version 3.3 Product	Primary Parameter	Resolution due to averaging	
		Horizontal	Vertical (<8km)
Level 1 **Measured**	Total_Attenuated_Backscatter_532 Perpendicular_Attenuated_Backscatter_532 Total_Attenuated_Backscatter_1064	1/3km	30m
Level 2 **LAYER** **Retrieved**	Cloud Layer_Top/ Base_Altitude	1/3, 1, 5km	30m
	Aerosol Layer_Top/ Base_Altitude	5km	30m
Level 2 **PROFILE** **Retrieved**	Cloud and Aerosol Total_Backscatter_Coefficient_532 Extinction_Coefficient_532	5km	60m
Level 2 **Vertical Feature Mask** **Retrieved**	Feature_Classification_Flags	5km	30m

Cloud Aerosol Discrimination

- The discrimination between clouds and aerosols is performed mainly based on the differences in their optical and physical properties. The algorithm is driven by the **confidence function**

$$f(X_1, X_2, \ldots, X_m) = \frac{p_{\text{cloud}}(X_1, X_2, \ldots, X_m) - p_{\text{aerosol}}(X_1, X_2, \ldots, X_m)k}{p_{\text{cloud}}(X_1, X_2, \ldots, X_m) + p_{\text{aerosol}}(X_1, X_2, \ldots, X_m)k},$$

  - where p_{cloud} and p_{aerosol} are the multidimensional PDFs, respectively, for clouds and aerosols, as a function of attributes X1, X2, . . . , Xm.

  - *k* is a scaling factor that is related to the ratio of the numbers of aerosol layers and cloud layers and is determined based on the measurement.
    - It may vary depending on locations, altitudes, and seasons.

Cloud Aerosol Discrimination (CAD)

- **Attributes X1, X2, . . . , Xm can be**
  - lidar observables:
    - backscatter intensity
    - wavelength dependency
    - depolarization ratio
    - layer heights
  - or ancillary parameters
    - temperature
    - pressure
    - location
    - season

$$f(X_1, X_2, \ldots, X_m) = \frac{p_{\text{cloud}}(X_1, X_2, \ldots, X_m) - p_{\text{aerosol}}(X_1, X_2, \ldots, X_m)k}{p_{\text{cloud}}(X_1, X_2, \ldots, X_m) + p_{\text{aerosol}}(X_1, X_2, \ldots, X_m)k},$$

- The function *f* is a normalized differential probability. Its value ranges from -1 to 1.
  - Within the CALIOP level 2 layer products, a percentile (integer) value **of *f* ranging from -100 to 100** is reported as the "**CAD** score" characterizing each feature.

Feature Identification

- The identification of a feature as either **cloud** or **aerosol** is performed based on the **sign of the CAD score**.
  - **If $f(X_1, X_2, \ldots, X_m) > 0$**
    - then the probability that $[X_1, X_2, \ldots, X_m]$ represents a cloud is **larger** than the probability that $[X_1, X_2, \ldots, X_m]$ represents an aerosol, and the feature is therefore classified as a **cloud**.
  - **Otherwise, if $f(X_1, X_2, \ldots, X_m) < 0$**
    - the cloud probability is **smaller than the aerosol probability**, and so the feature is classified as an aerosol.
  - **When $f(X_1, X_2, \ldots, X_m) = 0$**
    - the probability that the feature represented by $[X_1, X_2, \ldots, X_m]$ is a **cloud is equal to its probability of being an aerosol**, and thus the classification is **indeterminate**.

Feature Identification

- In regions where |*f*| = 1 (or |CAD| = 100), the classification can be made unambiguously.

- The **absolute value of the CAD score** provides a confidence level for the classification:
  - the **larger the magnitude of the CAD score**, the **higher the confidence that the classification is correct**.

- Theoretically, an absolute value of **100** therefore indicates **complete confidence**.

- **Absolute values less than 100**, corresponding to regions where the cloud and aerosol PDFs overlap**, indicate some ambiguity in the classification**.
  - In this case, a definitive classification cannot be made
  - although they can provide a "best guess" classification, this guess could be wrong.

Success Rate of Classification

- Theoretically, a **success rate R_s** (or a failure rate R_f), defined as the **ratio of correctly classified events to the total number of events** ($R_f = 1 - R_s$), is related to f by (Liuet al. 2005)

$$R_s(X_1, X_2, \ldots, X_m) = [1 + |f(X_1, X_2, \ldots, X_m)|]/2.$$

- The performance of the classification is limited essentially by the degree of the overlap in the cloud and aerosol PDFs
  - the **smaller the overlap region**, the more complete the separation between the cloud and aerosol distributions, and **the better the classification performance**.

Reducing PDF Overlaps

- To reduce the overlap, PDFs with a **larger number of attribute dimensions** are desired
  - separation between the cloud and aerosol clusters is more complete in a higher-dimensional space (Liu et al.2004).

- In principle, **as many of the available observables as possible should be used to achieve the best performance**.

- The addition of an attribute dimension **may not improve** the classification significantly if the attribute to be added is not totally independent from the other attributes used.
  - Some practical issues such as **computing time** and the **latency of any ancillary data** should also be considered when selecting attribute dimensions for operational classification.

Selecting Attributes – Cloud and Aerosol Discrimination

- A very strong preference should be given to the **intrinsic properties of features**:
  - **physical** and **optical characteristics** of the feature that depend solely on the layer composition and **are independent of particle concentration**.

- In many cases estimates of the intrinsic properties of a feature **can only be obtained after computing** (and subsequently correcting for) **the extinction profile within the feature**.

  - **The dilemma:**
    - deriving the extinction solution requires an estimate of the feature lidar ratio, this estimate in turn is derived from an assessment of layer type.

    - Because the CAD is the first step of the scene classification analysis that is performed before the extinction coefficient is retrieved by HERA, some intrinsic attributes (e.g., the particulate backscatter color ratio) are not available for use and, thus, are replaced by the corresponding extrinsic feature properties (e.g., the attenuated backscatter color ratio).

Development PDFs

- The core part of the cloud and aerosol classification is based on **multidimensional PDFs of clouds and aerosols.**

- Attributes of:
  - **layer-averaged attenuated backscatter** (β')
  - **attenuated total backscatter color ratio** (χ')
  - **and mid-layer heights** (z)
  - have been selected in the prelaunch version (version 1) that was used in the first lidar data release (Liu et al. 2004) and in version 2 of the CAD algorithm.

- The f function can then be rewritten as

$$f(\beta'_{532}, \chi', z) = \frac{p_{\text{cloud}}(\beta'_{532}, \chi', z) - p_{\text{aerosol}}(\beta'_{532}, \chi', z)k}{p_{\text{cloud}}(\beta'_{532}, \chi', z) + p_{\text{aerosol}}(\beta'_{532}, \chi', z)k},$$

Development PDFs

$$f(\beta'_{532}, \chi', z) = \frac{p_{\mathrm{cloud}}(\beta'_{532}, \chi', z) - p_{\mathrm{aerosol}}(\beta'_{532}, \chi', z)k}{p_{\mathrm{cloud}}(\beta'_{532}, \chi', z) + p_{\mathrm{aerosol}}(\beta'_{532}, \chi', z)k},$$

- Where:

$$\beta' = \frac{1}{(i_{\mathrm{base}} - i_{\mathrm{top}} + 1)} \sum_{i=i_{\mathrm{top}}}^{i_{\mathrm{base}}} B(z_i),$$

$$\chi' = \frac{\beta'_{1064}}{\beta'_{532}}$$

- and B is the **attenuated backscatter coefficient** at range z_i with additional corrections for the effects of **molecular** and **ozone attenuations** applied.

Development PDFs

- PDFs are implemented as a **100 x 100 x 20 three-dimensional array**.
- The attenuated backscatter dimension of the PDFs is logarithmic
  - 100 elements starting **at $\ln(\beta')$ = -12** with an **increment of 0.14**.
- The attenuated total backscatter color ratio dimension also has 100 elements
  - **starting at χ' = 0 with increments of 0.02**
- The mid-layer altitude dimension is binned for **every 1 km from 0 to 20 km (20 elements).**

Expert Classification

- The cloud and aerosol PDF database has been updated based on **expert manual classification of all layers** detected during one full day of data acquired by CALIOP on 12 August 2006.

- In contrast to the automated production CAD processing that performs feature classifications in isolation, based on the properties of single vertical layer, this expert reclassification identifies features by:
  - **simultaneous inspection of two-dimensional vertical–horizontal images of several different lidar measurements:**
    - attenuated backscatter,
    - attenuated backscatter color ratio,
    - and volume depolarization ratio

Expert Classification

- In addition to χ', β', and mid-layer altitude, this expert reclassification also makes use of additional information:
  - layer structures
  - textures
  - connections with the surrounding layers
  - geographic locations in the assessment of feature types.
- Due to the **large amount of data** that must be examined (e.g., **~0.3 million 5-km layers for the selected day**), manual classification of layer types can be very time consuming.
- For this reason, a computer tool has been **developed to facilitate this kind of image-based manual identification of features by immediately and interactively providing the quantitative, measured data associated with each layer**.
- Despite this computerized assistance and the application of spatial coherence tests, **there remain some cases that cannot be identified with high confidence.**

CAD “bad” Performance

- These cases include:
  - layers at **edges** of clouds
  - **mixed layers** of cloud and aerosol
  - and layers **below dense clouds** whose optical properties are not correctly measured due to the detection issues such as the detector transient response, multiple scattering, etc.
- These layers**, labeled as “no confidence” in the manual classification**, account for **~2%** of the selected day’s manually classified data.

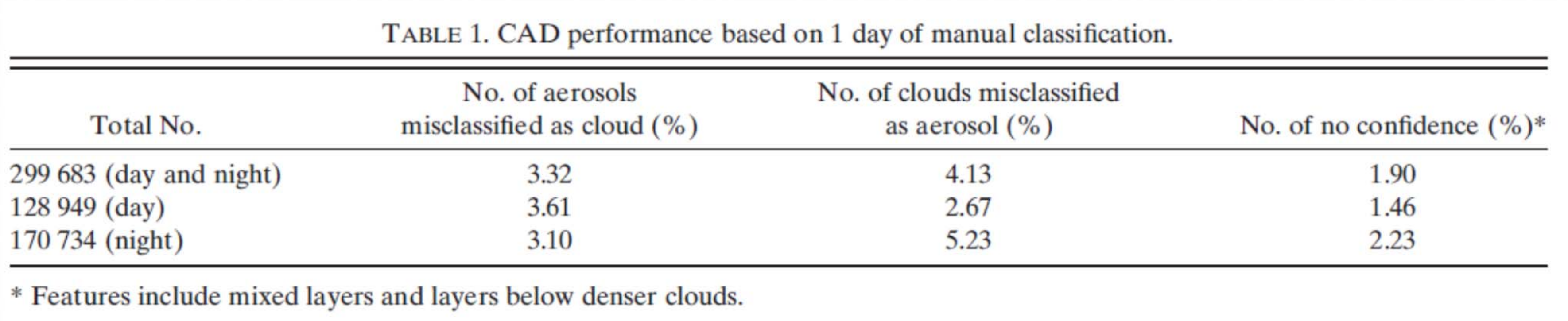


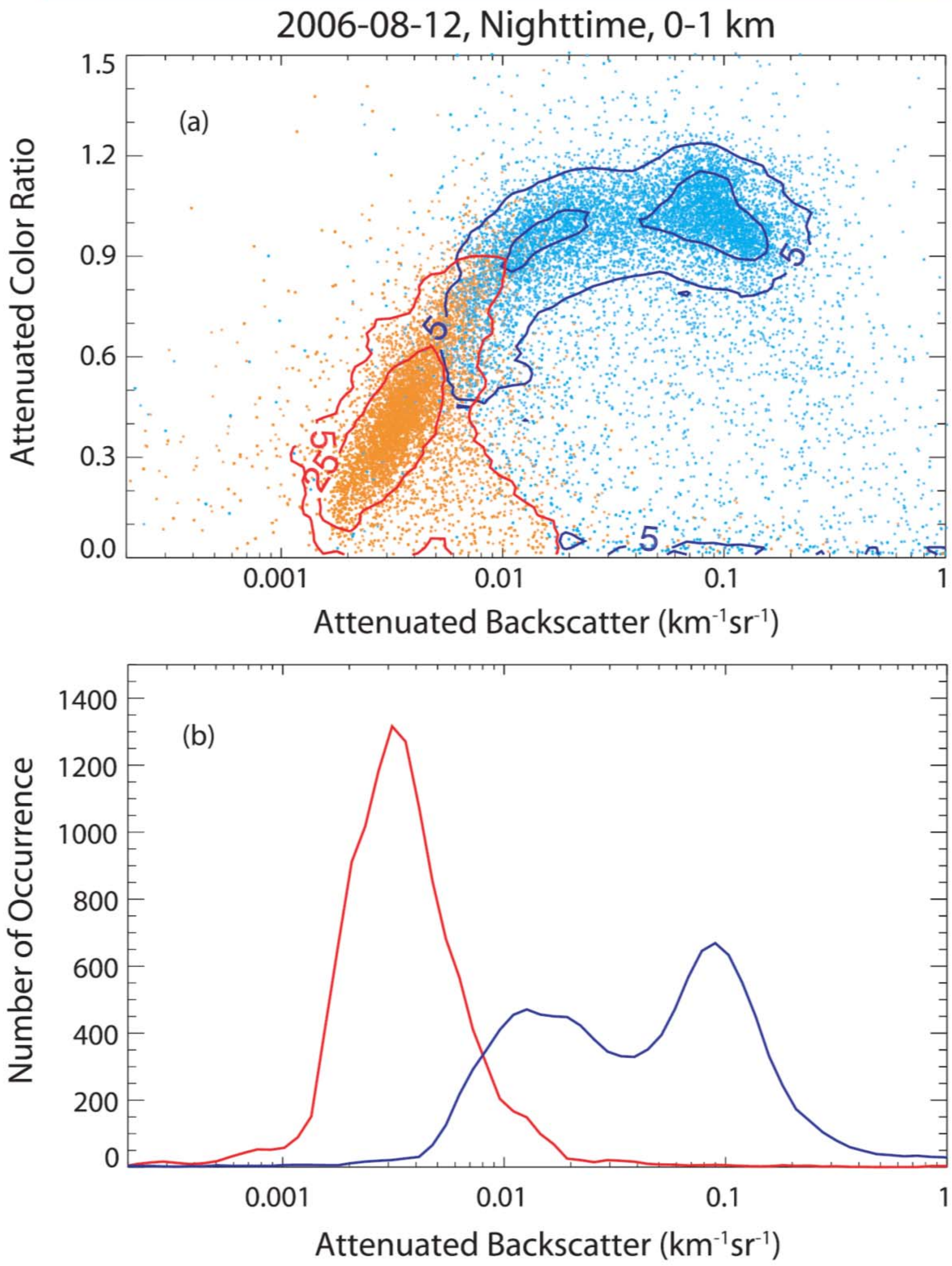
TABLE 1. CAD performance based on 1 day of manual classification.

Total No.	No. of aerosols misclassified as cloud (%)	No. of clouds misclassified as aerosol (%)	No. of no confidence (%)*
299 683 (day and night)	3.32	4.13	1.90
128 949 (day)	3.61	2.67	1.46
170 734 (night)	3.10	5.23	2.23

* Features include mixed layers and layers below denser clouds.

