CATS L2O Profile Products Quality Statements
Version Release: 3.00

01 Oct. 2018

1.0 Introduction

This document offers a general quality assessment of the CATS Level 2 Operational (L2O) Profile data products, as described in CATS Data Product Catalog, and explains the information needed by the science community for accurate and effective use of the CATS data products. We insist that all CATS data users examine this document for the latest updates before publishing any scientific papers using the CATS data products. This document describes the accuracy of CATS data products as determined by the CATS Algorithm Group. The purpose of this data quality summary is to briefly demonstrate significant validation results; inform users of areas that can lead to misinterpretation of the data; provide links to relevant documents describing the CATS data products and algorithms used to generate them; and propose planned algorithm revisions.

2.0 Data Product Maturity

The maturity levels of each parameter reported in the CATS L2O data products are identified in this document and may be different for the various parameters since validation efforts and uncertainties of some parameters are different compared to others. The data product maturity levels for the CATS data products, adapted from the CALIPSO maturity levels, are defined in Table 1. Since CATS was funded as a technology demonstration, some parameters in the L2O Profile data products are still assigned a product maturity level of provisional.

Table 1. CATS Maturity Level Definitions (adapted from CALIPSO)

Beta:	Early release products for users to gain familiarity with data formats and parameters. Users are strongly cautioned against the indiscriminate use of these data products as the basis for research findings, journal publications, and/or presentations.
Provisional:	Limited comparisons with independent sources have been made and obvious artifacts fixed.
Validated Stage 1:	Uncertainties are estimated from independent measurements at selected locations and times.
Validated Stage 2:	Uncertainties are estimated from more widely distributed independent measurements.
Validated Stage 3:	Uncertainties are estimated from independent measurements representing global conditions.
External:	Data are not CATS measurements, but instead are either obtained from external sources (e.g., GMAO, ISS) or fixed constants in the CATS retrieval algorithm (e.g., calibration altitude).

3.0 Documents and References

The following documents provide additional information for data users to reference:

1. The CATS Algorithm Theoretical Basis Document (ATBD)
2. The CATS Data Product Catalog: Release 7.0 (PDF)
3. Overview of L1 Data Processing Algorithms (PDF)
4. CATS Instrument and Project Overview (PDF)
5. CATS Data Read Routine in Interactive Data Language (IDL)

4.0 CATS Operating Modes

To meet the project science goals, CATS operated in two different modes using three instantaneous fields of view (IFOV) as shown in Figure 1:

- ***Mode 7.1: Multi-beam backscatter detection at 1064 and 532 nm, with depolarization measurement at both wavelengths***. The laser output is split into two transmit beams, one aimed 0.5º to the left and one 0.5º to the right, effectively making two tracks separated by 7 km (~4.3 mi) at Earth's surface. This operational mode was only used until 21 March 2015 due to a failure in laser 1 electronics.
- ***Mode 7.2: Demonstration of HSRL aerosol measurements***. This mode was designed to use the injection-seeded laser operating at 1064 and 532 nm to demonstrate a high spectral resolution measurement using the 532-nm wavelength. However, this mode was limited to 1064 nm backscatter and

depolarization ratio because of issues with stabilizing the frequency of laser 2 prevent collection of science quality HSRL data.

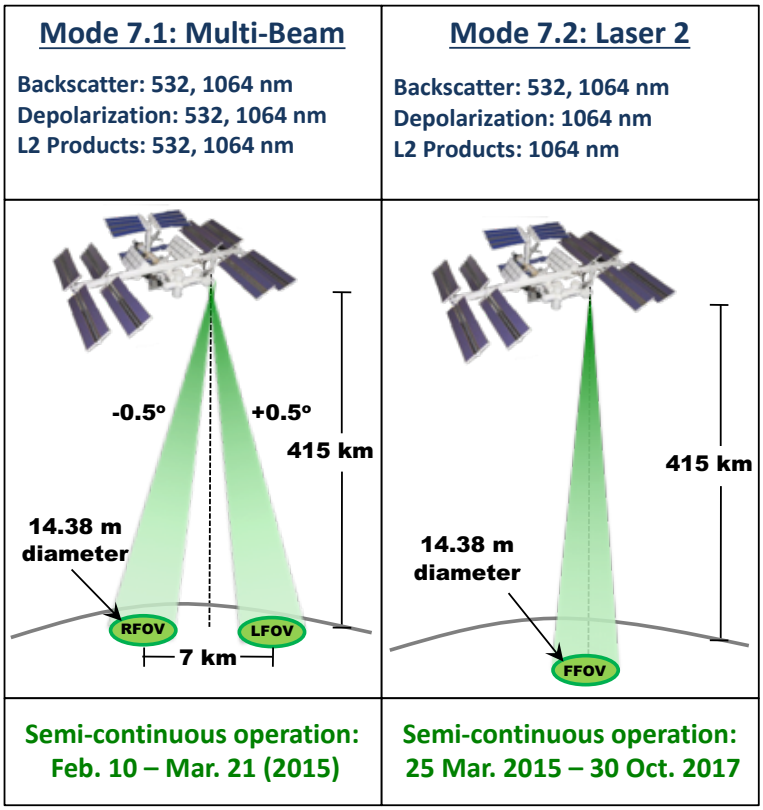

Figure 1. CATS two main Science Modes for operation, with details of each mode's capabilities and operational timeline.

