CATS L1B Products Quality Statements
Version 3.00

01 Oct. 2018

1.0 Introduction

This document offers a general quality assessment of the CATS Level 1B 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 L1B 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 L1B products are still assigned a product maturity level of provisional. Those products related to the 1064 nm backscatter data are designated as ValStage2.

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.

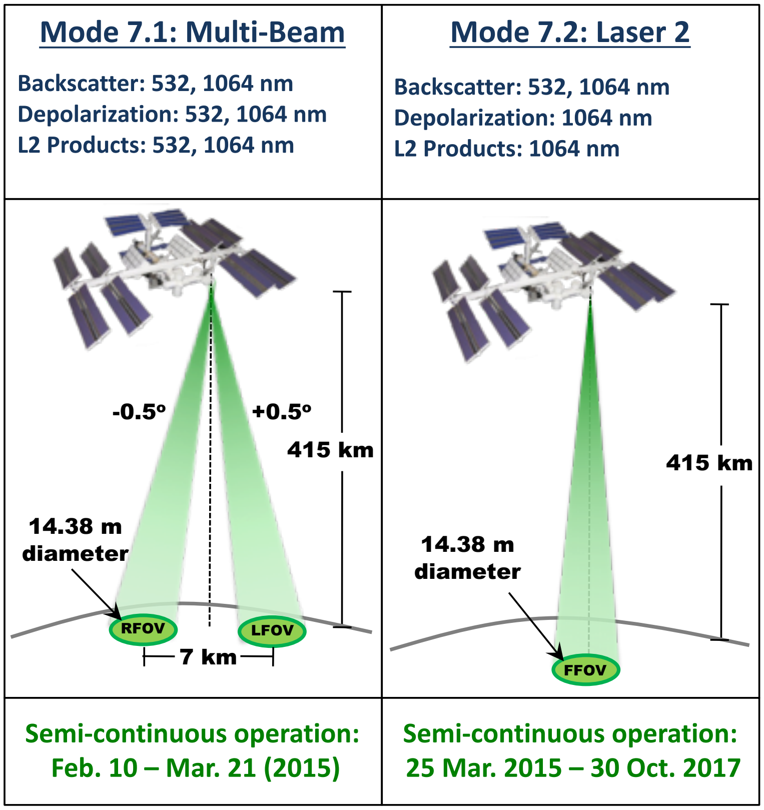

Figure 1. CATS two main Science Modes for operation, with details of each mode's capabilities and operational timeline.

5.0 CATS Level 1B Data Products

The CATS Level 1B data product includes day or night vertical profiles (approximately a half orbit) of data that have been calibrated, annotated with ancillary meteorological and spacecraft position data, and processed to sensor units. The main parameters reported in the CATS Level 1B data product are vertical profiles of attenuated backscatter and the depolarization ratio, which can be derived from these backscatter profiles.

5.1 Attenuated Backscatter Profiles

The primary product in the CATS Level 1B data is the calibrated backscatter, known as the attenuated total backscatter (ATB or β'), which has units of km^{-1} sr^{-1} and is reported at 532 and 1064 nm. The attenuated backscatter is the sum of the parallel and perpendicular polarization components (exception being Mode 7.2 532 nm data), as discussed in the CATS ATBD, and is derived from the calibrated, range-corrected, laser energy normalized, background subtracted raw photon count signal. Each 20 Hz (approximately 350 m along track distance) ATB profile has 533 elements that represent 60 m vertical bins that range from -2.0 to 30.0 km above mean sea level (AMSL).

The primary sources of uncertainty in the CATS attenuated backscatter signal are the calibration constant and signal noise. Thus, if the calibration constant is accurate, the CATS ATB profiles should compare favorably with the Rayleigh backscatter model above the first atmospheric layer of significance. 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 5.2.

Perpendicular Attenuated Backscatter

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 perpendicular polarization component of the CATS backscattered signal is reported in this field, in the same manner as profiles of the attenuated total backscatter. Additionally, vertical profiles of the CATS parallel backscatter can be acquired by simple subtraction of the perpendicular component from the total. 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 perpendicular attenuated backscatter for several granules, depending on how long the laser was off, until the laser polarization stabilizes. CATS Version 3-00 L1B data includes updates to the Depolarization Quality Flag (Section 5.8) to notify users of granules with depolarization ratio values of poor quality.