Example

- Figure 1 (Liu et al 2009) presents (a) a combination scatterplot–contour plot in the backscatter–color ratio space and (b) the occurrence distribution as a function of attenuated backscatter of clouds (blue) and aerosols (red) within the 0–1-km altitude range measured by CALIOP on 12 August 2006.
- As seen in Fig. 1, **aerosols generally have smaller backscatter intensities** and **attenuated backscatter color ratios** when compared with clouds, and the two classes are largely separated in the backscatter–color ratio space



Flowchart of the version 2 CAD algorithm

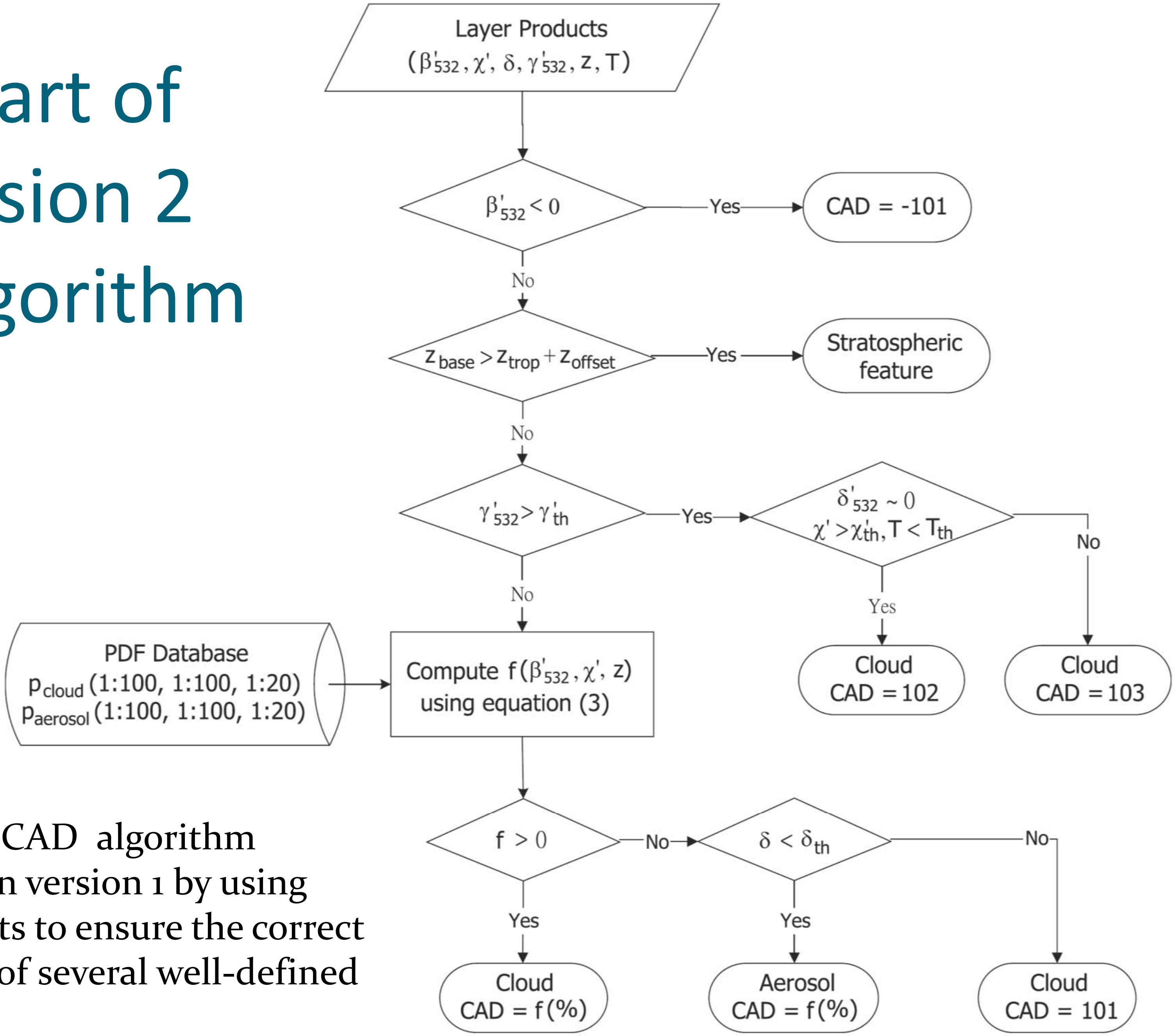


FIG. 2. Flowchart of the version 2 CAD algorithm.

The version 2 CAD algorithm improves upon version 1 by using additional tests to ensure the correct classification of several well-defined special cases.

CAD Special Scores

TABLE 3. Occurrence frequencies for selected CAD score ranges and special scores.

CAD	0 to 20	20 to 70	70 to 100	−101	101	102	103
Aerosol	0.033	0.14	0.83	N/A	N/A	N/A	N/A
Cloud	0.019	0.040	0.95	0.0013	0.0077	0.019	0.09
Total	0.008	0.066	0.92	0.0011	0.0067	0.017	0.08

- In addition to the standard CAD scores, which range between -100 and 100, special CAD scores are also reported in the CALIOP cloud-layer products
  - -101
  - 101
  - 102
  - 103
- These special scores distinguish features/artifacts identified by other tests as described in Fig. 2.
- Figure 5 presents an example of (a) the occurrence distribution and (b) the cumulative occurrence frequency of the CAD score derived from one month (July 2006) of the CALIOP 5-km-layer products data (version 2.01).

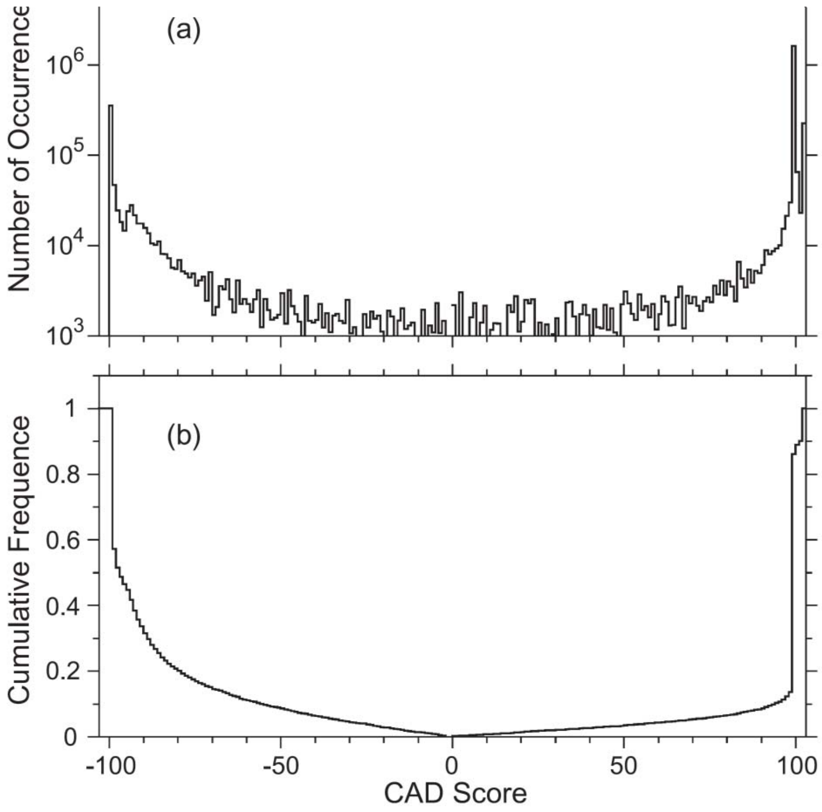


FIG. 5. (a) Number of occurrences and (b) cumulative occurrence frequency of the CAD score derived from one month (July2006) of the CALIOP layer products data (version 2.01).

CAD Special Score Meanings

- The special CAD **score of -101** indicates features that have a negative mean attenuated backscatter.
  - These features should not occur based on the algorithm design. However, they occurred in the current layer products due to some unknown programming reasons.
  - The fraction of these features is very low, ~0.1% of the total tropospheric features, including clouds and aerosols for the one month of data shown in Fig. 5, and they should be eliminated in future data releases.
  - **Layers flagged -101 should never be used**.

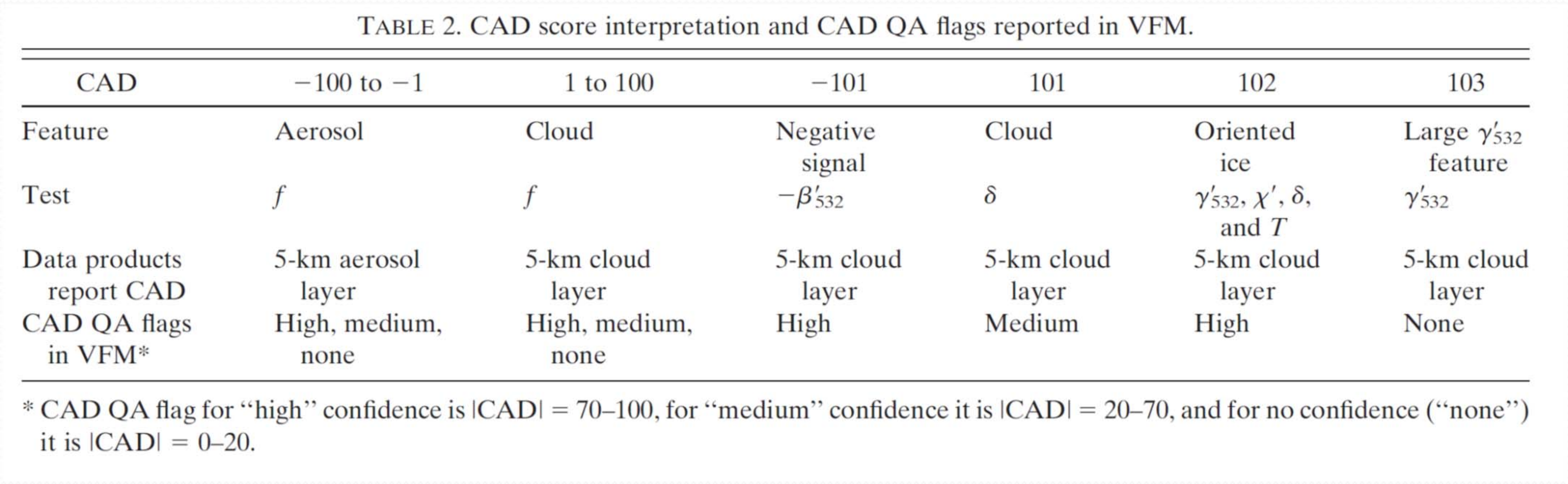


TABLE 2. CAD score interpretation and CAD QA flags reported in VFM.

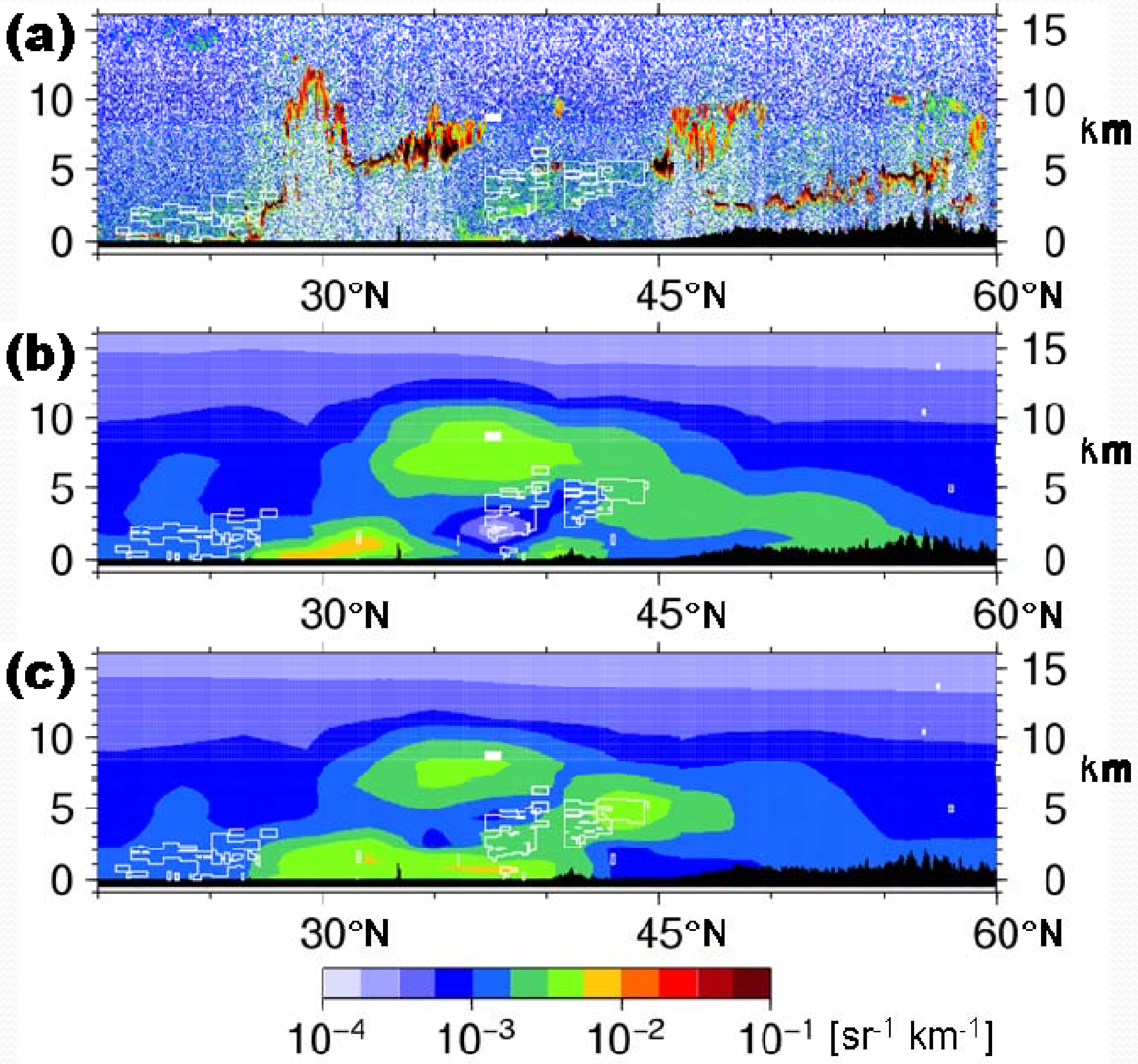
CAD	−100 to −1	1 to 100	−101	101	102	103
Feature	Aerosol	Cloud	Negative signal	Cloud	Oriented ice	Large γ'_{532} feature
Test	f	f	$-\beta'_{532}$	δ	γ'_{532}, χ', δ, and T	γ'_{532}
Data products report CAD	5-km aerosol layer	5-km cloud layer	5-km cloud layer	5-km cloud layer	5-km cloud layer	5-km cloud layer
CAD QA flags in VFM*	High, medium, none	High, medium, none	High	Medium	High	None

* CAD QA flag for "high" confidence is |CAD| = 70–100, for "medium" confidence it is |CAD| = 20–70, and for no confidence ("none") it is |CAD| = 0–20.