5.0 CATS Level 2O Profile Data Products

The CATS L2O Profile data product includes day or night vertical profiles (approximately a half orbit) of geophysical parameters derived from Level 1 data, such as the vertical feature mask and profiles of cloud and aerosol properties (i.e. extinction, particle backscatter). The main parameters reported in the CATS L2O data product are identification of atmospheric features and optical properties of these layers.

Through analysis of the CATS Version 2-01 L2O data products, two main issues were identified that impact the L2O V3-00 Profile data product:

1. 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 the horizontal persistence tests, applied to nighttime data in V2-01 but not to daytime data, and adding code to use variables such as Cloud_350_Fraction, the Perpendicular ATB, and MERRA-2 relative humidity to better differentiate clouds and aerosols.
2. There were two updates to the algorithms for constrained lidar ratios.

- 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.
- 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 about these updates are found in the sections below.

5.1 Profiles of Optical Properties

Particulate Backscatter Coefficient (Validated Stage 2)

Particulate backscatter coefficients are reported for each 5 km profile and 60 m range bin in which atmospheric particulates (i.e., clouds or aerosols) were detected. Range bins in which no particulates were detected contain fill values 0.0) and bins where the backscatter could not be calculated are marked invalid (-999.9). Particulate backscatter coefficients have units of km^{-1} sr^{-1}. For Mode 7.2 data, only the 1064 nm particulate backscatter coefficients are reported, derived from the sum of the parallel and perpendicular backscatter measurements (i.e., $\beta_{1064\ total} = \beta_{1064\ parallel} + \beta_{1064\ perp}$). For Mode 7.1 data, both the 532 and 1064 nm particulate backscatter coefficients are reported, and both are derived from the sum of the parallel and perpendicular backscatter measurements. The CATS L1B nighttime backscatter calibrations, and thus accuracy of the nighttime attenuated total backscatter profiles, at both 532 and 1064 nm were improved for CATS V2-08 L1B data.

The daytime backscatter calibration was updated in V3-00 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. This improved accuracy propagates through many of the L2O data products, including the particulate backscatter coefficient profiles.

Particulate Backscatter Coefficient Uncertainty (Provisional)

For version 1.05, the uncertainty in the particulate total backscatter coefficient contained fill values (-999.9). For V2-00 and V3-00, the uncertainty in the particulate total backscatter coefficient is reported for each 5 km profile and 60 m range bin in which the appropriate particulates are detected. The values reported are absolute uncertainties, not

relative, thus the units are identical to the units of the particulate backscatter coefficients (km^{-1} sr^{-1}).

Total Depolarization Ratio (Validated Stage 2)
Pulsed lasers, such as the ones used in the CATS instrument, naturally produce linearly polarized light. Using a beam splitter in the receiver optics, the perpendicular and parallel planes of polarization of the backscattered light are measured. The linear volume total depolarization ratio is defined as the ratio of perpendicular total (Rayleigh plus particle) backscatter to parallel total backscatter, and has values between 0.2 and 0.6 for non-spherical particles such as ice crystals. Deriving accurate depolarization ratios from CATS data requires knowledge of the relative gain between the perpendicular and parallel channels of the CATS receiver, referred to as the polarization gain ratio (PGR). Total depolarization ratios are reported for each 5 km profile and 60 m range bin in which atmospheric particulates (i.e., clouds or aerosols) were detected. Range bins in which no particulates were detected contain fill values (-999.9).

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 total depolarization ratios for several granules, depending on how long the laser was off, until the laser polarization stabilizes. CATS Version 2-00 and V3-00 L2O data includes a Depolarization Quality Flag (Section 5.9) to notify users of granules with depolarization ratio values of poor quality.

Total Depolarization Ratio Uncertainty (TBD)
For version 1.05, the uncertainty in the total depolarization ratio contained fill values (-999.9). For V2-00 and V3-00, the uncertainty in the total depolarization ratio is reported for each 5 km profile and 60 m range bin in which the appropriate particulates are detected. The values reported are absolute uncertainties, not relative.