Attenuated Total Backscatter Uncertainty (Validated Stage 1)

The uncertainty in the CATS ATB is due to two main types of errors: systematic error and random error. The source of the systematic error in the CATS ATB is the uncertainty in the calibration constant and is estimated at 5-10% for 1064 nm at night (10-20% for daytime data). The random error in the ATB is dominated by noise in the lidar signal. The total uncertainty, sum of the systematic and random errors, in the CATS ATB at 532 (Mode 7.1) and 1064 nm is estimated at 10-20% for nighttime data and 20-30% for daytime data.

For version 3-00, the uncertainty in the ATB is reported for each 5 km profile and 60 m range bin. The values reported will be absolute uncertainties, not relative, thus the units will be identical to the units of the ATB (km^{-1} sr^{-1}). The ATB uncertainty parameter is provided for both wavelengths (532 and 1064 nm) and IFOVs (Left and Right) in Mode 7.1, but only the 1064 nm Fore FOV in Mode 7.2.

Mode 7.1: 1064 nm ATB (Validated Stage 2)

The CATS backscatter signal is more robust at 1064 nm than 532 nm. The minimum detectable backscatter for Mode 7.1 for cirrus clouds at 12 km and horizontal resolution of 5 km are shown in Table 2. The CATS 1064 nm signal at both night and day has a much lower minimum detectable backscatter than 532 nm. This is attributed to the fact that the laser is outputting more energy at 1064 nm (1.40 mJ compared to 0.88 mJ at 532 nm). Additionally, both CATS wavelengths in daytime conditions have lower signal to noise ratio (SNR) and higher minimum detectable backscatter for Mode 7.1 than nighttime. The poorer performance during daytime is due to solar background noise, typically an issue for daytime operation of any lidar.

Table 2. Minimum Detectable Backscatter: CATS Mode 7.1, 5km (hori.) and 60 m (vert.), for cirrus clouds at 15 km

Data	Type	Backscatter (km-1 sr-1)
CATS 1064	Night	1.80E-4 ± 0.49E-4
CATS 532	Night	1.00E-3 ± 0.54E-3
CATS 1064	Day	7.60E-3 ± 0.24E-3
CATS 532	Day	2.20E-2 ± 0.35E-2

Mode 7.1: 532 nm ATB (Provisional)

The CATS depolarization purity (ratio of the desired polarization component to the undesired component) at 1064 nm was measured in the lab at GSFC as greater than 100:1 before launch. However, the depolarization purity at 532 nm was measured at about 7:1. The attenuated total backscatter is the sum of the parallel and perpendicular polarization channels and the depolarization ratio is the ratio of perpendicular to parallel backscattered signal. Thus, the accuracy of these products depends on the accuracy of the backscatter measured in the parallel and perpendicular polarization channels.

The low depolarization purity at 532 nm, if uncorrected, causes a high bias in the perpendicular backscatter and depolarization ratio at 532 nm, as well as a low bias in the 1064-532 backscatter color ratio. To improve the accuracy of CATS these parameters at 532 nm, this data must be corrected for this poor depolarization purity at 532 nm. A separate measurement of perpendicular backscatter is necessary to compare to the CATS measurements at both 1064 and 532 nm and estimate a polarization gain ratio (PGR, relative gain between the parallel and perpendicular backscatter channels) term to correct for these biases. We use Cloud Physics Lidar (CPL) perpendicular backscatter data at 1064 nm from a CATS validation flight on 22 February 2015 over dense ice clouds to determine this PGR term (see ATBD for more details).

The CATS Version 2-04 data release included these PGR terms, which significantly reduced the high biases in CATS 532 nm attenuated total backscatter and depolarization ratio. However, the statistical analysis of these parameters for cirrus clouds still yielded values 10-20% higher than those observed in the CATS 1064 nm data and over 10 years of CPL data at 1064 nm. This was largely due to uncertainties of as much as 15% in the computed PGR term. These values have been updated for V2-07 based on more statistical samples of coincident CPL and CATS data, reducing the PGR term uncertainties to 4.5% and thus minimizing the higher biases in the 532 nm attenuated total backscatter and depolarization ratio to 5-10%.