CAD Special Score Meanings

- The rest of the special scores (**101**, **102**, and **103**) correspond mostly to genuine atmospheric features.
  - **special score of 101** is assigned to the features that are **classified as cloud** by the depolarization ratio test (the d switch in Fig. 2).
    - About 0.7% of the total features have CAD scores of 101, and these mostly occur at high latitudes.
  - **special score of 102** is assigned to those features that are **highly likely to contain large fractions of oriented ice crystals**.
    - These features account for ~0.2% of the total features.
  - **special score of 103** may be a **mixture of oriented ice crystals with other types of cloud particles**, or a feature whose optical properties are artificial due to improper data processing, or may not be an atmospheric feature.
    - Therefore, caution should be taken in the interpretation and use of this class of features

CALIOP Data Screening by CAD Score



a) CALIOP Level 1B attenuated backscattering coefficients at 532nm;

b) **before** data assimilation in model;
  after data assimilation in model.

c) **after** data assimilation in model.

White squares are areas where the Cloud-Aerosol-Discrimination scores are less than -33.

Algorithm Conventions

- Conventions used in the version 2 CAD algorithm are provided in the following:

a) Only two classes of tropospheric features are defined in the CAD algorithm: “cloud” and “aerosol.”

  - The aerosol class is defined **as all airborne particles**, excluding activated water droplets and frozen ice crystals.
  - This class includes all commonly defined aerosol types (maritime, continental, dust, and smoke).
  - The cloud class is defined as an air mass containing any activated water droplets and/or ice crystals.
  - **All normally defined clouds** (high-, middle-. and low-cloud families) are **included in the cloud class**.

Algorithm Conventions

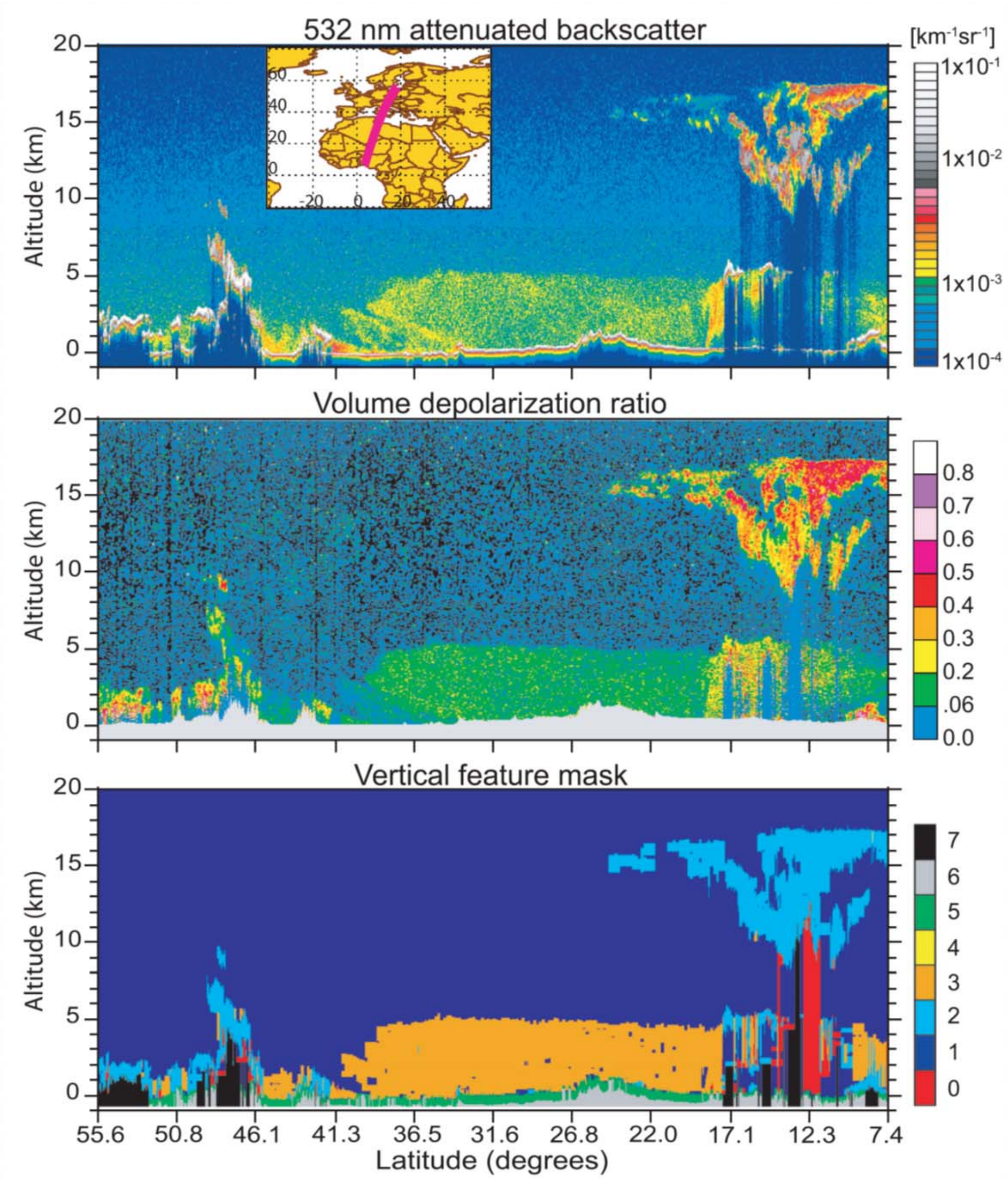
- Conventions used in the version 2 CAD algorithm are provided in the following:
  a) Based on the definition above, a **mixed layer of cloud and aerosol** that is erroneously identified as a single layer by the CALIOP feature finder is **classified as a cloud**.

  b) **Fogs**, in either liquid form or frozen form, are included in the **cloud class**.

  c) **Diamond dust** also belongs to **the cloud** class because it consists mostly of falling ice crystals.

  d) **Hazes belong to the aerosol class**, whereas **mists are classified as clouds**.

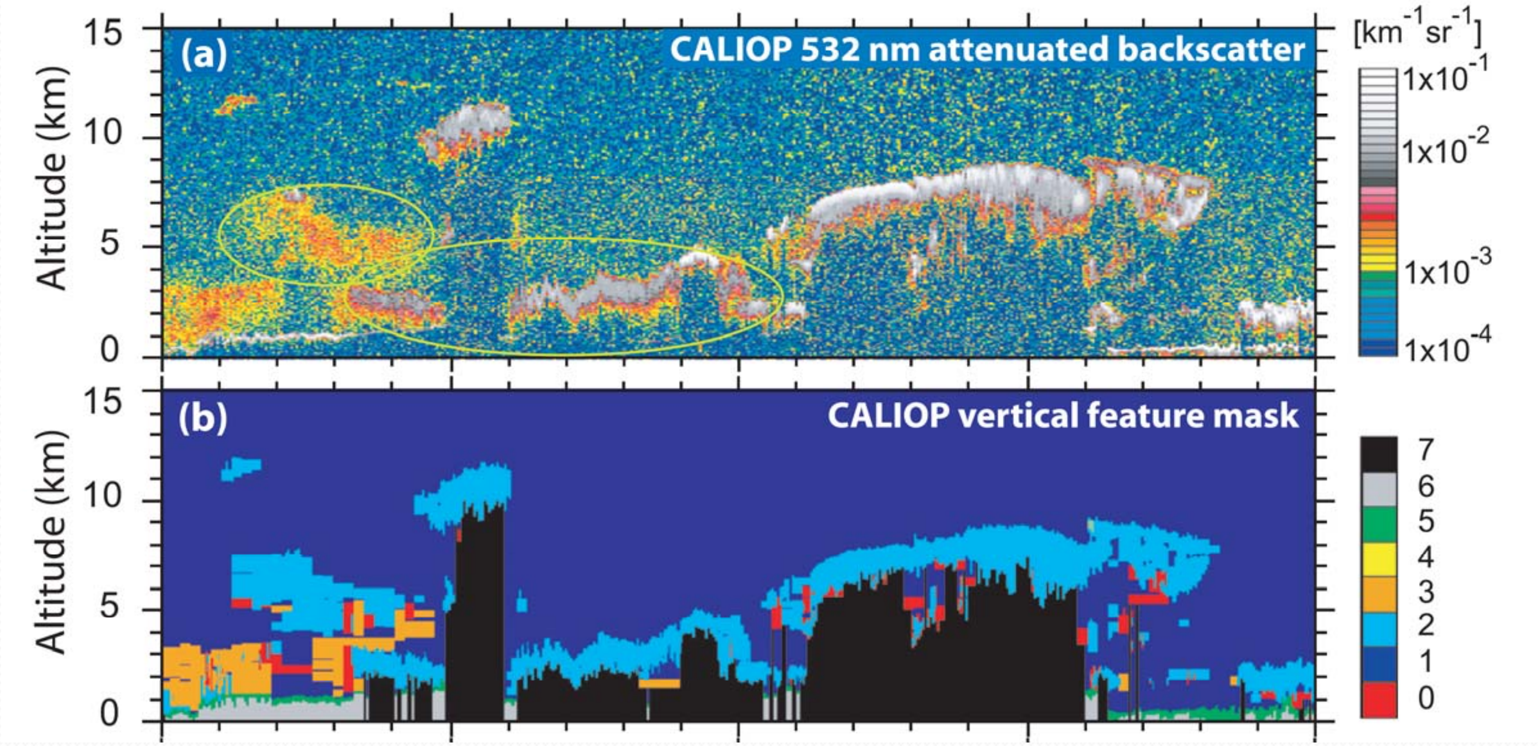
Example Cloud-Aerosol Discrimination



- Example of the cloud and aerosol discrimination measured by CALIOP on 27 Jun 2007 from a nighttime orbit across central and southern Europe and North Africa.
  - (top) Attenuated backscatter at 532 nm, along with the orbit track (pink line)
  - (middle) volume depolarization ratio
  - (bottom) the corresponding classification results.

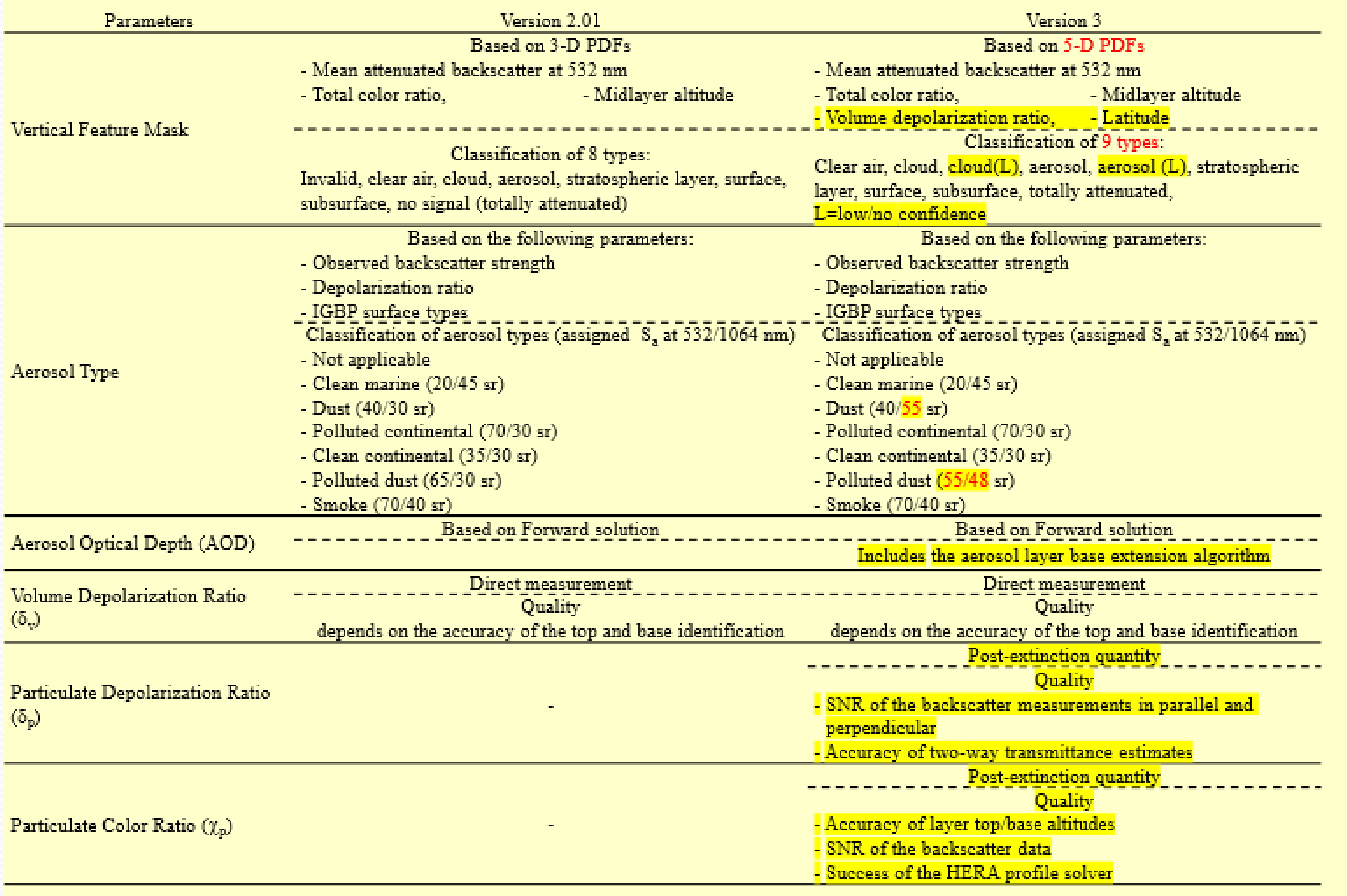
- Feature types in the bottom panel:
  - **0 = invalid (|CAD| , 20 or CAD 5 103);**
  - **1 = clear air**
  - **2 = cloud**
  - **3 = aerosol**
  - **4 = stratospheric feature**
  - **5 = surface**
  - **6 = subsurface**
  - **7 =no signal (total attenuated).**

Example Mis-classification



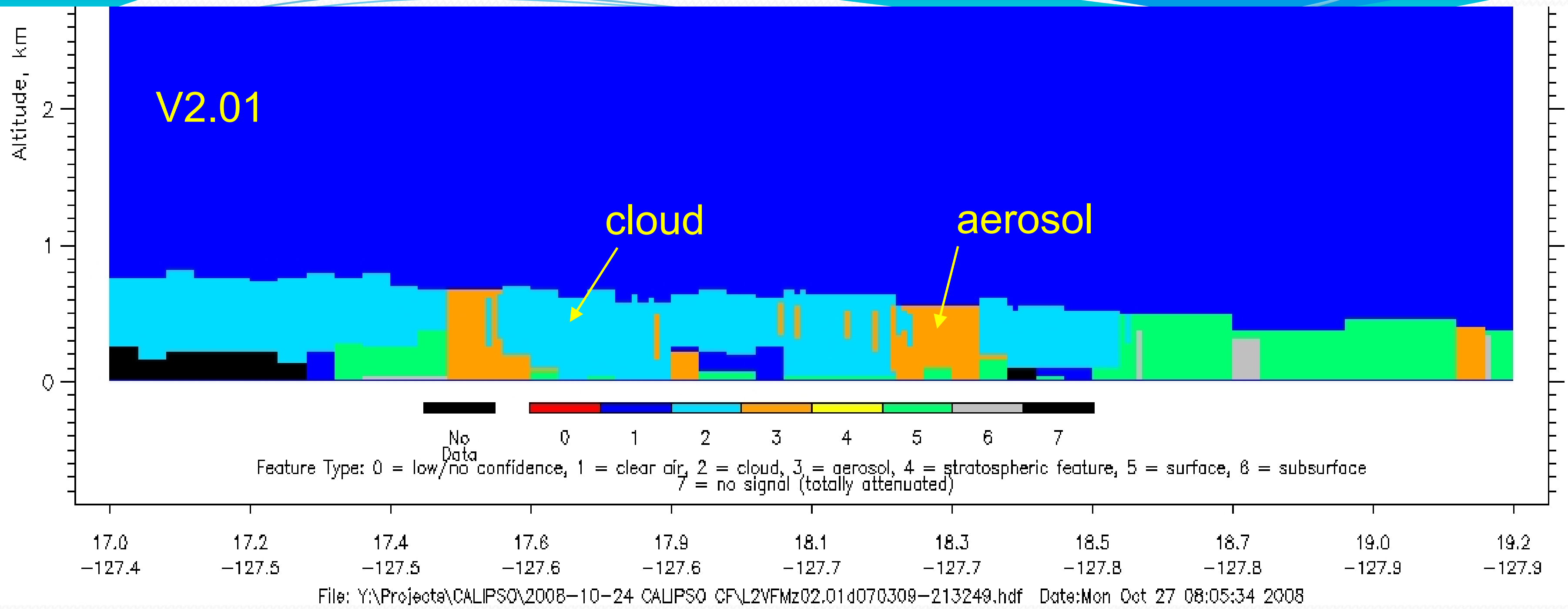
- Example of misclassification of a dust storm generated in the Gobi Desert observed on 30 Mar 2007:
  - (a) CALIOP 532-nm attenuated backscatter
  - (b) VFM (same color bar as in Fig. 5)
  - The circled features in (a) are dust layers that have been misclassified. Note that there are small-scale clouds on the top of each circled scene (7–8 km around 37.18 and 4–5 km near 448).