Extinction Coefficient (Validated Stage 1)
Particulate extinction coefficients are reported for each 5 km profile and 60 m range bin in which atmospheric particulates (i.e., clouds or aerosols) were detected. Range bins in which no particulates were detected contain fill values 0.0) and bins where the extinction could not be calculated are marked invalid (-999.9). Particulate extinction coefficients have units of km^{-1}. For Mode 7.2 data, only the 1064 nm particulate extinction coefficients are reported. For Mode 7.1 data, both the 532 and 1064 nm particulate extinction coefficients are reported. The particulate extinction coefficients are derived as outlined in the CATS ATBD.

The particulate extinction coefficients of all bins in which atmospheric clouds or aerosols are detected reported regardless of the lidar ratio selection method. Histograms of CATS L2O V1-05 cirrus optical depth exhibit a peak in the frequency distribution around a COD of 2.7 as a result of the CATS "modified default" lidar ratio algorithm. This issue is only apparent in CATS L2O V1-05 data when computing extinction and optical depth in cases where the lidar ratio was iteratively reduced in order to process to the bottom of the layer (Extinction QC_Flag = 2 [transparent] or 7 [opaque]). The algorithm was updated

for CATS L2O V2-00 to change the amount that the lidar ratio gets modified from a fixed value of 0.5 to the current lidar ratio adjusted by a scale factor. The value of scale factor is related to the two-way transmittance of the last high quality bin and/or the relative progress through the layer of the last high quality bin, depending on the situation. For cases where the lidar ratio was increased in order to stay within transmittance bounds (Extinction QC Flag= 3), the interval of the iteration remains a fixed value of 0.5.

For V3-00, the accuracy of the extinction coefficient at both wavelengths has improved as a result of:

- The more accurate daytime integrated attenuated backscatter due to the changes in the daytime calibration coefficient computation.
- 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 above cloud aerosols.
- 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.

Extinction Coefficient Uncertainty (Provisional)

For version 1.05, the uncertainty in the particulate extinction coefficient contained fill values (-999.9). For V2-00 and V3-00, the uncertainty in the particulate extinction coefficient are reported for each 5 km profile and 60 m range bin in which the appropriate particulates are detected. The values reported are absolute uncertainties, not relative, thus the units are identical to the units of the particulate extinction coefficient (km^{-1}).

Ice Water Content (Validated Stage 1)

Ice water content (IWC) is reported for each 5 km profile and 60 m range bin in which ice clouds were detected. Range bins in which no ice clouds were detected contain fill values (0.0) and bins where the ice water content could not be calculated are marked invalid (-999.9). IWC has units of gm^{-3}. For Mode 7.2 data, only the 1064 nm IWC is reported. For Mode 7.1 data, both the 532 and 1064 nm IWC is reported. The IWC is calculated as a parameterization function of the CATS ice particle extinction retrievals as outlined in the CATS ATBD. Thus, the changes discussed in the Extinction Coefficient Section will improve the accuracy of the IWC retrievals.

Ice Water Content Uncertainty (Provisional)

For version 1.05, the uncertainty in the IWC contained fill values (-999.9). For V2-00 and V3-00, the uncertainty in the IWC is reported for each 5 km profile and 60 m range bin in which ice particles are detected. The values reported are absolute uncertainties, not relative, thus the units are identical to the units of the IWC (gm^{-3}).

Multiple Scattering Factor (Provisional)

The multiple scattering factor, for each 5 km profile and 60 m range bin in which atmospheric particulates (i.e., clouds or aerosols) were detected, are reported at each wavelength according to layer type and subtype. Possible values range from just above 0, which indicates significant contributions to the backscatter signal from multiple

scattering, to 1, which corresponds to minimal (if any) multiple scattering (single scattering only). Multiple scattering effects are different for various aerosols particle types, ice particles, and water droplets. The CATS ATBD provides a discussion of multiple scattering factors for ice clouds and several aerosol types.

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. A value of 1.00 is still used for both wavelengths for aerosol multiple scattering effects.

5.2 Profiles of Feature Type

Feature Type (Validated Stage 2)
For each atmospheric layer, an assessment of the feature type (e.g., cloud vs. aerosol) is reported for each 5 km profile and 60 m range bin in which atmospheric particulate layers were detected. Range bins in which no layers were detected contain fill values (-999). The values that correspond to specific feature types are shown in Table 2. A comprehensive description of the feature types, including their derivation and physical significance, quality assessments, and guidelines for interpreting them can be found in the CATS ATBD.

Table 2. Definitions of the CATS Feature Type Parameter

Interpretation of Values
0 = Invalid
1 = Cloud
2 = Undetermined
3 = Aerosol

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:

- Horizontal Persistence Test: 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.