Another issue data (only for 532 nm Mode 7.1 data) users should be aware of is unexpected non-linear behavior of the CATS data system at high photon count rates (similar but separate from detector deadtime). This issue is not found in nighttime data, and only present in ~1% of daytime data, but cause erroneous backscatter values for profiles with during local midday with highly scattering clouds present, which cause high solar background and count rates. An algorithm to correct these data was incorporated into the CATS L1B V2-08 data, but users that want to do quantitative statistical analysis of CATS data should filter out these profiles using the First Saturated Bin Index (532 nm) described in CATS L1B Quality Statements document. If the First Saturated Bin Index at 532 nm is set to 1 for a given profile, then that profile is affected by this issue and should not be included in the analysis.

Mode 7.1: Left FOV vs. Right FOV

Mode 7.1 includes 1064 and 532 nm backscatter measurements that are nearly identical for two beams, one aimed 0.5º to the left (LFOV) and one 0.5º to the right (RFOV). Although these IFOVs are both utilized in Mode 7.1, the telescope optics are aligned separately using piezoelectric actuators, which are moved to various positions to find the largest return signal.

Initial telescope alignment procedures were conducted 5-9 February, 2015 for the LFOV and RFOV. The result was slightly better alignment in the RFOV optical path, as minimum detectable backscatter for the RFOV was 10% lower than the LFOV for data up to 09 March 2015. Additional telescope alignment procedures for the LFOV in early March reversed the affect. Thus, the LFOV signal is more robust for data after 09 March, 2015. Users should keep this in mind when comparing data from the two IFOVs.

Mode 7.2: 1064 nm ATB (Validated Stage 2) and 532 nm ATB (Provisional)

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 did not have the necessary controls to fix the problem, so we recommend averaging the data to ***at least*** 5 km (roughly 14 raw 20 Hz profiles) when analyzing the 532 nm data.

Table 3. Minimum Detectable Backscatter: CATS Mode 7.2, 5km (hori.) and 60 m (vert.), for cirrus at 15 km

Data	Type	Backscatter (km-1 sr-1)
CATS 1064	Night	5.00E-5 ± 0.77E-5
CATS 532	Night	1.60E-2 ± 0.84E-3
CATS 1064	Day	1.30E-3 ± 0.24E-3
CATS 532	Day	3.80E-2 ± 1.05E-2

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 SNR and lower minimum detectable backscatter than the 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).**

The CATS Version 2-06 data release included an error in the algorithm that remaps the raw CATS data to the final CATS data frame (-2.0 to 30.0 km at 60 m vertical resolution). The error caused certain bins in Mode 7.2 to contain the same value of backscatter as the bin above. For CATS Version 2-07 this error has been corrected. Users that are quantifying statistics of backscatter or depolarization ratio are advised to use the V2-07 data for their analysis. Qualitative studies of approximate vertical distributions and layer boundaries are generally unaffected by the error.

The changes to the backscatter calibration for V2-08 discussed in Section 5.2 result in CATS 1064 nm attenuated total backscatter (Mode 7.2) that compare very favorably with CALIOP and modeled Rayleigh profiles at the same wavelength.

5.2 Calibration Constant and Uncertainties

Calibration Constant at 532 and 1064 nm (Validated Stage 1)

The 532 and 1064 nm calibration constants are determined as outlined in section 3.2.5 of the CATS ATBD. The un-calibrated CATS signal is averaged to 4-minute segments at night and 46-minute segments during daytime operation to create mean profiles of the un-calibrated CATS signal in the calibration region of 23-27 km. The 532 and 1064 nm CATS calibration coefficient (C) profiles at each segment are derived by normalizing the mean un-calibrated CATS signal to the mean molecular backscatter signal, determined using GMAO data, in the calibration region.