Comparison of V 2.01 and V3

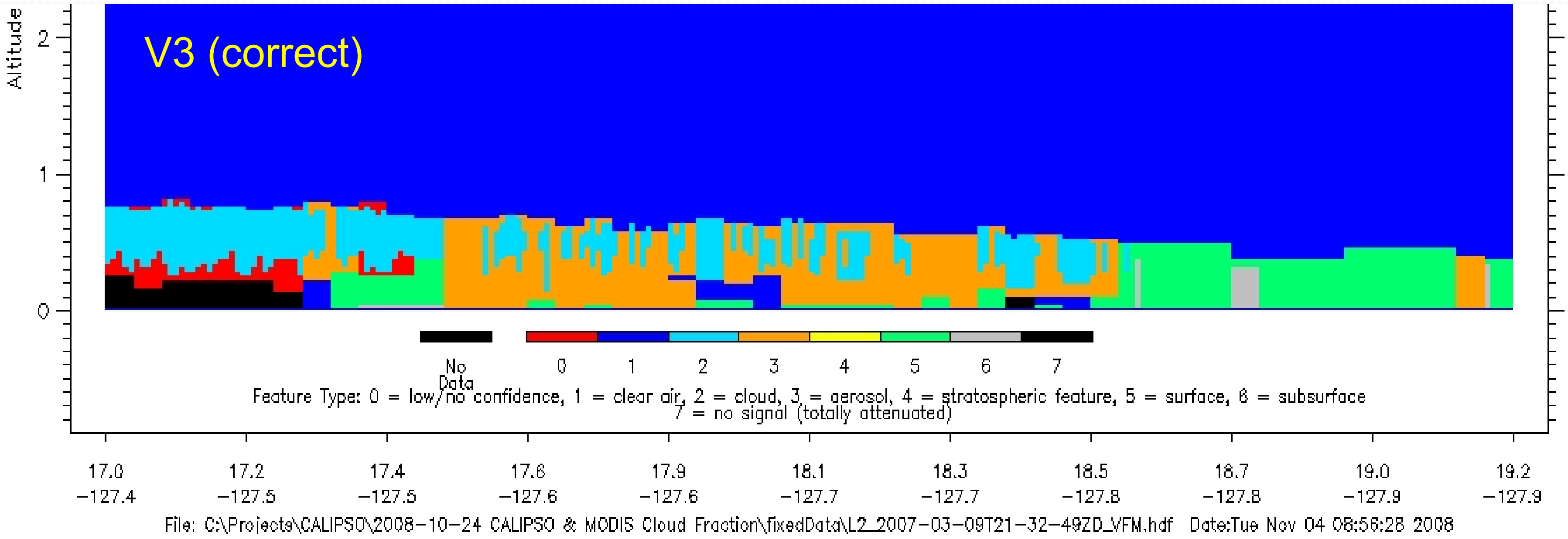


Parameters	Version 2.01	Version 3
Vertical Feature Mask	Based on 3-D PDFs - Mean attenuated backscatter at 532 nm - Total color ratio, - Midlayer altitude Classification of 8 types: Invalid, clear air, cloud, aerosol, stratospheric layer, surface, subsurface, no signal (totally attenuated)	Based on 5-D PDFs - Mean attenuated backscatter at 532 nm - Total color ratio, - Midlayer altitude - Volume depolarization ratio, - Latitude Classification of 9 types: Clear air, cloud, cloud(L), aerosol, aerosol (L), stratospheric layer, surface, subsurface, totally attenuated, L=low/no confidence
Aerosol Type	Based on the following parameters: - Observed backscatter strength - Depolarization ratio - IGBP surface types Classification of aerosol types (assigned S_a at 532/1064 nm) - Not applicable - Clean marine (20/45 sr) - Dust (40/30 sr) - Polluted continental (70/30 sr) - Clean continental (35/30 sr) - Polluted dust (65/30 sr) - Smoke (70/40 sr)	Based on the following parameters: - Observed backscatter strength - Depolarization ratio - IGBP surface types Classification of aerosol types (assigned S_a at 532/1064 nm) - Not applicable - Clean marine (20/45 sr) - Dust (40/55 sr) - Polluted continental (70/30 sr) - Clean continental (35/30 sr) - Polluted dust (55/48 sr) - Smoke (70/40 sr)
Aerosol Optical Depth (AOD)	Based on Forward solution	Based on Forward solution Includes the aerosol layer base extension algorithm
Volume Depolarization Ratio (δ_v)	Direct measurement Quality depends on the accuracy of the top and base identification	Direct measurement Quality depends on the accuracy of the top and base identification
Particulate Depolarization Ratio (δ_p)	-	Post-extinction quantity Quality - SNR of the backscatter measurements in parallel and perpendicular - Accuracy of two-way transmittance estimates
Particulate Color Ratio (χ_p)	-	Post-extinction quantity Quality - Accuracy of layer top/base altitudes - SNR of the backscatter data - Success of the HERA profile solver

Differences Between V2.01 and V3

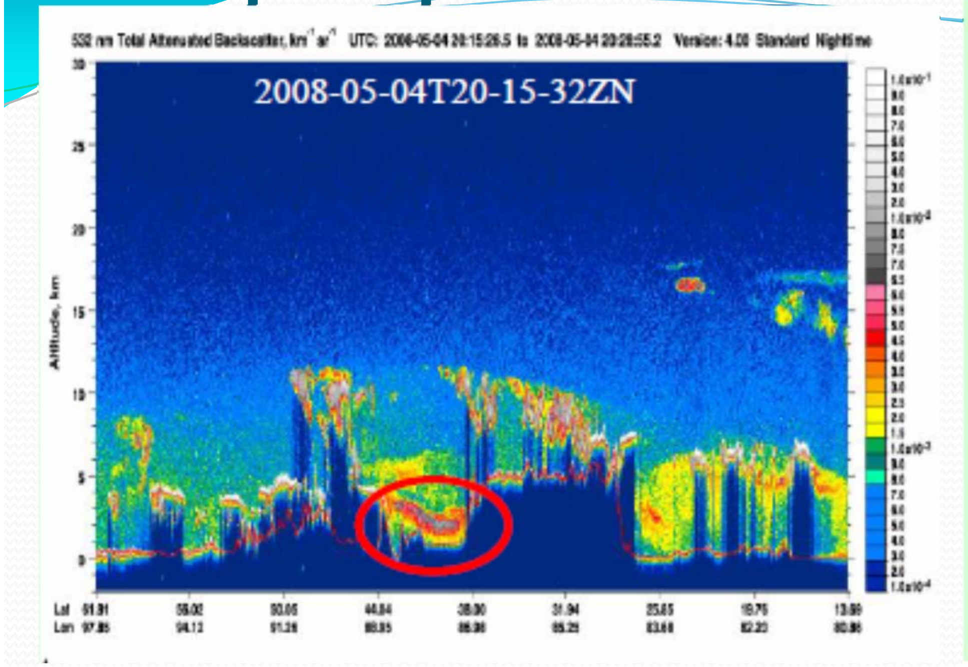


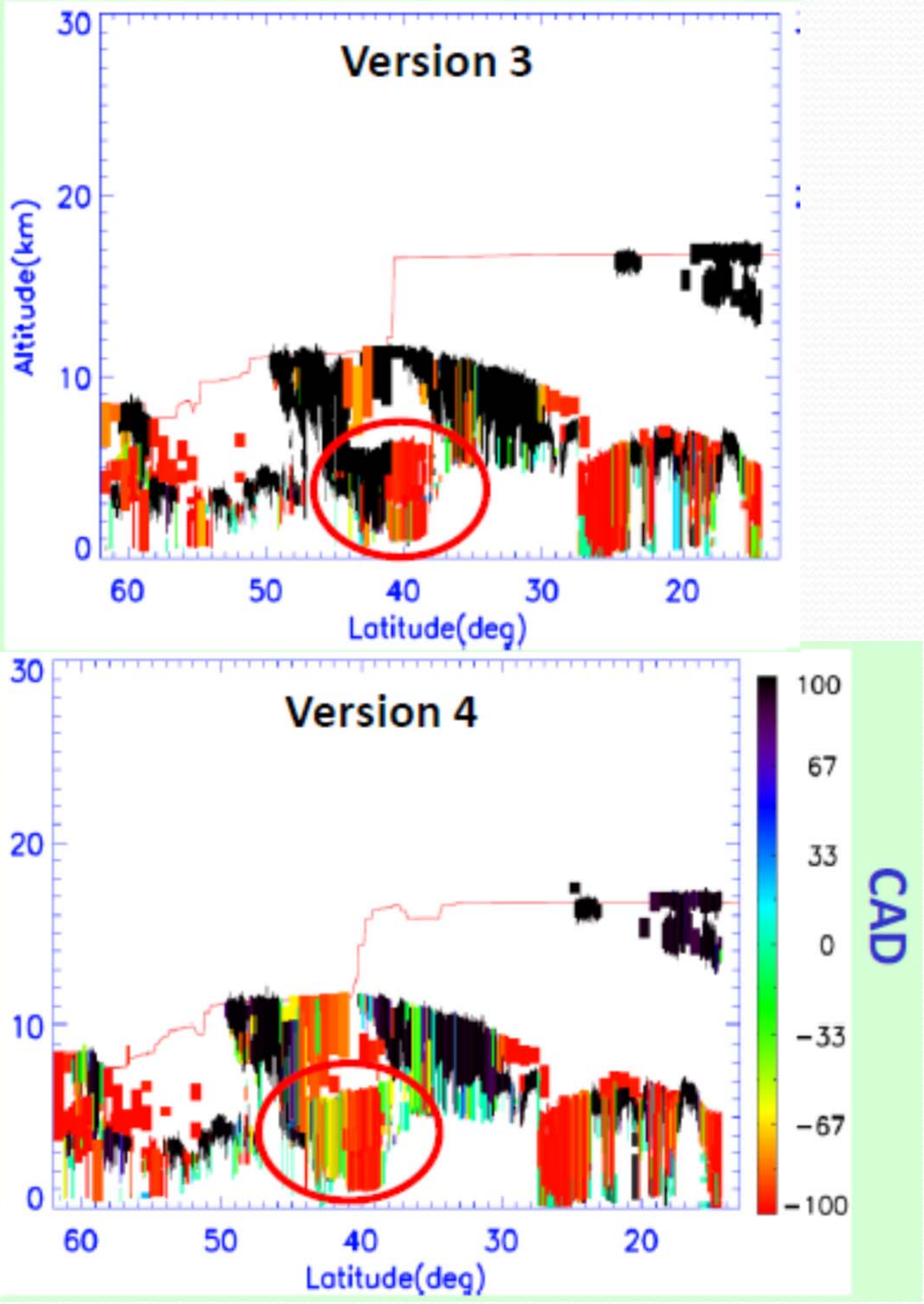
File: Y:\Projects\CALIPSO\2008-10-24 CALIPSO CF\L2VFMz02.01d070309-213249.hdf Date:Mon Oct 27 08:05:34 2008



File: C:\Projects\CALIPSO\2008-10-24 CALIPSO & MODIS Cloud Fraction\fixedData\L2_2007-03-09T21-32-49ZD_VFM.hdf Date:Tue Nov 04 08:56:28 2008

Troposphere Differences V3 and V4

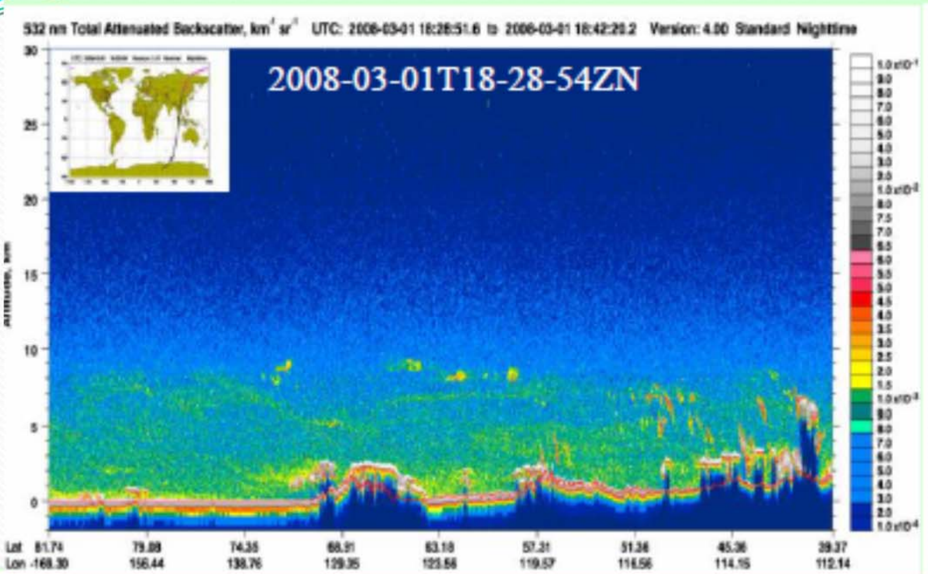




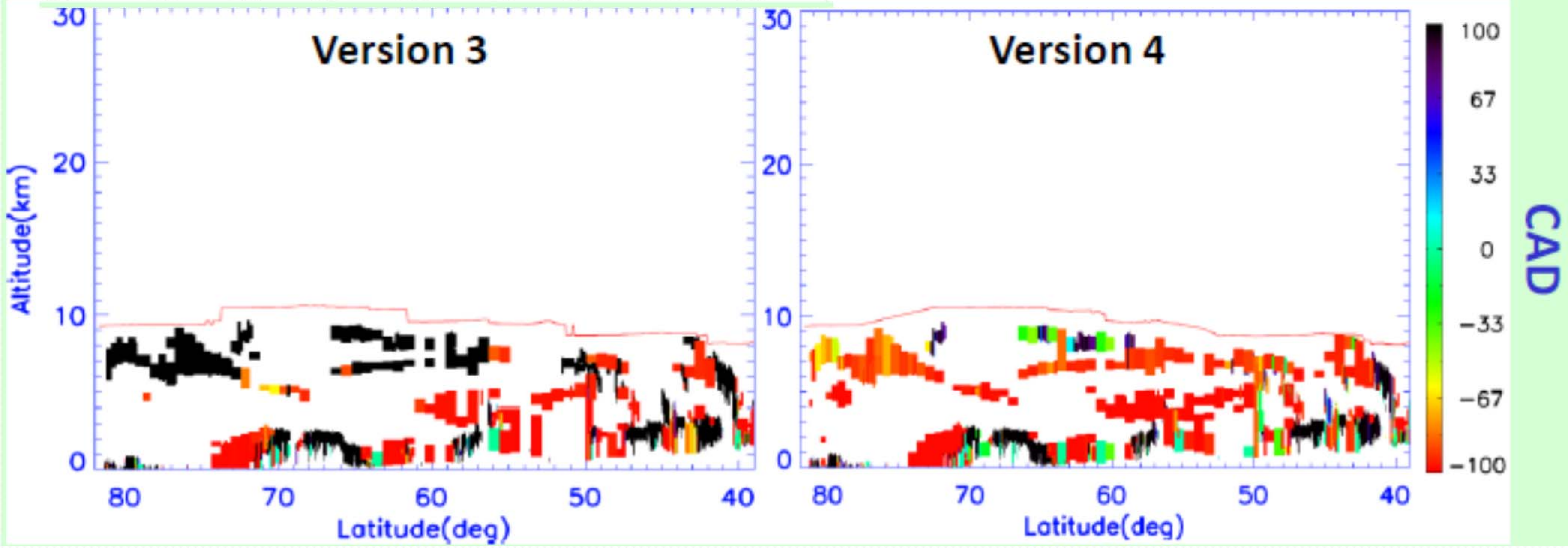
- Improved classification of thick dust layers as aerosols over Taklamakan desert— misclassification of these as clouds were reported in earlier versions (Chen et al., 2010, Jin et al., 2014).