Cloud Phase (Validated Stage 2)

For each atmospheric layer defined as a cloud in the feature type parameter, an assessment of the cloud phase (e.g., ice vs. liquid water) is reported for each 5 km profile and 60 m range bin in which cloud layers were detected. Range bins in which no cloud layers were detected contain fill values (-999). The values that correspond to specific cloud phases are shown in Table 3. A comprehensive description of the cloud phases, including their derivation and physical significance, quality assessments, and guidelines for interpreting them can be found in the CATS ATBD. Statistical comparisons of CATS V1-05 ice and water cloud detection frequencies with CALIPSO V4.1 data yield very similar results.

Table 3. Definitions of the CATS Cloud Phase Parameter

Interpretation of Values
0 = invalid
1 = water cloud
2 = unknown cloud phase
3 = ice cloud

Aerosol Type (Validated Stage 1)

For each atmospheric layer defined as an aerosol in the feature type parameter, an assessment of the aerosol type is reported for each 5 km profile and 60 m range bin in which atmospheric particulate layers were detected. Range bins in which no aerosol layers were detected contain fill values (-999). The values that correspond to specific aerosol types are shown in Table 4. A comprehensive description of the aerosol types, including their derivation and physical significance, quality assessments, and guidelines for interpreting them can be found in the CATS ATBD.

For previous versions, the aerosol feature subtype is one of eight types: invalid, marine, polluted marine, dust, dust mixture, clean/background, polluted continental, smoke, and volcanic. Smoke aerosols consist primarily of soot and organic carbon (OC), while clean/background is a lightly loaded aerosol consisting of sulfates ($SO4^{2-}$), nitrates ($NO3^{-}$), OC, and Ammonium ($NH4^{+}$). Polluted continental is background aerosol with a substantial fraction of urban pollution. Marine is a hygroscopic aerosol that consists primarily of sea-salt (NaCl), whereas polluted marine is a mixture of marine with smoke, dust or polluted continental aerosols. Dust mixture is a mixture of desert dust and smoke or urban pollution (polluted continental). If the CATS observables do not clearly indicate one of these 8 aerosol types, the aerosol layer is interpreted as "invalid".

Table 4. Definitions of the CATS Aerosol Type Parameter

Interpretation of Values
0 = Invalid
1 = Marine
2 = Polluted Marine
3 = Dust
4 = Dust mixture
5 = Clean/Background
6 = Polluted Continental
7 = Smoke
8 = UTLS

The CATS L2O V1-05 aerosol typing algorithm was unable to classify polluted continental aerosols over water, as the algorithm required surface type and layer elevation and thickness criteria for discriminating spherical smoke and polluted continental aerosols owing to similarity between backscatter and depolarization properties. Therefore, in the V2-00 aerosol typing algorithm, simulated aerosols from the NASA Goddard Earth Observing System version 5 (GEOS-5) model are incorporated to help discriminate smoke from polluted continental aerosols when CATS observations (depolarization ratio, layer elevation, and layer thickness) alone could not identify an aerosol type for spherical aerosols. Aerosols in GEOS-5 are constrained by the utilization of the MODIS derived Quick Fire Emission Database (QFED) for carbonaceous aerosols, the use of advanced emission inventories of nitrates and sulfates, and through the assimilation of MODIS Aerosol Optical Thickness (AOT) for constraining the aerosol loading.

The CATS aerosol typing routine for L2O V2-00 now employs the GEOS-5 aerosol speciation information sampled along the ISS track to assist the algorithm in differentiating smoke aerosols from polluted continental aerosols over land only when GEOS-5 simulates an aerosol layer within the detection limits of CATS at the exact altitude of the CATS observed aerosol layer. The result is an increase of polluted continental aerosol detection, particularly over water, and a decrease in smoke aerosol detection over highly populated regions of the Earth (China, Europe, Eastern U.S.) in CATS L2O V2-00 data.

Comparing the frequency of occurrence of aerosol type between CATS and CALIPSO, it was determined that CATS had a high bias in smoke layers in regions where smoke is known to mix with dust (e.g. south Asia). Therefore, CATS depolarization-based thresholds for classifying dust and dust mixture were reduced from 0.30 and 0.20 to 0.25 and 0.15, respectively.

Superficial “striping” is also visible in the CATS L2O V1-05 aerosol type browse images for horizontally homogeneous dust and smoke aerosol layers. Horizontal persistence tests were added to the CATS aerosol typing algorithm to avoid this “striping” and report

aerosol types that are more consistent with the profiles in an 80 km range surrounding a specific 5 km CATS L2O V2-00 profile.
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.).

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.

Sky Condition (Validated Stage 2)
For each 5 km profile, an assessment of the sky condition (e.g., cloudy vs. clear) of the column is reported for each profile. The values that correspond to specific sky conditions are shown in Table 5.