The final calibration coefficient at each segment (typically 6-8 mins for night, 46-47 mins for day) is simply the mean of the calibration coefficient profile from 23 to 27 km. For nighttime conditions, this provides 6-8 calibration coefficients per granule compared to only 1-2 per daytime granules. The final calibration constant is computed by either calculating the mean of the calibration coefficient data points in each granule or by a linear fit (pre-determined by Mode and SNR). If the calibration coefficient at a specific segment does not meet a threshold value, it is not used in the average or fit. In daytime granules, it is possible that no calibration coefficients meet these threshold values. When this occurs, a default calibration constant is set for the entire granule based on historical data and/or manual normalization to the modeled Rayleigh signal.

The backscatter calibrations (1064 nm in both modes, 532 nm in Mode 7.1) have been improved for CATS Version 2-08 L1B data. Detailed comparisons of CATS V2-07 1064 nm attenuated total backscatter data with CALIPSO 1064 nm data and modeled Rayleigh 1064 nm profiles revealed a low bias in CATS V2-07 attenuated total backscatter values due to higher uncertainties in the correction for molecular folding than expected. For V2-08, the molecular folding correction factor, alpha, is computed every 10 seconds (as opposed to once per granule in earlier versions) and more iterations were added. In addition, the altitude range for computing solar background counts was changed to 33-35 km to remove effects of multiple scattering from liquid water clouds near the surface. The molecular folding slope (22-26 km) and calibration (now 22-26 km) altitudes were also adjusted for more accurate estimates and consistency with one-another.

For V3-00, 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.

Calibration Constant Uncertainty (Provisional)

The uncertainty in the CATS calibration constant is due to two main types of errors: systematic error and random error. The systematic error in the CATS calibration constant has four sources:

1) Uncertainty in the stratospheric scattering ratios provided by CALIPSO
2) Uncertainty in the molecular backscatter coefficient derived from the GMAO data
3) Uncertainty in the background transmission from molecules and ozone in the atmosphere
4) Errors induced by non-ideal optical performance of the CATS lidar system.

The total relative systematic error in the calibration constant is estimated to be 5%.

The random error in the calibration constant results from normalizing the 532 and 1064 nm signals to the modeled molecular signal and is dominated by noise in the lidar signal. This error can be estimated by determining the variability of the intermediate calculated coefficients computed at each averaging segment (6-7 minutes for nighttime data) that are averaged to produce the final calibration constants. Typical values of the random error for the CATS calibration constant are 5-7% at 532 nm and 1064 nm. Thus the total uncertainty, sum of the systematic and random errors, in the CATS calibration constants at 532 and 1064 nm is estimated at 5-10%.

5.3 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 interpolated to the CATS vertical bin width of 60 m over a range of 0 to 60 km AMSL to better match the vertical structure of the CATS lidar backscatter data. These parameters, listed below, are output in the Level 1B files for each 10 Hz profiles reported by MERRA-2 and for each 533 CATS vertical bins:

1. **Met Data Latitude** - This is an HDF metadata field that defines the latitudes of the ancillary meteorological data (i.e., temperature, pressure, and relative humidity).
2. **Met Data Longitude** - This is an HDF metadata field that defines the longitudes of the ancillary meteorological data (i.e., temperature, pressure, and relative humidity).
3. **Met Data Date** - This is an HDF metadata field that defines the date (DDMMYYY) of the ancillary meteorological data (i.e., temperature, pressure, and relative humidity).
4. **Met Data Time** - This is an HDF metadata field that defines the time, in fraction of the day, of the ancillary meteorological data (i.e., temperature, pressure, and relative humidity).
5. **Pressure Profile**- Pressure, in millibars, reported for each MERRA-2 profile at the 533 CATS altitudes recorded in the Bin Altitude Array field.
6. **Relative Humidity Profile** - Relative humidity reported for each MERRA-2 profile at the 533 CATS altitudes recorded in the Bin Altitude Array field. Relative humidity values are obtained from the ancillary meteorological data provided by the MERRA-2.
7. **Surface Wind Velocity** - Surface wind velocity, in meters per second, are reported for each MERRA-2 profile as eastward (zonal) and northward (meridional) surface wind stress. Surface wind speed values are obtained from the ancillary meteorological data provided by the MERRA-2.
8. **Temperature Profile** - Temperature, in degrees C, reported for each MERRA-2 profile at the 533 CATS altitudes recorded in the Bin Altitude Array field. Temperature values are obtained from the ancillary meteorological data provided by the MERRA-2.
9. **Tropopause Height** - Tropopause height, in kilometers, reported for each MERRA-2 profile. Tropopause height values are obtained from the ancillary meteorological data provided by the MERRA-2.
10. **Tropopause Temperature** - Tropopause temperature, in degrees C, reported for each MERRA-2 profile. Tropopause temperature values are obtained from the ancillary meteorological data provided by the MERRA-2.
11. **Ozone Mixing Ratio** – Ozone mixing ratio, in g/g, reported for each MERRA-2 profile at the 533 CATS altitudes recorded in the Bin Altitude Array field.
12. **Molecular Backscatter (532 & 1064 nm)** – Molecular Backscatter Coefficient, in units $km^{-1}sr^{-1}$, reported for each MERRA-2 profile. Molecular backscatter values are computed from the ancillary meteorological data (temperature and pressure) provided by the MERRA-2.

