CATS L2O Profile Products Quality Statements
Version Release: 1.04

06 June 2016

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 has only been in operation for one year, many parameters in the L2O 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 3.0 (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 operates in three different modes using four 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 can no longer be used 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 has been limited to 1064 nm backscatter and depolarization ratio because issues with stabilizing the frequency of laser 2 prevent collection of science quality HSRL and 532 nm data.

- ***Mode 7.3: Demonstration of 355-nm profiling***. This mode was designed to use the injection-seeded laser operating at 1064, 532, and 355 nm to demonstrate 355-nm laser performance. Unfortunately, due to an unexpected failure in the laser optical path, CATS will not collect data in this mode.

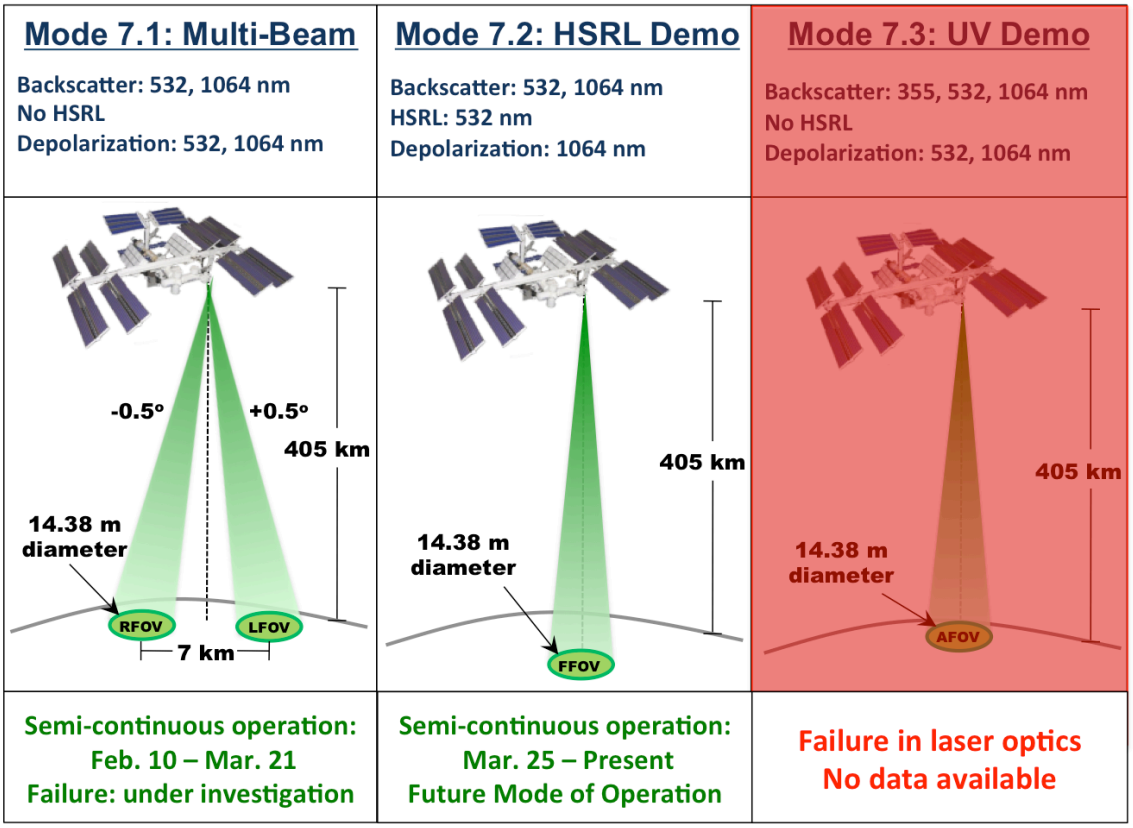

Figure 1. CATS three main Science Modes for operation, with details of each mode's capabilities and operational status.

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.

5.1 Profiles of Optical Properties

Particulate Backscatter Coefficient (Provisional)

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.

Particulate Backscatter Coefficient Uncertainty (TBD)

For version 1.03, the uncertainty in the particulate total backscatter coefficient contains fill values (0.0). For future versions, the uncertainty in the particulate total backscatter coefficient will be reported for each 5 km profile and 60 m range bin in which the appropriate particulates are detected. The values reported will be absolute uncertainties, not relative, thus the units will be identical to the units of the particulate backscatter coefficients (km^{-1} sr^{-1}).