Table 5. Definitions of the CATS Sky Condition Parameter

Interpretation
0 = clean skies (no clouds/aerosols)
1 = clear skies (no clouds)
2 = cloudy skies (no aerosols)
3 = hazy/cloudy (both clouds/aerosols)

Horizontal Resolution of Layer Detection
The horizontal resolution an atmospheric layer was detected at is reported for each atmospheric layer within a 5 km profile. The values correspond to the horizontal resolution needed to detect that specific layer. There are only three values that can be reported:

- 0 = a layer was not detected
- 5 = the layer was detected at 5 km
- 60 = the layer was detected at 60 km

Layers detected at 60 km are common in the CATS L2O V3-00 daytime data, but rarely reported in the nighttime data, as these layers are typically detected at 5 km.

Percent Opacity (Provisional)
The quantification of opacity is reported for each 5 km CATS L2O V3-00 profile. The values correspond to the fraction of the total number of L1B 350 m profiles that make up

that L2O 5 km profile in which no surface return was detected. For CATS, a profile is considered opaque if no surface return is detected in all L1B 350 m profiles that make up that L2O 5 km profile. The opacity flag has a value of either 1 (opaque profile) or 0 (transparent profile). Thus, the percent opacity will be 1.0 for opaque profiles, and some value less than 1.0 for transparent profiles. Please note that the opacity flag distinguishes when the backscatter signal becomes completely attenuated due to that feature.

5.3 Column Optical Properties

Column Optical Depth (1064 nm – Validated Stage 1, 532 nm - Provisional)
Cloud Optical Depth (1064 nm – Validated Stage 1, 532 nm - Provisional)
Aerosol Optical Depth (1064 nm – Validated Stage 1, 532 nm - Provisional)
The optical depth of all atmospheric particulate layers, clouds, and aerosol throughout the column are reported for each 5 km profile. The optical depths are obtained by integrating the 532 (Mode 7.1 only) and 1064 nm cloud and/or aerosol extinction profiles, reported in these profile products. Since the column optical depths are a column integral product, any large uncertainties or poor extinction retrievals from layers within the column (i.e. clouds or aerosols) will propagate downward and may impact the quality of all the column optical depths. Therefore, users are strongly encouraged to use the column optical depth uncertainties, extinction QC flag, and feature type score to assess the quality of the column optical depths.

CATS data users should be aware of three main things when using column optical depth data:

1. CATS is only capable of penetrating to the surface if the total column optical depth is less than ~4. If the column is opaque to the lidar, then the reported column optical depths are set to -1.0 because the lidar is only measuring the apparent base of the lowest feature observed, not the true optical depth of the column.
2. The extinction QC values in the column should be examined to determine if any of the extinction retrievals were bad. In general, solutions where the final lidar ratio is unchanged (extinction QC = 0) yield physically plausible solutions more often.
3. Features with invalid or undetermined feature type, cloud phase, or aerosol type, may impact the quality of the column optical depths. For example, if the top-most feature in the column has an unknown cloud phase, it is possible that the assigned lidar ratio may be incorrect, impacting the extinction retrieval for that feature and all the data below that feature.

The optical depth 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. Histograms of CATS L2O V1-05 cirrus optical depth exhibit a peak in the frequency distribution around a COD of 2.7 as a result of the CATS “modified default” lidar ratio algorithm. This issue is only apparent in CATS L2O V1-05 data when computing extinction and optical depth in cases where the lidar ratio was iteratively reduced in order to process to the bottom of the layer (Extinction QC_Flag = 2 [transparent] or 7

[opaque]). The algorithm was updated for CATS L2O V2-00 to change the amount that the lidar ratio gets modified from a fixed value of 0.5 to the current lidar ratio adjusted by a scale factor. The value of scale factor is related to the two-way transmittance of the last high-quality bin and/or the relative progress through the layer of the last high quality bin, depending on the situation. For cases where the lidar ratio was increased in order to stay within transmittance bounds (Extinction QC Flag= 3), the interval of the iteration remains a fixed value of 0.5.

For V3-00, the accuracy of the column optical depth at both wavelengths has improved as a result of:

- The more accurate daytime integrated attenuated backscatter due to the changes in the daytime calibration coefficient computation.
- 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 above cloud aerosols.
- 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.

As discussed above, CATS is only capable of penetrating to the surface if the total column optical depth is less than ~4. If the column is opaque to the lidar, then the reported column optical depths are set to -1.0 because the lidar is only measuring the apparent base of the lowest feature observed, not the true optical depth of the column. If users want to know the feature optical depth of a layer that resides above an opaque layer, or the AOD above an opaque water cloud, they should use the L2O Layer data product. Since some data users expressed a desire for the optical depth values of opaque layers 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).