13. **Molecular 2-Way Transmission (532 & 1064 nm)** – Molecular 2-way transmission reported for each MERRA-2 profile. Molecular 2-way transmission is estimated from the molecular backscatter values, which are computed from the ancillary meteorological data (temperature and pressure) provided by the MERRA-2.

5.4 ISS Position and CATS Geolocation

ISS Position Variables (External)

The ISS Broadcast Ancillary Data (BAD), reported on the ISS at a rate of 1 Hz, contains time and position information of the ISS required for CATS science and alignment processing. The CATS instrument ingests the ISS BAD and reports these parameters in the raw data files at a 20 Hz rate, where the values are repeated in 20 profiles before refreshing, except latitude and longitude, which are interpolated. The parameters below are reported in the CATS L1B products:

1. **ISS Altitude** – Altitude of the ISS, in kilometers, reported for each 20 Hz CATS profile originating from the ISS BAD.
2. **ISS CTRS Position XYZ** – Conventional Terrestrial Reference System position values of the ISS, in feet, reported for each 20 Hz CATS profile originating from the ISS BAD. This array has three dimensions: x, y, z.
3. **ISS CTRS Velocity XYZ** – Conventional Terrestrial Reference System velocity values of the ISS, in feet per second, reported for each 20 Hz CATS profile originating from the ISS BAD. This array has three dimensions: x, y, z.
4. **ISS Roll Angle** – Roll angle of the ISS, in degrees, reported for each 20 Hz CATS profile originating from the ISS BAD.
5. **ISS Pitch Angle** – Pitch angle of the ISS, in degrees, reported for each 20 Hz CATS profile originating from the ISS BAD.
6. **ISS Yaw Angle** – Yaw angle of the ISS, in degrees, reported for each 20 Hz CATS profile originating from the ISS BAD.
7. **ISS Latitude** – Ground latitude of the ISS, in degrees, reported for each 20 Hz CATS profile originating from the ISS BAD.
8. **ISS Longitude** – Ground longitude of the ISS, in degrees, reported for each 20 Hz CATS profile originating from the ISS BAD.

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 can be 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. The computation requires a series of coordinate transformations and rotations to find the geodetic latitude and longitude of the laser spot at the height of the Digital Elevation Model (DEM). The geolocation parameters reported in the CATS L1B data products are:

1. **Index Top Bin (all IFOVs)** – The bin id of the top of the CATS data profile, as

computing 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.

Over rugged terrain, differences are observed between the DEM and surface altitude detected using the lidar signal in earlier releases of CATS L1B data. These differences are attributed to two factors.

1) CATS is mounted on the Japanese Experiment Module-Exposed Facility (JEM-EF), which is a distant extremity of the ISS. It is reasonable to assume that an angular offset exists between the ISS central body, where the BAD are measured, and the CATS local reference system on the JEM-EF. However, the angle between the ISS point of reference for the position data and CATS instrument is unknown and assumed to be zero in V2.05. This assumption is likely a main source of error in the CATS V2.05 geolocation algorithm.
2) A communications defect in which a time lag (1-2 seconds in some cases) from when the ISS position data is collected to when it is included into the CATS data stream occurs. Statistically this time lag is found to be 1 second in 80% of CATS data profiles, so the L0 data is corrected by adjusting the ISS position data by 1 second. However, the time lag is not constant so instances when the time lag is not 1 second do occur and users should be careful when analyzing surface returns over rugged terrain.