http://stm.dpc.cira.colostate.edu/sites/default/files/2016_posters/17-Kar-SCMeeting_poster_CAD_final.pdf

Troposphere Differences V3 and V4

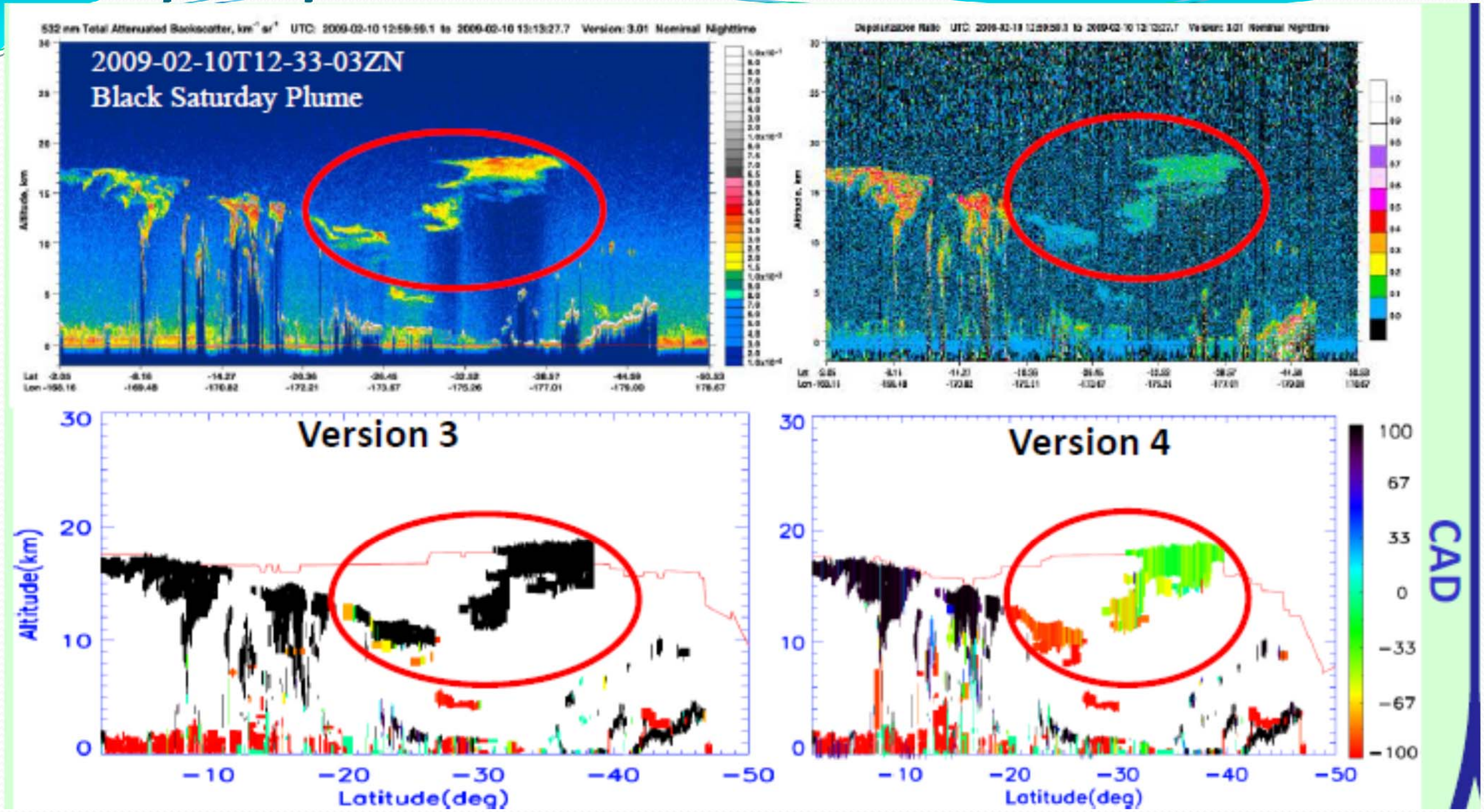


- Significant improvement in classifying Asian dust and polluted dust layers transported to the Arctic in Spring (clouds in V3). Misclassification reported earlier (Di Pierro et al. 2011) have been mostly resolved.



http://stm.dpc.cira.colostate.edu/sites/default/files/2016_posters/17-Kar-SCMeeting_poster_CAD_final.pdf

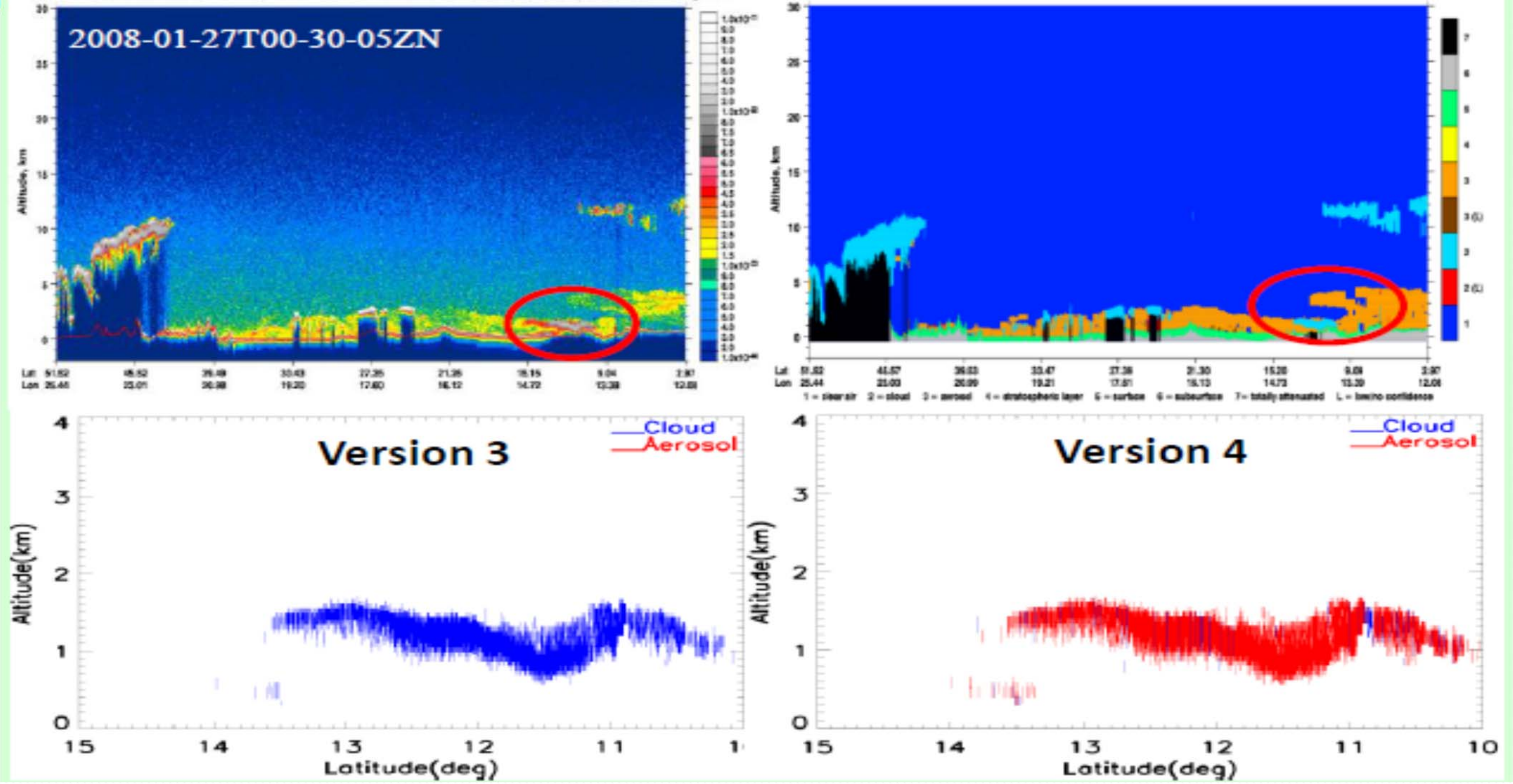
Troposphere Differences V3 and V4



- Correct classification of high altitude smoke layers as aerosols in V4 rather than clouds in V3. Lower CAD scores for the plume between 300S-400S are likely due to the high backscatter and depolarization ratios.

http://stm.dpc.cira.colostate.edu/sites/default/files/2016_posters/17-Kar-SCMeeting_poster_CAD_final.pdf

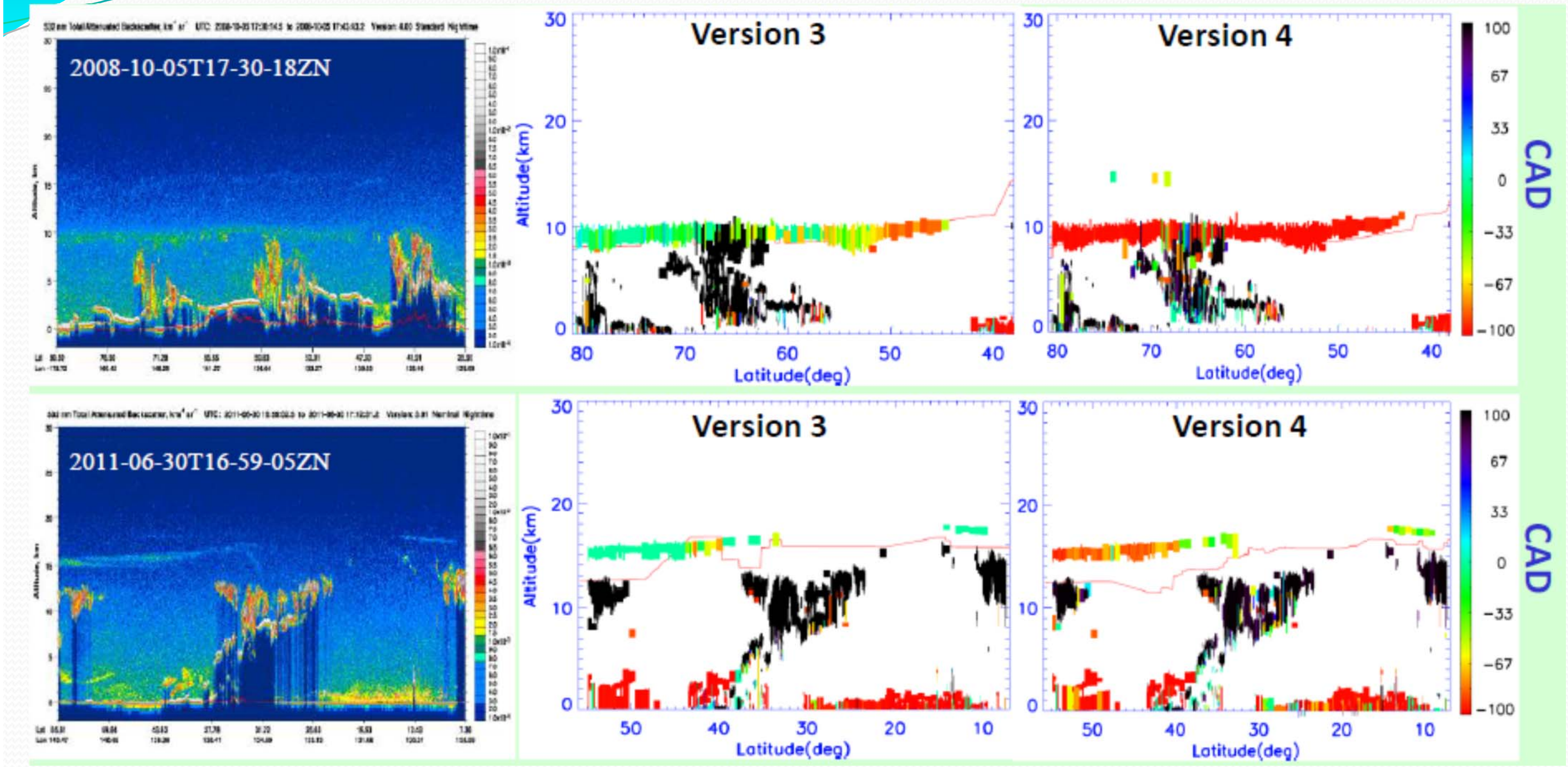
Troposphere Differences V3 and V4



- Thick single shot layers (333m)often embedded within extended dust or smoke layers classified as clouds in V3 (by default) are now classified as aerosols.

http://stm.dpc.cira.colostate.edu/sites/default/files/2016_posters/17-Kar-SCMeeting_poster_CAD_final.pdf