Column Optical Depth Uncertainty (Provisional)
Cloud Optical Depth Uncertainty (Provisional)
Aerosol Optical Depth Uncertainty (Provisional)

There are three main sources (ignoring multiple scattering) of the uncertainty in the column optical depth, estimated at each wavelength:

- signal-to-noise ratio (SNR) within a layer
- calibration accuracy
- accuracy of the lidar ratio used in the extinction retrieval

Except for constrained solutions, where a lidar ratio estimate can be obtained directly from the attenuated backscatter data, lidar ratio uncertainties are almost always the dominant contributor to optical depth uncertainties, and the relative error in the layer optical depth will always be at least as large as the relative error in the layer lidar ratio. For version 1.05, the uncertainty in the column optical depth contains fill values (-999.9).

For V2-00 and V3-00, the uncertainty in the column optical depths is reported for each 5 km profile. The values reported are absolute uncertainties, not relative.

5.4 Meteorological Data (External)

For V3-00, meteorological and aerosol type information is now provided by MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) reanalysis data. In previous versions, CATS used the NASA Goddard Earth Observing System version 5 (GEOS-5) forecasts provided by the NASA Global Modeling and Assimilation Office (GMAO). MERRA-2 Reanalysis data provides the atmospheric temperature and pressure profiles for 72 vertical levels (0-85 km AGL) at a horizontal resolution of 10 seconds that is subset along the ISS orbit track, identical to the GEOS-5 forecasts. The molecular backscatter and extinction coefficients are computed using temperature and pressure from MERRA-2 (see ATBD for more details). These parameters are read in from the L1B data product and interpolated to the CATS 5 km L2O horizontal resolution. These parameters, listed below, are output in the Level 2O files for each 5 km profile and for each 533 CATS vertical bins:

1. **Pressure Profile**- Pressure, in millibars, reported for each 5 km L2O profile at the 533 CATS altitudes recorded in the Bin Altitude Array field. Pressure values are interpolated from the ancillary meteorological data provided by the MERRA-2.
2. **Relative Humidity Profile** - Relative humidity reported for each 5 km L2O profile at the 533 CATS altitudes recorded in the Bin Altitude Array field. Relative humidity values are interpolated from the ancillary meteorological data provided by the MERRA-2.
3. **Surface Wind Velocity** - Surface wind velocity, in meters per second, are reported for each 5 km L2O profile as eastward (zonal) and northward (meridional) surface wind stress. Surface wind speed values are interpolated from the ancillary meteorological data provided by the MERRA-2.
4. **Wind Velocity 10 m**- wind velocity 10 meters above the earth's surface, in meters per second, are reported for each 5 km L2O profile as eastward (zonal) and northward (meridional) surface wind stress. Wind velocity values are interpolated from the ancillary meteorological data provided by the MERRA-2.
5. **Temperature Profile** - Temperature, in degrees C, reported for each 5 km L2O profile at the 533 CATS altitudes recorded in the Bin Altitude Array field. Temperature values are interpolated from the ancillary meteorological data provided by the MERRA-2.
6. **Tropopause Height** - Tropopause height, in kilometers, reported for each 5 km L2O profile. Tropopause height values are interpolated from the ancillary meteorological data provided by the MERRA-2.
7. **Tropopause Temperature** - Tropopause temperature, in degrees C, reported for each 5 km L2O profile. Tropopause temperature values are interpolated from the ancillary meteorological data provided by the MERRA-2.
8. **Solar Azimuth Angle** – Solar azimuth angle, in degrees, reported for each 5 km L2O profile. Solar azimuth angle values are interpolated from the ancillary meteorological data provided by the MERRA-2.
9. **Solar Zenith Angle** - Solar zenith angle, in degrees, reported for each 5 km L2O

profile. Solar zenith angle values are interpolated from the ancillary meteorological data provided by the MERRA-2.

5.5 CATS Geolocation

CATS Geolocation (Validated Stage 2)

Knowledge of the location of the CATS laser spot on the earth is required for the useful analysis of the CATS backscatter data. The location of the CATS laser spots are calculated from the position, velocity, and attitude information found in the ISS Broadcast Ancillary Data (BAD) together with the known angular offset of the laser line-of-site (LOS) vector from the instrument's nadir vector in the CATS L1B processing. For more details about improvements to the CATS geolocation algorithms, please see the CATS L1B Products Quality Statement for Version 2.08. The geolocation parameters reported in the CATS L2O data products have three elements for each 5 km L2O profile. These elements represent the first, mean, and last value of the 13 L1B profiles that make up one 5km L2O profile:

1. **Index Top Bin (all IFOVs)** – The bin id of the CATS data frame where the top of the CATS profile is located, as computed from the ISS BAD.
2. **CATS Latitude (all IFOVs)** – Ground latitude of the CATS laser spot, in degrees, as computed from the ISS BAD.
3. **CATS Longitude (all IFOVs)** – Ground longitude of the CATS laser spot, in degrees, as computed from the ISS BAD.
4. **CATS Angle (all IFOVs)** – The off-nadir viewing angle of the CATS laser spot, in degrees, as computed from the ISS BAD.
5. **Lidar Surface Altitude (all IFOVs)** - This is the surface elevation at each laser IFOV footprint, in kilometers above local mean sea level, obtained from identifying the backscatter return of the earth's surface.