The angular offset between the ISS point of reference for the position data and CATS instrument was determined using statistical analysis of the differences between the surface altitude detected using the CATS backscatter data and the DEM of the latitude and longitude computed using the V2.05 algorithm. These differences can be reduced or eliminated by applying a constant angular correction to the yaw, pitch, and roll parameters that are determined from the BAD quaternion values. In each scene, systematic incremental adjustments were made to the yaw, pitch, and roll until the surface height values agree. The offsets to the ISS yaw and roll were constant for the many scenes that were tested but the pitch offset varied. An empirical distribution function of the pitch offsets was derived from many cases and the mean and median were determined from the distribution. The mean pitch offset was used as the correction.

From this analysis, the angles between the ISS point of reference for the position data and CATS instrument was determined as 2.00 degrees for yaw, -0.50 degrees for roll, and -0.25 degrees for pitch. These "offset" angles have been incorporated into the V2.06 algorithms. Figure 2 shows the CATS attenuated total backscatter at 1064 nm for 19 Aug. 2015 (top panel) as the instrument passed over the continent of Africa (ISS track shown in blue in bottom panel, with the red track indicating the scene plotted). The DEM surface altitude is overlaid (green) for the CATS footprint geolocation computed using the V2.06 algorithm in the top panel, which shows very good agreement with the CATS attenuated total backscatter. The variation in the pitch correction is caused by the uncorrected time lag, which can shift the laser spot geolocation compared to the CATS backscatter data along the track of the ISS, as shown in Figure 3.

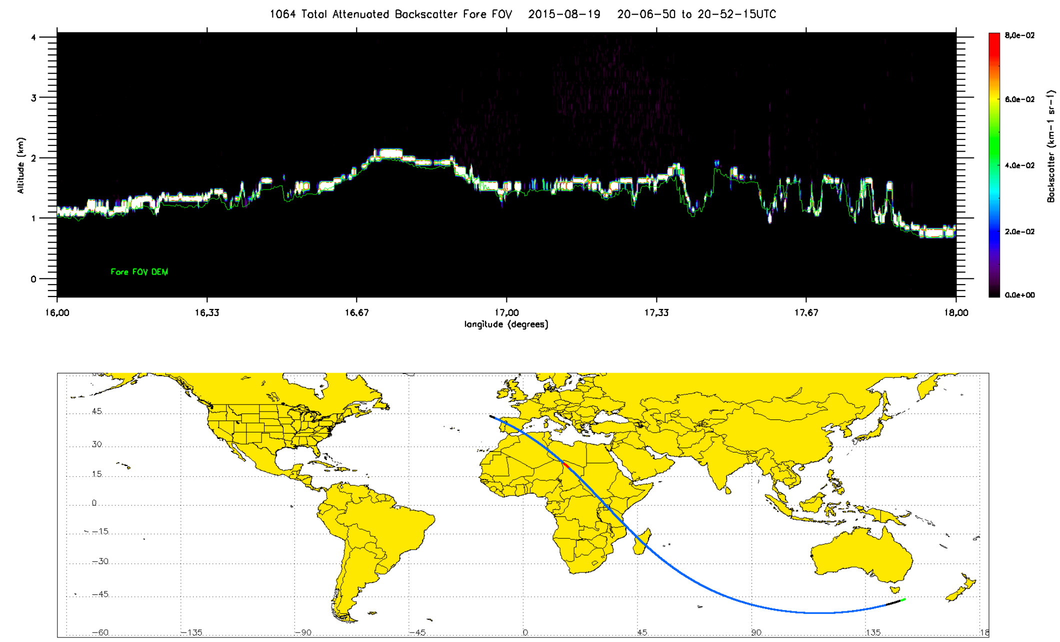

Figure 2. Comparison of the CATS attenuated total backscatter at 1064 (top panel) shows that the surface detected by the instrument (white colors) agrees favorably with the DEM values (green).

