CATS Data Release Notes
L1B Version 3.00
L2O Version 3.00

01 Oct. 2018

The Cloud-Aerosol Transport System (CATS) is a lidar remote sensing instrument that provided vertical profiles of atmospheric aerosols and clouds from the International Space Station (ISS) during the period of February 2015 through October 2018. The vertical profile information obtained by CATS, particularly at multiple wavelengths and with depolarization information, provides height location of cloud and aerosol layers, as well as information on particle size and shape. The CATS instrument provided measurements of cloud and aerosol profiles similar to CALIPSO, filling in the gap in diurnal coverage of CALIPSO, so this information can continually be used to improve climate models and our understanding of the Earth system and climate feedback processes. Changes in algorithms for our seventh release corresponding to our Version 3.00 Level 1 data products and Version 3.00 Level 2 data products are described here. **This is the last planned data product release for the CATS project.**

1.0 Algorithm Changes

The following lists the algorithm changes made in L1B Version 3.00 (V3-00):

- For CATS V2-08 L1B data, the nighttime backscatter calibrations, and thus accuracy of the attenuated total backscatter profiles, at both 532 and 1064 nm were improved. These improvements enabled a more accurate daytime calibration calculation using the nighttime attenuated total backscatter (ATB) data. This

improved daytime accuracy propagates through many of the L2O daytime data products as well. More details follow in Section 2.0.
- CATS V3-00 L1B data includes changes to the values of the Depolarization Quality Flag, which notifies users of granules with depolarization ratio values of poor quality. More granules were also added to the list of poor depolarization quality.
- For V3-00, meteorological and aerosol type information is now provided by MERRA-2 Reanalysis data. In previous versions, CATS used GMAO forecasts to provide this data.

The following lists the algorithm changes made in L2O Version 3.00 (V3-00):
- The L2O profile numbers were updated to match the L1B profile numbers.
- The algorithms to compute the uncertainty in the L2O layer-integrated parameters in V2-01 had an error that biased these values too low. For V3-00, the algorithms have been improved for more accurate uncertainty in the L2O layer-integrated parameters (layer-integrated backscatter, depolarization ratio, color ratio, etc.).
- The updated Depolarization Quality Flag from the L1B V3-00 data is also now reported in the L20 V3-00 data products.
- A new parameter called "Cloud_350m_Fraction_XXX_FOV" was added to the L2O Layer data product that reports the fraction of the L1B 350 m bins within a 5 km detected layer that have an ATB > 0.03 km^{-1} sr^{-1} and are assumed to be a cloud. This parameter is then used to improve the CATS Cloud-Aerosol Discrimination (CAD) algorithm and feature type score parameter.
- The accuracy of the CATS Feature Type and Feature Type Score variables were significantly improved for V3-00, especially for daytime data. This was achieved using (1) horizontal persistence tests applied to daytime data (V2-01 only applied these horizontal persistence tests to the nighttime data), and adding code to use variables such as (2) Cloud_350_Fraction, (3) the Perpendicular ATB, and (4) MERRA-2 relative humidity to better differentiate clouds and aerosols. More details are provided in Section 2.
- For V3-00, the aerosol type classification "volcanic" has been changed to "UTLS Aerosol" (Aerosol Type = 8) because CATS observed multiple types of aerosols in the upper troposphere and lower stratosphere (UTLS).
- New parameters called "Opaque_Feature_Optical_Depth_1064_XXX_FOV" and "Opaque_Feature_Optical_Depth_Uncertainty_1064_XXX_FOV" were added to the Mode 7.2 L2O Layer data product. Similarly, these variables at both 532 and 1064 nm were added to the Mode 7.1 L2O Layer data product. These variables report the optical depth of a layer/feature down to the point of attenuation of the CATS laser beam for layers flagged as opaque.
- There were two updates to the algorithms for constrained lidar ratios.
    1. An algorithm was created based on Hu et al. (2007) to constrain lidar ratios for cirrus clouds or aerosol layers above opaque liquid water clouds using the multiple scattering from these liquid water clouds. These cases are now noted in the Lidar Ratio Method flag as 8.

2. The algorithm for computing constrained lidar ratios in cirrus clouds and aerosol layers using the transmission loss technique (Lidar Ratio Method = 4) was updated to produce more accurate retrievals. More details are provided in Section 2.