5.6 Instrument Parameters and Laser Energy

There are several parameters that report details on instrument constants, calibration, performance, and laser energy. These parameters are:

1. **Horizontal Resolution** - This is an HDF metadata field that defines the horizontal resolution of the CATS data profiles, which is currently set to 5 km.
2. **Bin Size** - This is an HDF metadata field that defines the size, in kilometers, of the CATS vertical (range) bins. The bin size is 60 meters or 0.06 km.
3. **Number Bins** - This is an HDF metadata field that defines the number of vertical bins in each CATS data frame. Since the CATS data frame ranges from -2.0 km to 28.0 km, and the bin size is 0.06 km, there are 533 bins in each profile.
4. **Number 5 km Profiles** - This is an HDF metadata field that defines the number of 5 km CATS L2O profiles in the granule file.
5. **Bin Altitude Array** – Altitude, in kilometers, at the middle of each of the 533 vertical bins in each CATS data frame, which ranges from roughly -2.0 km to 30.0 km.

5.7 Time and Profile Parameters

The following parameters are reported in the Level 2O data product to identify each 5 km CATS L2O record (profile).

1. **Profile UTC Date** - This is an HDF metadata field that defines the date (DDMMYYY) of each 5 km CATS L2O record.
2. **Profile UTC Time** - This is an HDF metadata field that defines the time, in fraction of the day, of each 5 km CATS L2O record. The time reported in the CATS L2O data products have three elements for each 5 km L2O profile. These elements represent the first, mean, and last value of the 13 L1B profiles that make up one 5km L2O profile
3. **Profile ID** - This is an HDF metadata field that contains the ID number of each 5 km CATS L2O record. For V3-00, the L2O profile numbers were updated to match the L1B profile numbers.
4. **Day Night Flag** - This is an HDF metadata field that identifies the illumination condition (day, night, twilight) of each 5 km CATS L2O record. In L2O V3-00, the local time of day is indicated with values of 0 (night), 1 (twilight), or 2 (day) as determined from the MERRA-2 solar azimuth and zenith angles.

5.8 Ancillary Data

There are two ancillary data parameters, other than those already listed from MERRA-2 and the ISS, in the CATS L2O data products:

1. **Surface Type (all IFOVs)** - International Geosphere/Biosphere Programme (IGBP) classification of the surface type at each laser IFOV footprint. The IGBP surface types reported by CATS are the same as those used in the CERES/SARB surface map.
2. **DEM Mean Elevation (all IFOVs)** - This is the surface elevation at each laser IFOV footprint, in kilometers above local mean sea level. The DEM for version prior to V2-08 were obtained from the 1x1 km GMTED2010 digital elevation map (DEM) (see **http://topotools.cr.usgs.gov/gmted_viewer/** for details). The CATS V2-08 L1B data release includes a new Digital Elevation Model (DEM) from JPL created for CloudSat and CALIPSO. The DEM has a horizontal resolution of ~500 m. For CATS L1B V2-08, the DEM from JPL is interpolated and reported in the data products with a horizontal resolution of 350 m.

5.9 Quality Flags

Depolarization Quality Flag

CATS V1-05 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 2-01 L2O data included a new Depolarization Quality Flag to notify users of granules with depolarization ratio values of poor quality. Granules with suspect depolarization values were indicated with values of 1 or 2.

CATS V3-00 L2O data includes changes to the values of the Depolarization Quality Flag, as well as the addition of more granules to the list of poor depolarization quality. 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 12. 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

Feature Type Score (Provisional)

The feature type score provides a numerical confidence level for the classification of layers by the CATS cloud-aerosol discrimination (CAD) algorithm. The feature type score is reported for each 5 km profile and 60 m range bin in which atmospheric particulate layers were detected. Range bins in which no layers were detected contain fill values (-999).

The CATS feature type score is similar to the CALIPSO CAD Score, but the CATS feature type score is an integer value ranging from -10 to 10 for each atmospheric layer (CALIPSO CAD Score ranges from -100 to 100). Table 7 illustrates that the sign of the feature type score identifies a layer as either cloud (positive) or aerosol (negative), while the magnitude of the feature type score represents the confidence in our classification. A value of 10 indicates complete confidence that the layer is a cloud, while -10 indicates the accurate classification of an aerosol layer. When the feature type score equals 0, the layer is just as likely to be a cloud as it is an aerosol, and thus the classification is undetermined. If the optical and physical properties of the layer are considered invalid for clouds and aerosols, these layers are assigned a feature type score of -999.