Stratosphere Differences V3 and V4



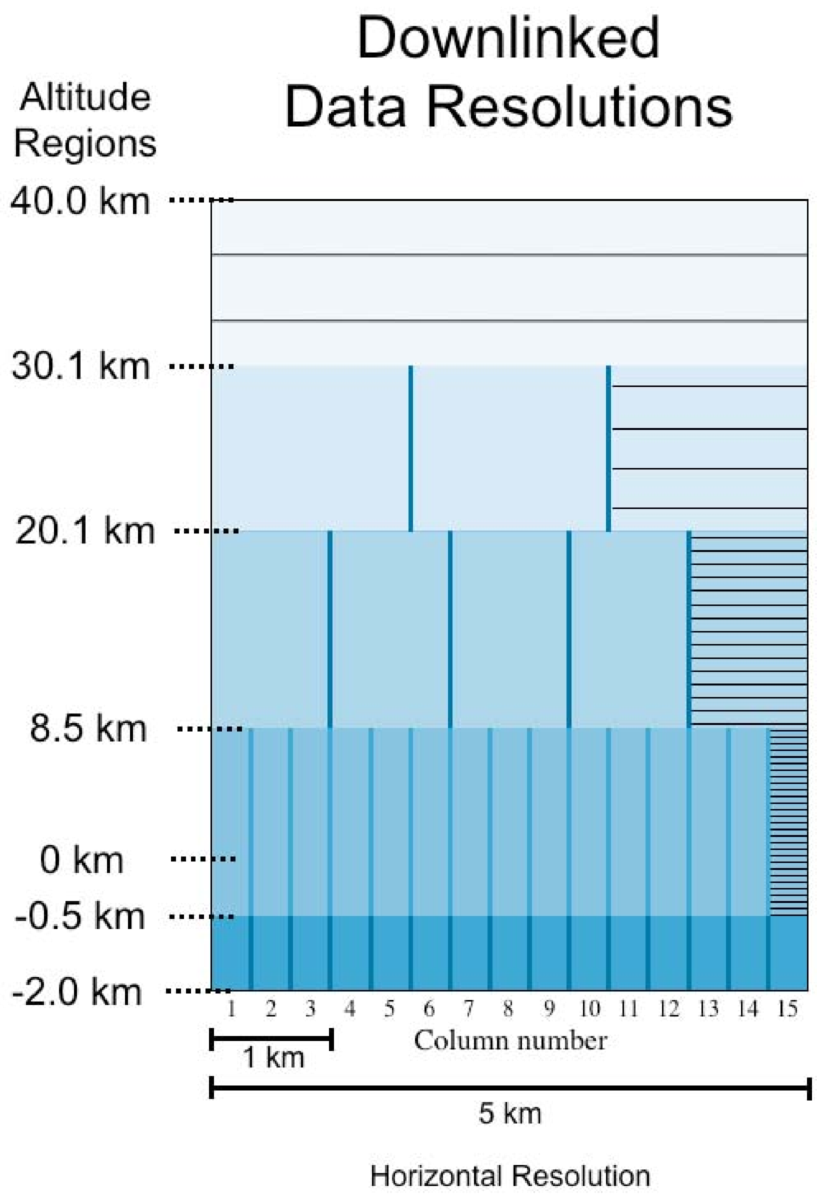
- Volcanic layers ("stratospheric features" in V3) are classified as aerosols in V4 CAD. (Top—Kasatochi; Bottom—Nabro)

http://stm.dpc.cira.colostate.edu/sites/default/files/2016_posters/17-Kar-SCMeeting_poster_CAD_final.pdf

Vertical and Horizontal Resolution

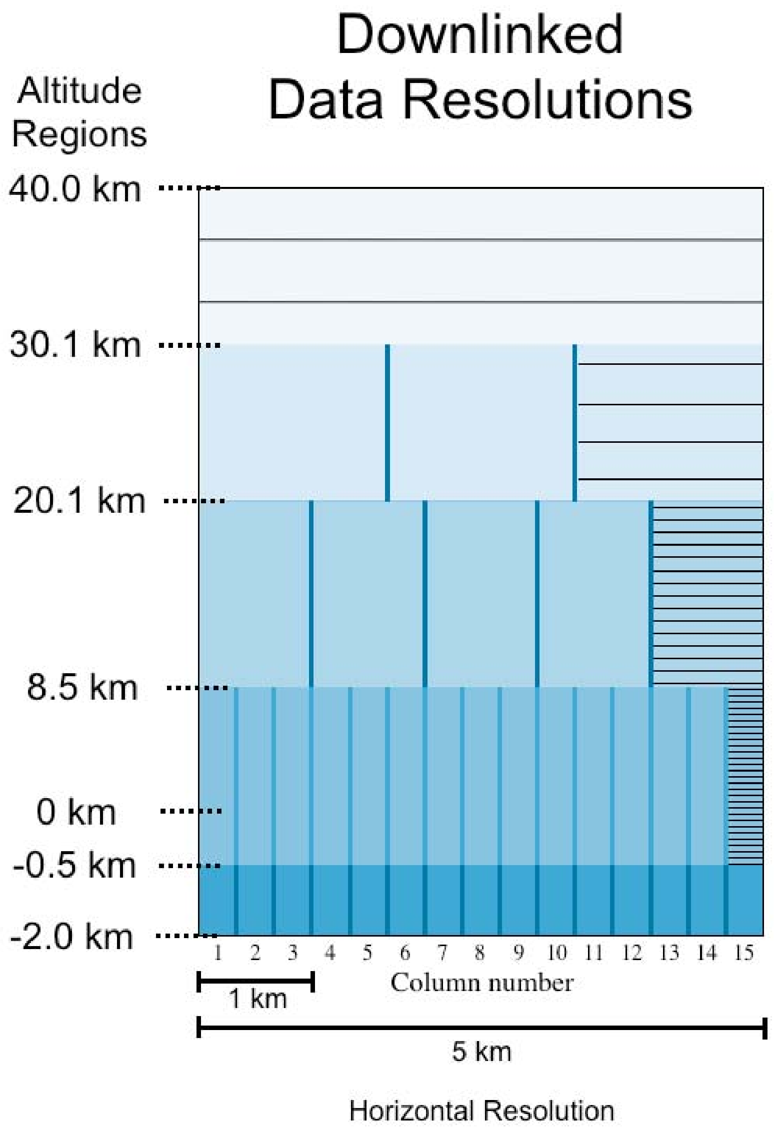
- Schematic of 15 consecutive full-resolution lidar profiles (i.e., a 5-km horizontal distance), annotated to illustrate how CALIOP's on-board averaging scheme varies vertically and horizontally as a function of altitude.

- The **five different averaging regimes** are shown using five different shades of blue.



Vertical and Horizontal Resolution

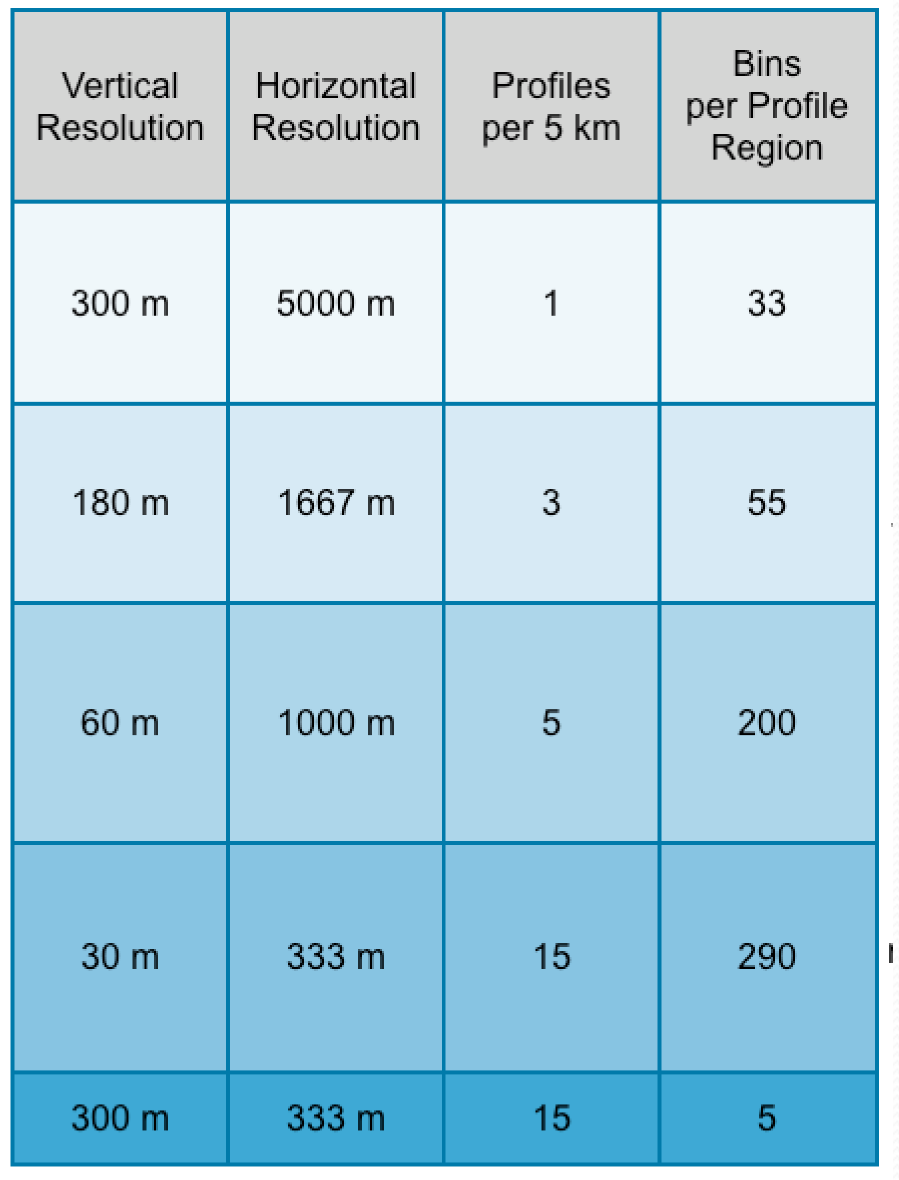
- The vertical lines within each blue **band delineate the individual profiles created by horizontally averaging the full resolution data**.
  - For example, between 8.5-km and 20.1-km the data is averaged horizontally to a nominal spatial resolution of 1-km; i.e., the data from 3 full resolution (333 m) profiles are averaged to create each 1 km averaged profile segment.
  - Similarly, between 20.1 km and 30.1 km, 5 full resolution (333 m) profiles are averaged to create 3 profiles that each spans a nominal horizontal extent of 5/3 km.
- **Processing in the vertical** is done in a similar fashion, as indicated by the **thin horizontal black lines** shown in the profile on the far right within each altitude regime.



Vertical and Horizontal Resolution

- The table in the middle gives the numerical values of the horizontal and vertical averaging for all the altitude regions.

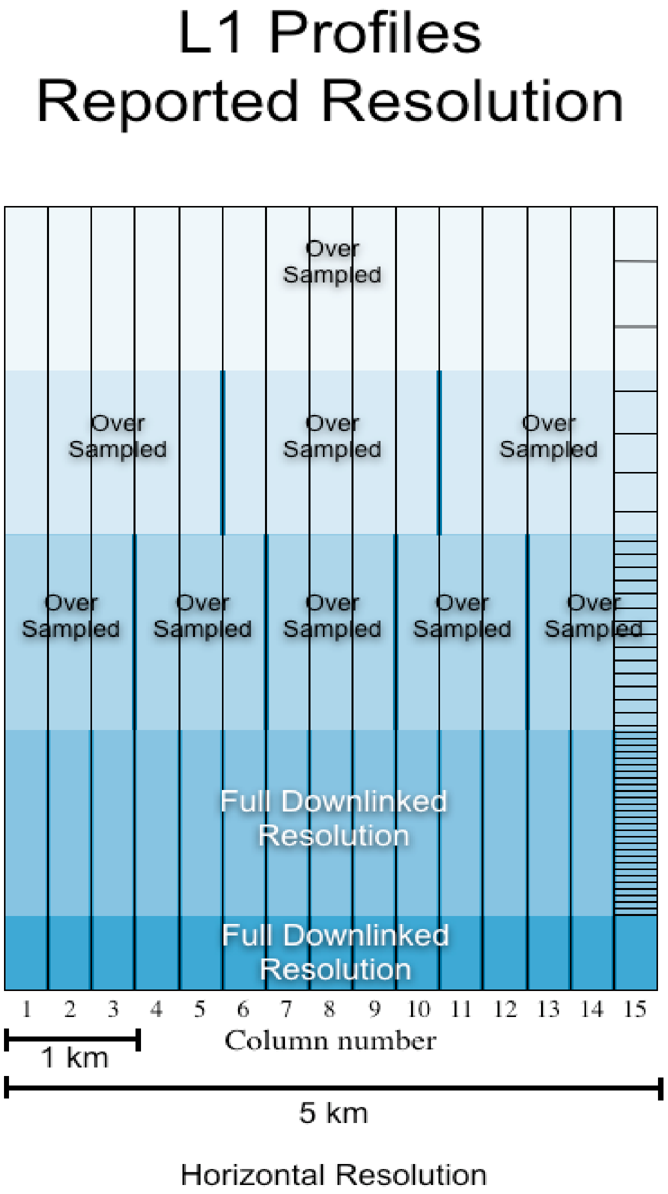
- The **highest resolution data available** is in the region between **-0.5 and 8.5 km** which is provided at **333 m** horizontally and **30 m** in the vertical.



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

Vertical and Horizontal Resolution

- During level 1 processing the data is regridded to a uniform horizontal grid of 333 m (see the right hand image above
- However, the vertical (i.e. altitude) resolution remains identical to that of the downlinked data.
  - Even though the level 1B profile data is reported at a uniform horizontal resolution of 333 m, in regions above 8.5 km it is **over sampled**.
  - For example, to create 15 "pseudo single shot" profiles in the altitude region between 8.5 km to 20.1 km, the downlinked 1 km profiles in this region are **replicated** and grafted onto the top of three consecutive full resolution (single shot) profiles.



Vertical and Horizontal Resolution

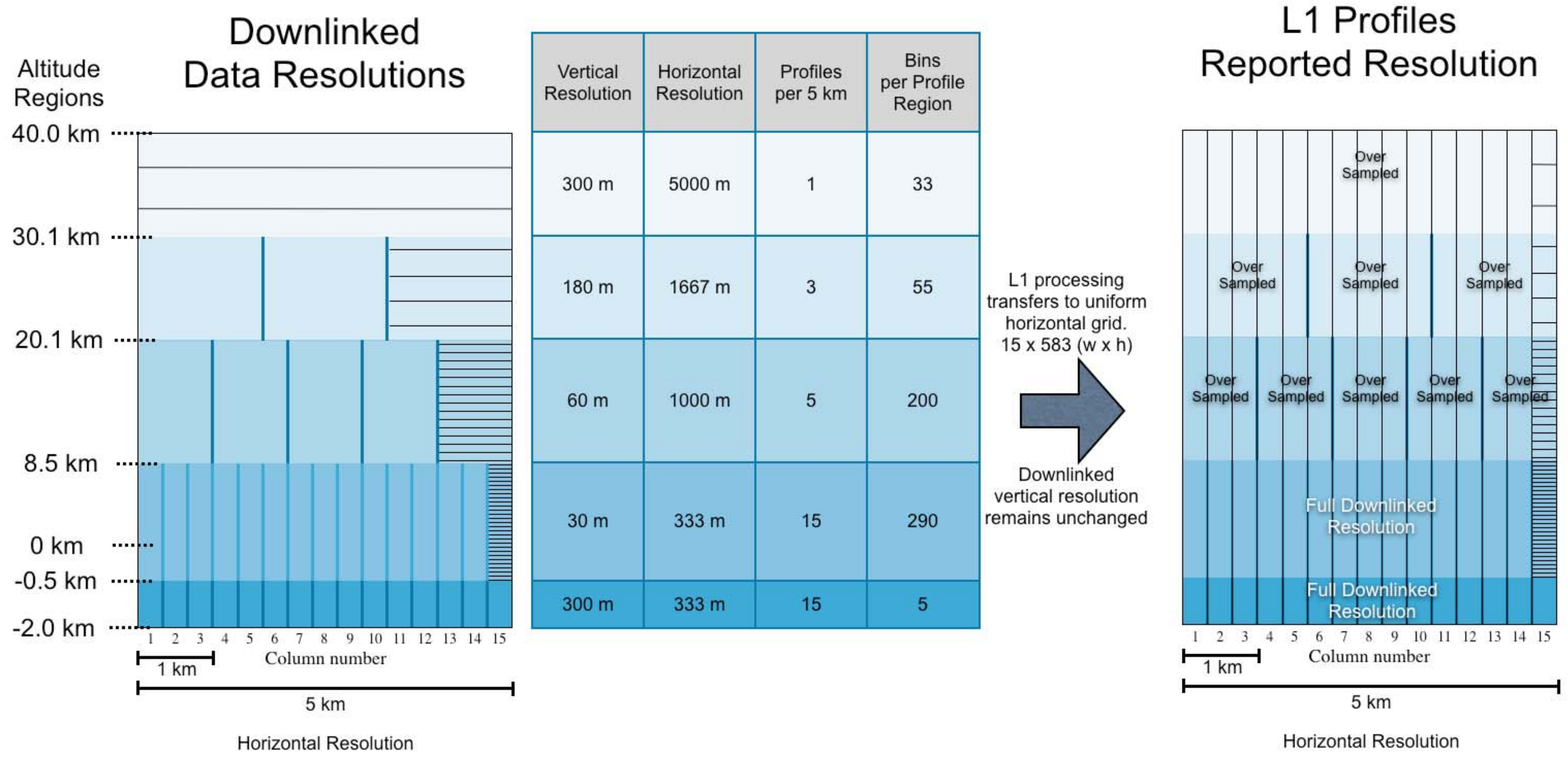
- The preceding commentary refers specifically to the **532 nm parallel and perpendicular channels only**.