- A new parameter called "Num_Profs_Avg_LRatio_XXX_FOV" was added to the L2O Layer data product that reports the number of profiles used to average the below cloud signal and constrain an accurate 1064 nm lidar ratio for cirrus clouds or aerosol layers using the transmission loss technique.
- Given the improvements in the quality of the CATS constrained lidar ratios, the CATS layer effective multiple scattering factor for ice clouds was updated in V3-00 products to 0.52 for both modes and both wavelengths.

2.0 Parameter Specific Comments

Attenuated Total Backscatter at 532 nm (Mode 7.1) and 1064 nm (both modes)
The backscatter calibrations at both 532 and 1064 nm were improved for nighttime CATS Version 2-08 L1B data. The CATS nighttime 1064 nm attenuated total backscatter compares very favorably with CALIOP, ground based 1064 nm Raman lidars, and modeled Rayleigh profiles at the same wavelength. Given that the 1064 nm attenuated total backscatter is used to retrieve nearly all L2O data products, the accuracy of these products was also improved.

The daytime backscatter calibration was updated to use a more quantitative analysis for transferring the nighttime calibration coefficients. For V2-08, the daytime backscatter calibrations at both 532 and 1064 nm were determined using a qualitative method of transferring the nighttime calibration coefficients. More specifically, the data was broken up into several week periods and the nighttime calibration coefficient that appeared to normalize the profile best to Rayleigh was used. For V3-00, the frequency distributions of layer-integrated attenuated backscatter for opaque ice clouds with a physical thickness less than 2 km was compared for night and daytime data for each month of data. Given the accuracy of the nighttime backscatter calibration, it was considered to be the "truth". The daytime calibration coefficient was computed as the value needed to match the nighttime frequency distribution for a given month. For some months, there was very little change in the daytime calibration coefficient. For others, this technique improved the accuracy of the daytime ATB at both wavelengths.

Mode 7.2 532 nm Attenuated Total Backscatter and Integrated Backscatter
Unlike the Mode 7.1 data, where the 532 and 1064 nm signals are comparable, the Mode 7.2 532 and 1064 nm signals are very different. Mode 7.2 data at 532 nm is noisy due to issues with stabilizing the seeded laser (laser 2). Since the frequency stability is poor on laser 2, it is not aligned properly with the CATS etalon causing very weak signal transmission. Unfortunately, we do not have the necessary controls to fix the problem so we recommend averaging the nighttime data to ***at least*** 5 km (roughly 14 raw 20 Hz profiles) when analyzing the 532 nm data. **We do not recommend using the daytime 532 nm data in Mode 7.2 for any application.**

Due to the signal transmission issues at 532 nm, laser 2 was thermally tuned to increase the laser energy at 1064 nm to 2 mJ per pulse. Thus the 1064 nm signal in mode 7.2 is very robust, with higher signal-to-noise ratio and lower minimum detectable backscatter than Mode 7.1 data. **We highly recommend using the 1064 nm data for any analysis that is wavelength-independent (i.e. layer detection, relative backscatter intensity).**

1064 nm Attenuated Perpendicular Backscatter and Depolarization Ratio
CATS V2-07 1064 nm depolarization ratios within cirrus clouds for Mode 7.2 yielded more variability than expected compared to CPL 1064 nm and CALIOP 532 nm data. When the CATS laser begins operation after being turned off (for ISS activities, instrument reboots, etc.), the laser polarization is not pure. This results in inaccurate depolarization values for several granules, depending on how long the laser was off, until the laser polarization stabilizes.

CATS Version 3-00 data includes an updated Depolarization Quality Flag to notify users of granules with depolarization ratio values of poor quality (Table 1). In L1B V2-08 and L2O V2-01, granules with suspect depolarization values were indicated with values of 1 (low due to recent laser turn on) or 2 (biased high as laser stabilizes) in the Depol_Quality_Flag. For V3-00, granules with suspect depolarization values are now flagged as Depol_Quality_Flag = 1 for simplicity. Users should only use granules with Depol_Quality_Flag = 0 for studies of particle sphericity. Users should also be cautious when using any L2O data for the suspect granules, as the algorithms for cloud phase and aerosol type use depolarization ratio. The Mode 7.1 laser does appear to suffer from a similar issue, but not to the same extent. That laser stabilizes more quickly.