Table 7. The interpretation of the CATS Feature Type Score.

Layer Type	CAD Score
Cloud	**1 to 10**
Aerosol	**-10 to -1**
Undetermined	**0**
Bad Data	**-999**

The CATS CAD algorithm is a multidimensional probability density function (PDF) technique that is based on the CALIPSO algorithm. The PDFs were developed based on CPL measurements obtained during over 11 field campaigns and 10 years. The attributes of the operational CATS PDFs depend on the CATS mode of operations. Measured cloud/aerosol properties available include layer altitudes and thickness, attenuated backscatter, depolarization, and attenuated backscatter color ratio (1064/532-nm).

Ancillary data, such as mid-layer temperature can also be utilized. More details about the CATS CAD algorithm are available in the CATS ATBD.

The Feature Type Score was significantly improved for V3-00, especially for daytime data. This was achieved using the horizontal persistence tests, applied to nighttime data in V2-01 but not to daytime data, and adding code to use variables such as Cloud_350_Fraction, the Perpendicular ATB, and MERRA-2 relative humidity to better differentiate clouds and aerosols. More details are provided in section discussing the Feature Type variable.

Cloud Phase Score (Provisional)

The cloud phase score provides a numerical confidence level for the classification of cloud phase by the CATS cloud phase (CP) algorithm. For each cloud layer, the CP score is reported for each 5 km profile and 60 m range bin in which clouds were detected. Range bins in which no clouds were detected contain fill values (-999).

The CATS CP score is similar to the CATS Feature Type Score, but the sign of the CP score identifies a layer as either ice (positive) or liquid water (negative), while the magnitude of the CP score represents the confidence in our classification. A value of 10 indicates complete confidence that the layer is an ice cloud, while -10 indicates the accurate classification of a liquid water cloud. When the CP score equals 0, the layer is just as likely to be ice as it is liquid water, and thus the classification is undetermined. If the optical and physical properties of the layer are considered invalid for ice clouds and liquid water clouds, these layers are assigned a CP score of -999. More details about the CATS CP algorithm are available in the CATS ATBD. For V1-05, the cloud phase score was updated to represent less confidence in layers with mid-layer temperatures between 0 and -20 C. More details about the CATS CP algorithm are available in the CATS ATBD.

Extinction QC Flag

This is an integer indicating a specific extinction condition, as defined by Table 8.

Table 8. Definition of CATS Extinction QC Flag.

Interpretation of Values
-1 = calculation not attempted
0 = non-opaque layer extinction analysis nominal
1 = layer hit earth's surface before layer bottom reached, adjusted bottom
2 = lowering lidar ratio thru iteration process successful
3 = raising lidar ratio thru iteration process successful
4 = # of iterations maxed out, analysis stopped
5 = signal inside layer saturated before bottom, analysis stopped
6 = layer is opaque, layer OD= -1, initial lidar ratio accepted
7 = layer is opaque, layer OD= -1, lidar ratio iteration successful
8 = layer OD out of bounds (invalid) OD= -999.9
9 = layer analysis invalid because final lidar ratio out of bounds

5.10 Metadata Parameters

Below is a list of metadata parameters not discussed in the previous sections:

Parameter
ProductID
Product_Version_Number
Product_Creation_Date
Product_Creator
Granule_Start_DateTime
Granule_Stop_DateTime
Granule_Production_DateTime
Granule_Start_Latitude
Granule_Start_Longitude
Granule_Stop_Latitude
Granule_Stop_Longitude
Granule_Start_RDM
Granule_Stop_RDM
Granule_Start_Record_Number
Granule_Stop_Record_Number
L1B_Input_Version_Number

6.0 Data Release Versions

CATS Level 2 Operational Profile Data Product			
Night/Day Granules profile products			
Release Date	**Version**	**Data Date Range**	**Maturity Level**
March 2016	1.03	3/25/2015 to Present (Mode 7.2)	Provisional
June 2016	1.04	3/25/2015 to Present (Mode 7.2)	Provisional
Aug. 2016	1.05	2/10/2015 to Present (All Modes)	Provisional
July 2017	2.00	3/25/2015 to Present (All Modes)	Provisional/Validated Stage 1
Sept. 2017	2.01	2/10/2015 to Present (All Modes)	Provisional/Validated Stage 1
Oct. 2018	3.00	2/10/2015 to 10/30/17 (All Modes)	Provisional-Validated Stage 2