Total Depolarization Ratio (Provisional)

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 (-999.99).

Total Depolarization Ratio Uncertainty (TBD)

For version 1.03, the uncertainty in the total depolarization ratio contains fill values (-999.99). For future versions, the uncertainty in the total depolarization ratio will be reported for each 5 km profile and 60 m range bin in which the appropriate particulates are detected. The values reported will be absolute uncertainties, not relative.

Extinction Coefficient (Provisional)

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.

Extinction Coefficient Uncertainty (TBD)
For version 1.03, the uncertainty in the particulate extinction coefficient contains fill values (0.0). For future versions, the uncertainty in the particulate extinction coefficient will be reported for each 5 km profile and 60 m range bin in which the appropriate particulates are detected. The values reported will be absolute uncertainties, not relative, thus the units will be identical to the units of the particulate extinction coefficient (km^{-1}).

Ice Water Content (Provisional)
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.

Ice Water Content Uncertainty (TBD)
For version 1.03, the uncertainty in the IWC contains fill values (0.0). For future versions, the uncertainty in the IWC will be reported for each 5 km profile and 60 m range bin in which ice particles are detected. The values reported will be absolute uncertainties, not relative, thus the units will be 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.

5.2 Profiles of Feature Type

Feature Type (Provisional)
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

Cloud Phase (Provisional)

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.

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 (Provisional)

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.

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 = Volcanic

For aerosols, the 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 7 aerosol types, the aerosol layer is interpreted as "invalid".

Sky Condition (Provisional)
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. A comprehensive description of the algorithms used to determine feature types can be found in the CATS ATBD.

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)

5.3 Column Optical Properties

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

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

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 1.03, the uncertainty in the column optical depth contains fill values (-888.8). For future versions, the uncertainty in the column optical depths will be reported for each 5 km profile. The values reported will be absolute uncertainties, not relative.

5.4 Meteorological Data (External)

NASA Goddard Earth Observing System version 5 (GEOS-5) forecasts provided by the NASA Global Modeling and Assimilation Office (GMAO) deliver a forecast of 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. 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 GMAO.
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 GMAO.
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 GMAO.

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 GMAO.
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 GMAO.
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 GMAO.
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 GMAO.
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 GMAO.
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 GMAO.

5.5 CATS Geolocation

CATS Geolocation (Validated Stage 1)

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. 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 computing from the ISS BAD.
3. **CATS Longitude (all IFOVs)** – Ground longitude of the CATS laser spot, in degrees, as computing from the ISS BAD.
4. **CATS Angle (all IFOVs)** – The off-nadir viewing angle of the CATS laser spot, in degrees, as computing 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.
4. **Day Night Flag** - This is an HDF metadata field that identifies the illumination condition (day or night) of each 5 km CATS L2O record.

5.8 Ancillary Data

There are two ancillary data parameters, other than those already listed from GMAO 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 Surface Altitude (all IFOVs)** - This is the surface elevation at each laser IFOV footprint, in kilometers above local mean sea level, obtained from the 1x1 km GMTED2010 digital elevation map (DEM) (see **http://topotools.cr.usgs.gov/gmted_viewer/** for details).

5.9 Quality Flags

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. For each atmospheric layer, 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 6 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 6. 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.

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.

Extinction QC Flag

This is an integer indicating a specific extinction condition, as defined by Table 7.

Table 7. Definition of CATS Extinction QC Flag.

Interpretation of Values
-1= calculation not attempted
0 = layer extinction analysis nominal
1 = layer hit earth's surface before layer bottom reached, adjusted bottom
2 = Tp_sq below min, lowering lidar ratio thru iteration process
3 = Tp_sq above max, raising lidar ratio thru iteration process
4 = # of iterations maxed out
5 = signal inside layer saturated before bottom
6 = layer is opaque, layer OD= -1
7 = open slot (not used)
8 = layer OD out of bounds (invalid) OD= -999.99
9 = layer OD 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 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	2/10/2015 to Present (All Modes)	Provisional