Table 1. Definitions of the CATS Depolarization Quality Flag

Interpretation of Values
0 = Valid, good quality depolarization data
1 = Depolarization ratio is suspect and should not be used

Number of Layers, Layer Top/Base Altitude
The CATS V3-00 L2O data, like the V2-01 data, includes layer detection at both 5 and 60 km horizontal resolutions, as well as a parameter that specifies the horizontal resolution a layer was detected at. The reported number of layers, and corresponding layer properties are the merged product of layers detected at both 5 and 60 km. Layers detected at 60 km are reported in the 12 corresponding 5 km profiles, with the same top and base altitudes. The CATS V2-00 L2O data now reports more layers than the V1-05, especially during daytime over land. Initial comparisons of CATS V2-00 and CALIPSO V4.10 cloud and aerosol detection frequencies are much more favorable during daytime.

Cloud 350 m Fraction
The quantification of cloud fraction for each feature/layer is reported in the CATS L2O V2-00 Layer data product. The values correspond to the fraction of the total number of L1B bins, with a horizontal resolution of 350 m, that make up a given L2O feature/layer,

with a horizontal resolution of 5 km profile, in which the 1064 nm ATB is greater than 0.03 km^{-1} sr^{-1}. Any such bins are considered to be a cloud in the L1B 350 m profiles. The Cloud 350 m Fraction variable will be 1.0 for opaque liquid water clouds and will be 0.0 for thin aerosol plumes that are homogeneous across a 5 km distance. Values less than 1.0 and greater than 0.0 represent layers that are potentially a mix of aerosols and physically thin clouds (i.e. fair-weather or marine boundary layer cumulus clouds). Please note that it is possible that cloud edges fail to meet the 1064 nm ATB threshold, so clouds can have a fraction slightly lower than 1.0. Similarly, some aerosol plumes can have thick portions that exceed the 1064 nm ATB threshold, so thick dust and smoke aerosols can have a fraction slightly higher than 0.0.

Feature Type

The CATS CAD algorithm is a multidimensional probability density function (PDF) technique that is based on the CALIPSO algorithm (Liu et al. 2009). The PDFs were developed based on CPL measurements obtained during over 11 field campaigns and 10 years. Based on statistical comparisons of CATS L2O V1-05 and V2-01 cloud and aerosol detection frequencies with CALIPSO, and aerosol type with GEOS-5, it was determined that the CATS CAD algorithm struggles to correctly classify clouds and aerosols in three circumstances:

1. Depolarizing liquid water clouds in the lower troposphere are sometimes classified as lofted dust mixture or smoke aerosols. This is result of enhanced depolarization ratios within liquid water clouds due to multiple scattering (which is not represented in the CPL measurements used for the PDFs), and an inability to utilize the backscatter color ratio in the CAD algorithm due to the noisy 532 nm backscatter data.
2. Complex scenes in which boundary layer cumulus clouds are present at the top of an aerosol layer are often wrongly classified. This is a challenge for any lidar system and in most cases these scenes/layers are not realistically one type of layer.
3. Thin aerosol plumes in the UTLS, especially depolarizing dust plumes, have very similar characteristics as thin ice clouds. The CATS CAD algorithm occasionally classifies ice cloud edges as aerosols and dust in the upper troposphere as an ice cloud. This is primarily due to these aerosol layers being under-represented in the CPL measurements used for the PDFs and the lack of backscatter color ratio in Mode 7.2 CATS data.

To improve the CATS CAD algorithm performance for these three circumstances, the algorithm was updated for V3-00 to utilize the following tests:

- <u>Horizontal Persistence Test:</u> Since true lofted dust and smoke layers tend to have large horizontal extent, a horizontal persistence test was added to the CATS CAD algorithm for nighttime L2O V2-01 data to identify liquid water clouds with enhanced depolarization ratios of small horizontal extent and correctly classify them as clouds. However, the same test was not as effective during daytime due to the noisy daytime signals so it was not implemented in V2-01. The result is a reduction of dust mixture and smoke aerosol detection over remote parts of the Earth's oceans in nighttime CATS L2O V2-00 data, but the issue still remained in the daytime data. A slightly modified version of the horizontal persistence test was added to the CATS CAD algorithm for daytime data in V3-00.