- The 1064 nm channel is recorded at a vertical resolution of 60 m in the range be -0.5 and 8.2 km, also no 1064 nm data is available above 20.1 km.

- Nominal vertical resolution of **15 m (10 MHz sampling rate)**
  - at a laser pulse repetition rate of **20.16 Hz**
  - Horizontal profile spacing of **~333 m** (when accounting the satellites orbital velocity)
  - Within the lower atmosphere the footprint of each profile is **~90 m in diameter**.

Summary Vertical and Horizontal Resolution

- The on-board averaging scheme provides the highest resolution in the lower troposphere where the spatial variability of clouds and aerosols is the greatest and coarser resolutions higher in the atmosphere. The degree of averaging varies with altitude, as detailed in the figure below.



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

Multi-Gridded Averaging Scheme

- The **peak backscatter intensities** of the features measured by space-borne lidar range over **several orders of magnitude**.

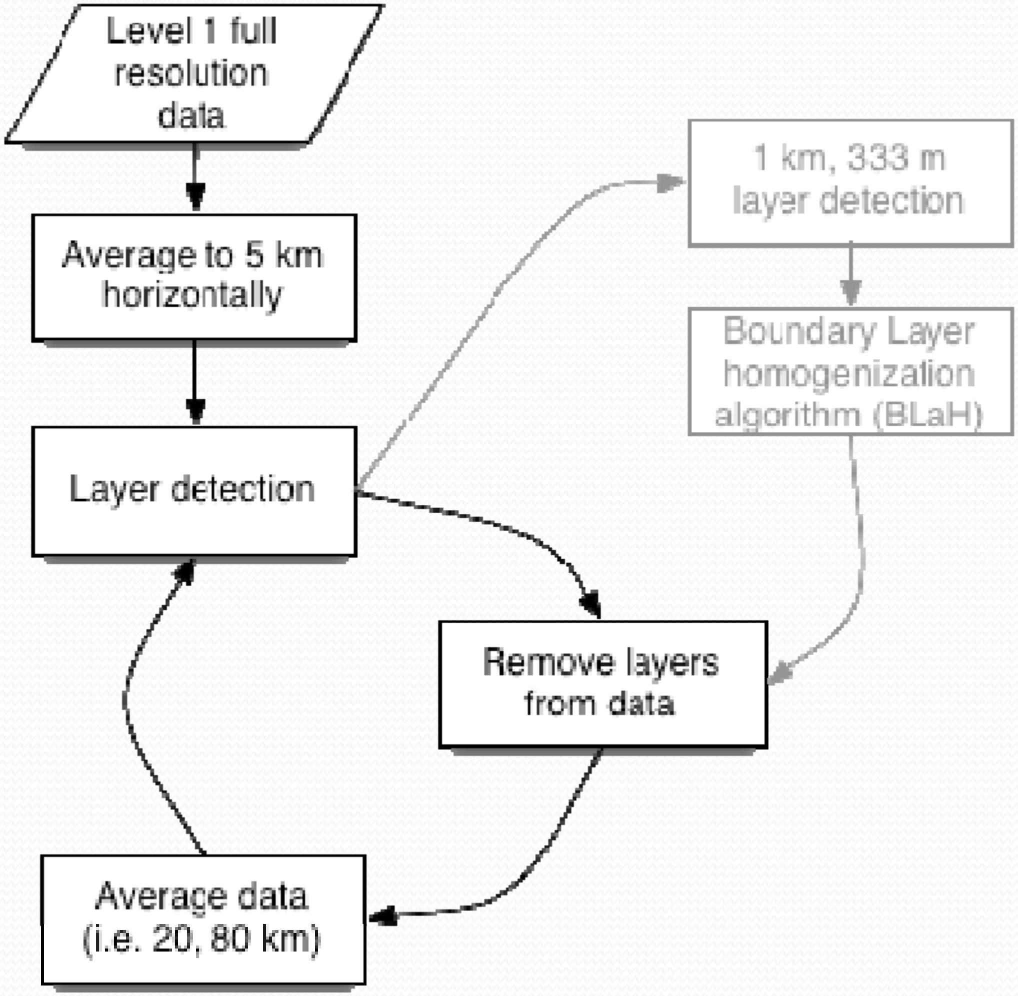
- **Strongly scattering** features such as stratus and fair weather cumulus **are easily detected** using a **single laser pulse**.

- For more **tenuous features** - e.g., thin cirrus clouds - the **average of several laser pulses may be required** to obtain the signal-to-noise ratio necessary to differentiate feature boundaries from the ambient scattering environment.

- **The unambiguous detection of the very weakest features - faint aerosol layers and sub-visible cirrus - may require averaging over a substantial number of pulses.**

Multi-Gridded Averaging Scheme

- To identify all of the features within a given scene at the maximum possible spatial resolution we employ **a Selective Iterated Boundary Location (SIBYL)** scheme.
- The SIBYL algorithm makes multiple passes through a specified scene, constructing profiles of attenuated scattering ratios at a series of increasingly coarse spatial resolutions, nominally at 5, 20 and 80 km.
- Immediately after construction, each profile is scanned for the presence of clouds, aerosol layers, and/or surface returns using a profile scanner, (the 'Layer detection' box at right).



Level 1 full resolution data

Average to 5 km horizontally

Layer detection

1 km, 333 m layer detection

Boundary Layer homogenization algorithm (BLaH)

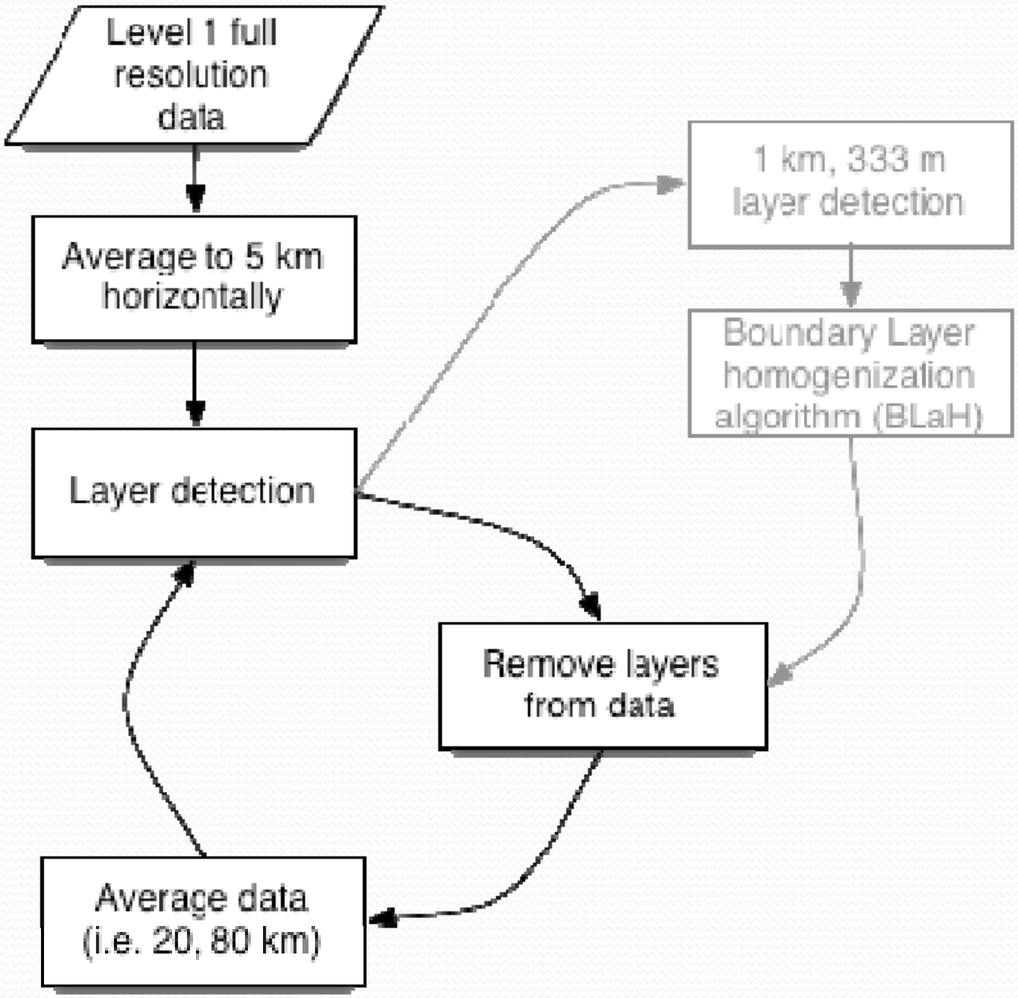
Remove layers from data

Average data (i.e. 20, 80 km)

Basic multi-gridded averaging flow

Multi-Gridded Averaging Scheme

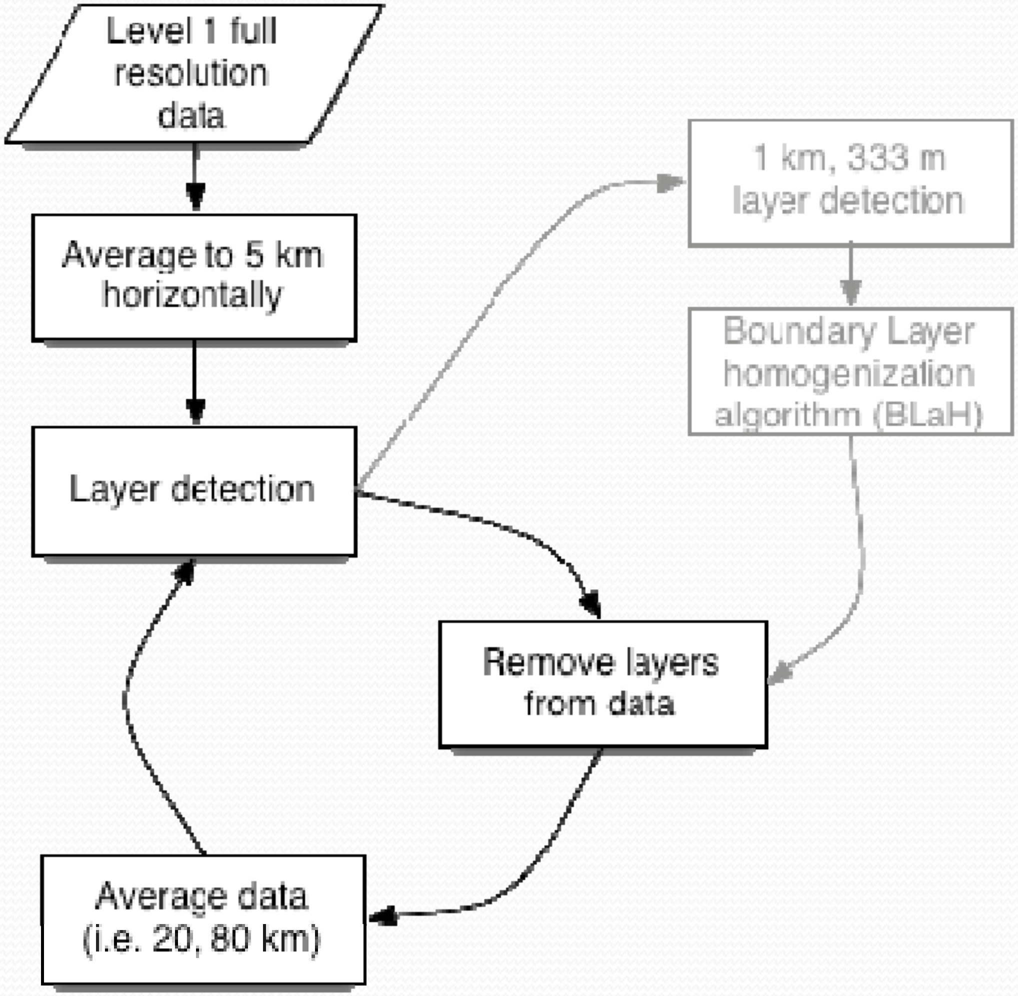
- The backscatter data from those regions identified as containing a feature are removed from subsequent processing.
- As a consequence, features found at high spatial resolutions (i.e., with less averaging) will not be included in the profiles of attenuated scattering ratios scanned at coarser resolutions (i.e., more averaging).
- This encompasses the 'Remove layers...' and 'Average data to 20 or 80 km' boxes.



Basic multi-gridded averaging flow

Multi-Gridded Averaging Scheme

- Note that the layer detection at 1 km and 333 m horizontal resolution are only performed for those regions where 5 km layers were detected.
- The *boundary layer homogenization algorithm* (**BLaH**) will not be further discussed. Users are encouraged to read section 4 (section 4.4 is about BLaH) in the feature detection ATBD.



Basic multi-gridded averaging flow

Example

- Browse image of the total 532 nm attenuated backscatter signal (the sum of the 532 nm parallel and perpendicular return signals).