- Cloud Fraction Test: The Cloud 350m Fraction variable was used to identify complex scenes/layers in which boundary layer cumulus clouds are mixed with aerosols (#2 above). Many of these layers are now defined as “undetermined” in the V3-00 data. This variable is also very helpful in differentiating aerosols from depolarizing liquid water clouds in the lower troposphere (#1 above) and tests have been added to ensure any layers with a Cloud 350m Fraction greater than 0.90 are classified as clouds and any layers with a Cloud 350m Fraction less than 0.10 are classified as aerosols.
- Integrated Perpendicular Backscatter Test: Previous versions of the CATS CAD algorithm utilized the layer-integrated attenuated backscatter intensity in leu of the layer-integrated attenuated backscatter color ratio that the CALIPSO CAD algorithm uses. This works well for thin aerosol layers, but some optically thick dust and smoke plumes are falsely classified as clouds. To overcome this issue in the V3-00 data, a test using the layer-integrated perpendicular backscatter has been employed. The multiple scattering from ice and liquid water clouds results in layer-integrated attenuated backscatter values that are significantly higher than aerosols. For cloud and aerosol layers with low Feature Type Scores (-5 to +5), a threshold value of 0.004 km^{-1} sr^{-1} is used to differentiate clouds and aerosols. This test also improves the discrimination of UTLS aerosols and thin ice clouds.
- Relative Humidity Test: In previous versions of the CATS data products, dust plumes in the upper troposphere, which can reach as high as 12 km as they are transported from Asia over the northern Pacific Ocean and have depolarization ratios greater than 0.25, were classified as ice clouds. To better identify these layers, a relative humidity test was added to the CATS CAD algorithm that identifies horizontally persistent layers with top altitudes greater than 10 km, mid-layer temperatures less than -20 C, and relatively weak backscatter intensity (layer-integrated perpendicular backscatter less than 0.001). If the mean MERRA-2 relative humidity for the layer is less than 45%, then the layer is classified as an aerosol and assigned a Feature Type Score of -6.

The Feature Type Scores are then updated for layers that pass or fail these tests. If a layer passes multiple tests, the score becomes more confident (± 9 or 10) if it isn’t already the highest confidence. If the layer only passes one test, the Feature Type Scores only increases/decreases by 1 resulting in more layers with a Feature Type Score of ± 6 or 7 than in previous versions.

Aerosol Type

For V3-00, the aerosol type classification “volcanic” has been changed to “UTLS Aerosol” (Aerosol_Type = 8). Early in the CATS lifetime, all aerosols detected in the upper troposphere and lower stratosphere (UTLS) were volcanic. However, near the end of the CATS lifetime many energetic fires lofted smoke layers into the UTLS. The CATS aerosol typing algorithms do not attempt to differentiate volcanic aerosols from smoke aerosols in the UTLS because these features are too similar in the Mode 7.2 data (1064 nm ATB, depolarization, etc.).

Table 2: CATS Aerosol Type Classifications

Aerosol Type	Value
Marine	1
Marine Mixture	2
Dust	3
Dust Mixture	4
Clean/Background	5
Polluted Continental	6
Smoke	7
UTLS	8

There were no fundamental changes to the CATS L2O aerosol typing algorithms for V3-00. However, two other changes improved the accuracy of the aerosol types reported in the data products. The first is a switch to the MERRA-2 aerosol products from the GMAO aerosol forecasts, which are incorporated to help discriminate smoke from polluted continental aerosols when CATS observations (surface type, layer elevation, and layer thickness) alone could not identify an aerosol type for spherical aerosols. The second are the improvements to the CATS CAD algorithm, which result in less frequent false detection of dust mixture and smoke over remote parts of the ocean, especially in daytime data.

Lidar Ratio

The particulate extinction-to-backscatter ratio, or lidar ratio, is required to retrieve extinction coefficient profile and feature/column optical depth from CATS measurements. For clouds and aerosols, the lidar ratio is typically assigned from a look-up table based on the aerosol type and cloud phase. However, it is also possible to constrain lidar ratios for ice clouds and some aerosol types (most commonly dust and smoke). There are now two algorithms to achieve this, which are described below:

<u>Constrained Lidar Ratio: Transmission Loss Technique (Lidar Ratio Method=4)</u>

In CATS V3-00 the constrained lidar ratio using the transmission loss technique (Lidar Ratio Method= 4) now utilizes an averaged signal below the layer of interest to determine the transmission loss (note this is not done at 532 nm). This is done for 1064 nm (both modes) and 532 nm in Mode 7.1 data. Up to 20 profiles can be used in the averaging (ten on each side of the profile of interest). The algorithm tests for continuity in the layer base height, layer type, and for atmosphere clear of layers below the feature. Only consecutive profiles, to the right and left of the profile of interest, that pass these tests are used for the averaging. This method successfully reduces the noise in the signal below the layer, allowing for more accurate transmission loss and lidar ratio estimates. Additionally, the standard deviation of the below layer signal must be below 8E-5 km^{-1} sr^{-1} for the calculated lidar ratio to be accepted. If no averaging of the below layer signal is performed, the standard deviation of the signal must be lower than 3E-5 km^{-1} sr^{-1} to be accepted. A new parameter called "Num_Profs_Avg_LRatio_XXX_FOV" was added to the L2O Layer data product that reports the number of profiles used to average the below cloud signal and constrain an accurate lidar ratio for cirrus clouds or aerosol layers using the transmission loss technique. This parameter will only have valid values for layers which were successfully constrained and is the same for both wavelengths in Mode 7.1.

<u>Constrained Lidar Ratio: Layer Above Opaque Cloud Method (Lidar Ratio Method=8)</u>
For V3-00, an algorithm was created based on Hu et al. (2007) to constrain lidar ratios (both at 1064 nm and at 532 nm in Mode 7.1) for cirrus clouds or aerosol layers above opaque liquid water clouds using the multiple scattering from these liquid water clouds. These cases are now noted in the Lidar Ratio Method flag as 8. This method for determining the lidar ratio is based on the concept that backscatter of an opaque cloud will be reduced by a factor proportional to the two-way transmittance of the overlying transparent layer (Hu et al. 2007). Once the overlying layer's two-way transmittance is estimated, the layer lidar ratio can be determined using the same equations as the traditional transmission loss technique. More details about this method can be found in Hu et al. (2007). The addition of this algorithm creates more cases in which the above cloud aerosol (ACA) optical properties (AOD, extinction profile, etc.) are more accurate.

To determine the CATS layer effective multiple scattering factor, the CATS constrained lidar ratios are compared to CPL for cirrus clouds over the same time period and geographic location. Given the improvements in the quality of the CATS constrained lidar ratios at 1064 nm, the CATS layer effective multiple scattering factor for ice clouds was updated in V3-00 products to 0.52 (both modes and wavelengths). This change will also impact the retrievals of ice cloud extinction and feature optical depth. The values for liquid water clouds also changed to 0.40.

Feature/Column Optical Depth, Extinction Coefficient
The optical depth and extinction of all atmospheric particulate layers, clouds, and aerosol throughout the column are reported for each 5 km profile, regardless of the lidar ratio selection method. For V3-00, the accuracy of these parameters has improved as a result of:

- The improved multiple scattering factor for cirrus (now 0.52) and liquid water clouds (0.40) for V3-00.
- The improved accuracy of the constrained lidar ratios and added capabilities for ACA.
- The improved Feature Type and Feature Type Score parameters, which can now be used to better screen out data of poor quality during statistical analysis.

Highly scattering opaque layers that completely attenuate the backscatter signal will cause the reported layer base to be higher than reality and the layer optical depth to be lower than reality. Thus, the base bin/altitude reported may not be the true base and the Feature Optical Depth variable reports -1.0 for these features. Since some data users expressed a desire for these optical depth values to be reported in the data products, new parameters called Opaque Feature Optical Depth 1064 XXX FOV and Opaque Feature Optical Depth Uncertainty 1064 XXX FOV are now reported in the Mode 7.2 L2O Layer data product. Identical variables at both 532 and 1064 nm were also added to the Mode 7.1 L2O Layer data product. These variables report the optical depth of a layer/feature down to the point of attenuation of the CATS laser beam for layers flagged as opaque (i.e. layers with a Feature Optical Depth = -1.0).

L2O Uncertainty Parameters

For V2-00, algorithms were created to compute the uncertainty in all the L2O parameters, which were reported as absolute uncertainties in the CATS L2O V2-00 data products and considered provisional. All of these uncertainty parameters underwent significant testing and proved to be accurate except the following layer-integrated parameters:

- Integrated Attenuated Backscatter Uncertainty (1064 nm Mode 7.2, 532 & 1064 Mode 7.1)
- Integrated Volume Depolarization Ratio Uncertainty (1064 nm Mode 7.2, 532 & 1064 Mode 7.1)
- Integrated Spectral Depolarization Ratio Uncertainty (Mode 7.1)
- Integrated Attenuated Total Color Ratio Uncertainty (Mode 7.1)

The algorithms to compute the uncertainties in these parameters had an error in the V2-01 code that has been fixed for V3-00. Users should only use these parameters in the CATS V3-00 data products and not in earlier versions.