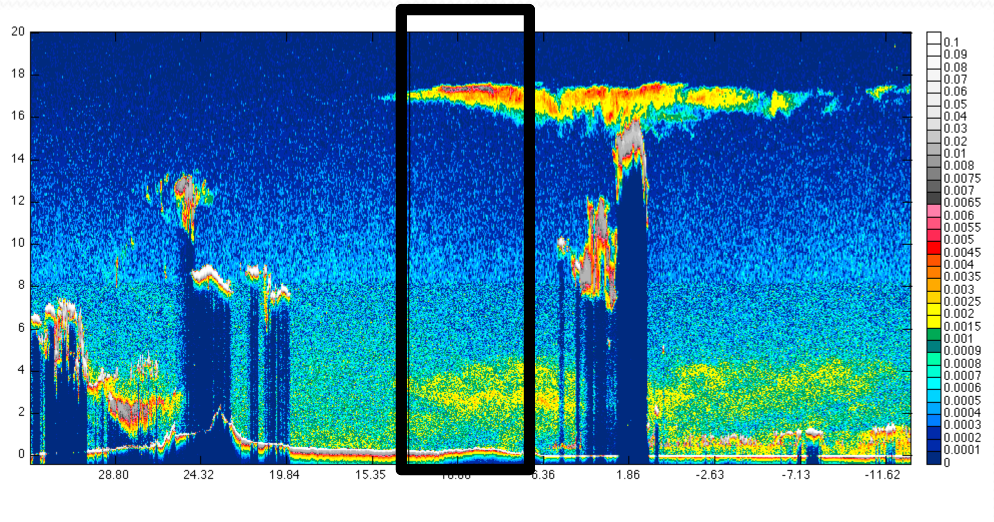
- Zoomed in version of above image from the area between the black lines.

- There is a **transparent cirrus** cloud located at ~17 km and an aerosol layer (most likely dust) located from the surface or in some places ~ 1km up to an altitude of 4 km.

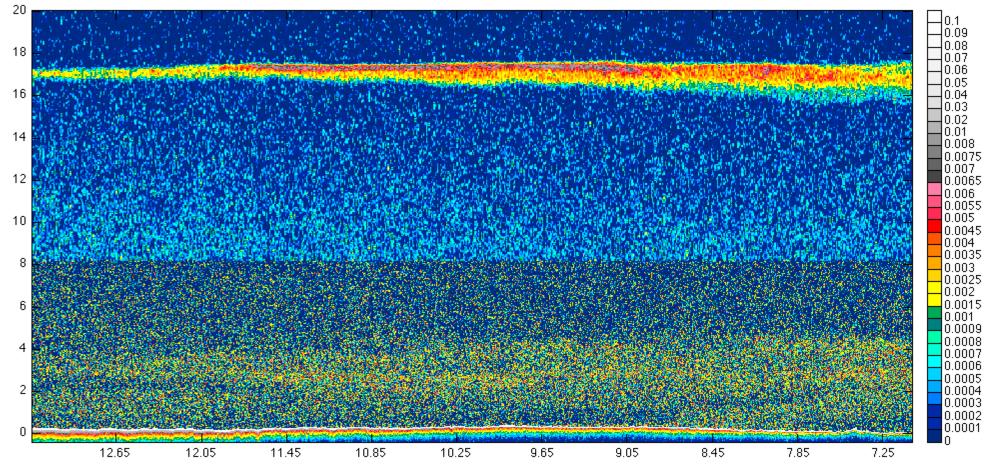
- The **surface return** is seen as the white/red/yellow band near 0 km.

- The **horizontal line at 8 km** is from the **changing noise characteristics** in the data due to the change in horizontal and vertical averaging of the data.

- **Data is plotted a 333 m horizontal resolution.**



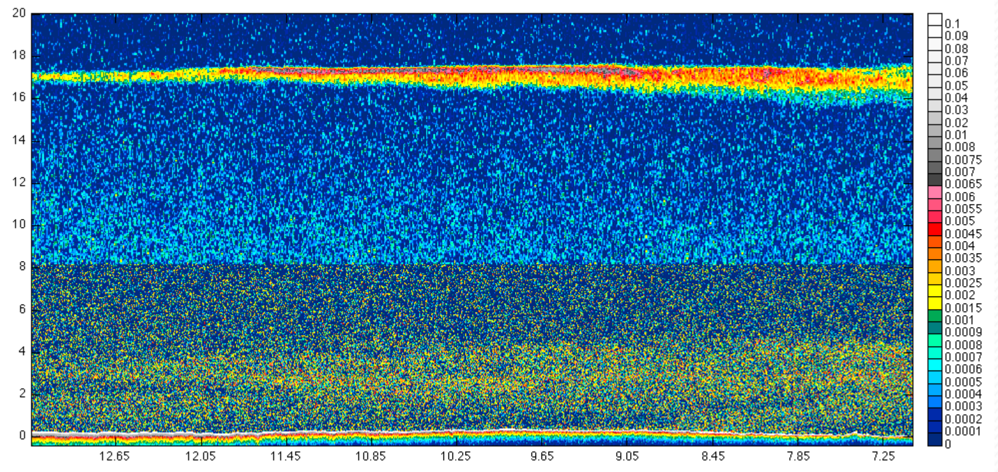
~333m



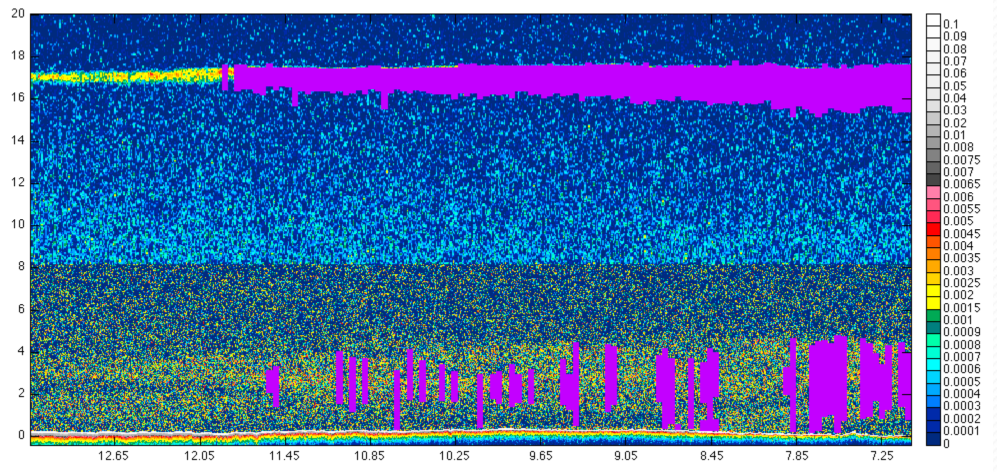
Example

- BELOW: vertical and horizontal locations of all features that were detected at the 5 km horizontal resolution.
- Only the data in the regions as identified by the magenta color are used to compute the layer optical properties as would be found in the 5 km layer products.
- **The layer data in those regions will then be zeroed-out before the 5 km is averaged to 20 km.**

~333m



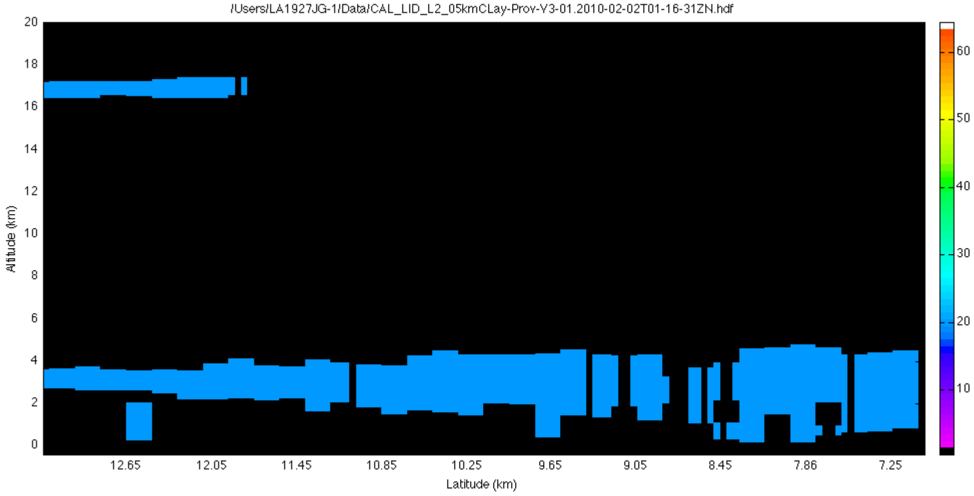
5 km & ~333m



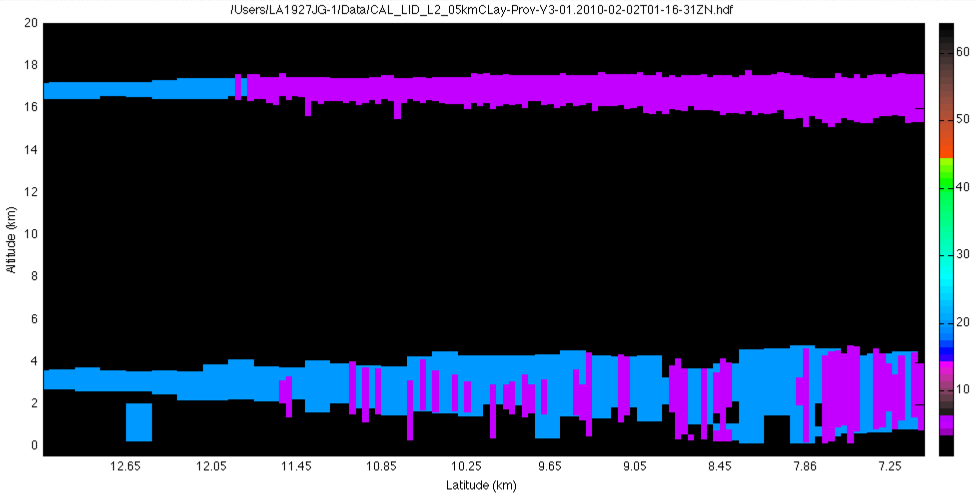
Example

- After the removal of features that were detected at the 5 km resolution, a search is made for features at the 20 km resolution.
- The image at right shows **features that are found at the 20 km** resolution in blue.
- The image (below-right) shows both the 5 km features and the 20 km features.
- Only the data in the regions shown in blue are used to calculate the layer optical properties for those same regions.
- The regions in **magenta** are not included in the averages for the features detected on the 20 km resolution. Layer optical properties are repeated (i.e. reported in the data products) for each 5 km column in which they appear.

20 km



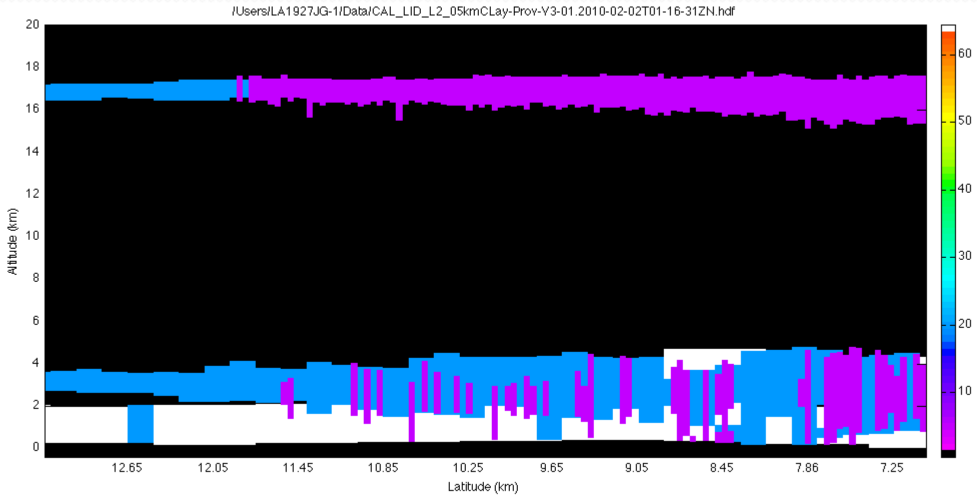
5 km & 20 km



Example

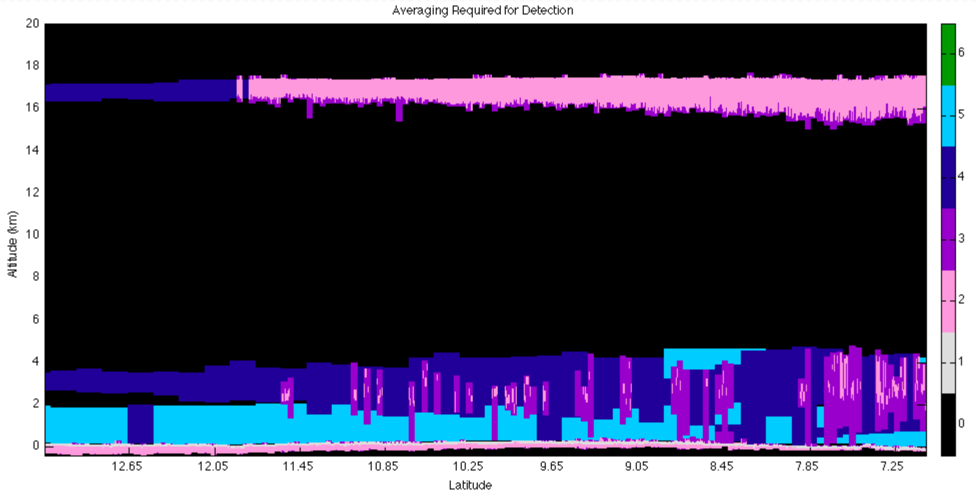
5, 20, & 80 km

- **Final composite 'feature mask' image showing 5, 20 and 80 km horizontal resolutions.**



- **Below:** Another version of the 'feature mask' showing the same horizontal resolution as above-right but including the 1 km and 333 m layer extents.

- The 1 km and 333 m profile data are only scanned for layers in regions where a 5 km layer was found, therefore 1 km layers will only be found in regions where a 5 km layers were found and subsequently 333 m are only found where 1 km layers were found.



0 - NA, 1 - 1/3 km, 2 - 1 km, 3 - 5 km, 4 - 20 km, 5 - 80 km

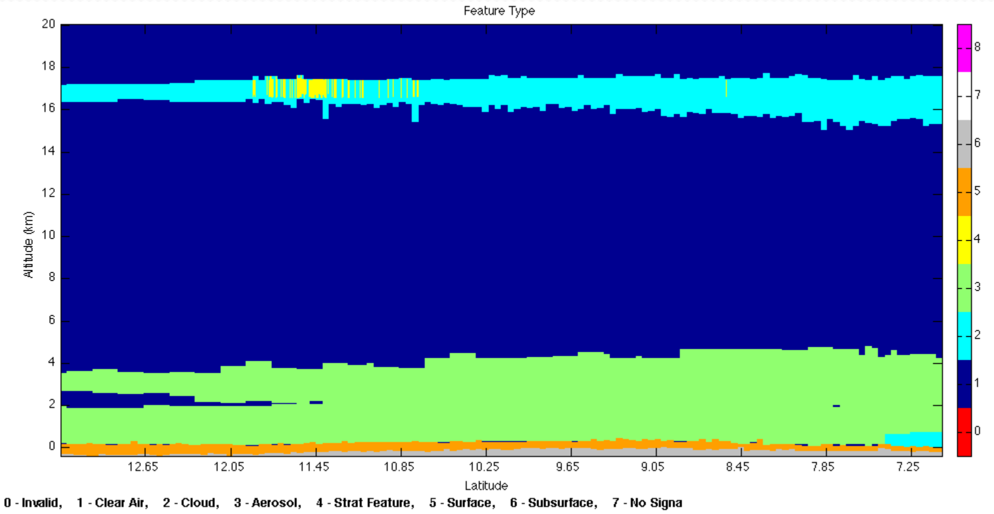
Example

- This **'vertical feature mask'** image shows the vertical locations of all layers detected by the level 2 processing code, colors represent the type of layer as determined by the scene classification algorithm.

- **Cloud layers** are identified by the **cyan color**

- **Aerosols** by **green**

- **Dark blue** is **'clear air'** where no layers were detected, etc.



Original ~333m