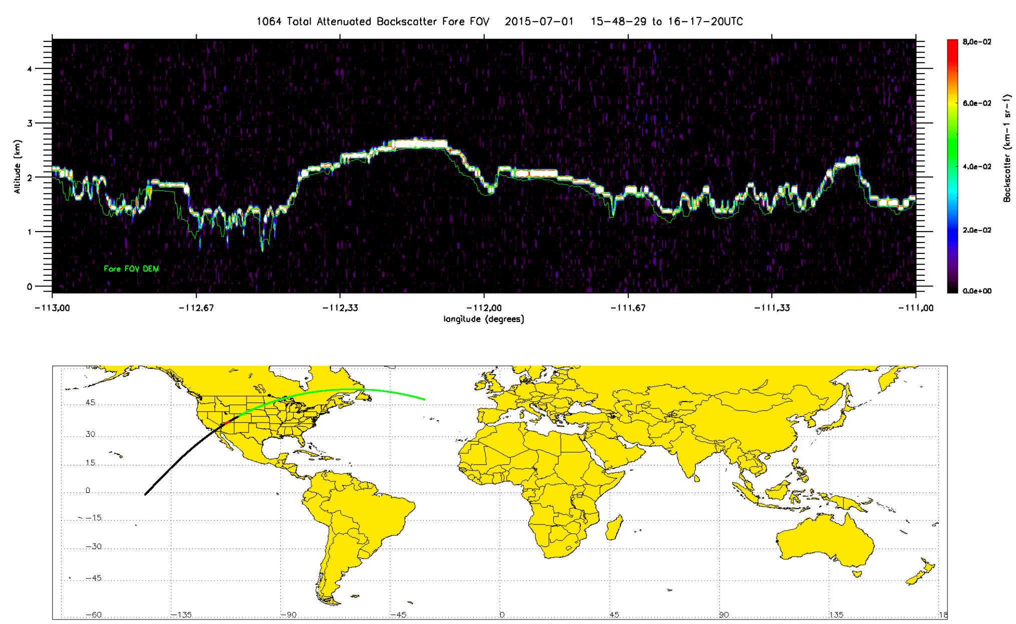

Figure 3. Comparison of CATS attenuated total backscatter at 1064 (top panel) shows that the surface detected by CATS (white colors) is offset slightly along the CATS track compared to DEM values (green).

The CATS Version 2-07 L1B data is corrected for the time offset (described in #2 on the previous page) by adjusting the ISS position data by 1 second. However, the time lag is not constant so instances when the time lag is not 1 second do occur. For CATS Version 2-08 L1B, an algorithm was created to compare the Earth's surface height as determined by the CATS ground signal to the DEM over rugged terrain. An offset is computed and the geolocation is adjusted to correct for these cases when the time offset is not 1 second. The Earth's surface height as determined by the CATS ground signal now compares very well with the new JPL DEM, showing the improvement in the CATS footprint geolocation.

5.5 Instrument Parameters and Laser Energy

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

1. **Profile Repetition Rate** - This is an HDF metadata field that defines the repetition rate of the CATS data profiles, which is currently set to 20 Hz.
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 profile. 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. **Laser Repetition Rate** - This is an HDF metadata field that defines the repetition rate of the CATS laser used to collect the data. For laser 1, the repetition rate is 5 kHz. For laser 2, the repetition rate is 4 kHz. These raw profiles are accumulated into the 20 Hz profile data.
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.
6. **Calibration Top Altitude** – Top altitude, in kilometers, of the vertical region in which the CATS backscatter data is normalized to the molecular backscatter model.
7. **Calibration Bottom Altitude** – Bottom altitude, in kilometers, of the vertical region in which the CATS backscatter data is normalized to the molecular backscatter model.
8. **Polarization Gain Ratio (532 & 1064 nm, all IFOVs)** – The relative gain between the perpendicular and parallel channels of the CATS receiver, referred to as the polarization gain ratio (PGR).
9. **Polarization Gain Ratio Uncertainty (532 & 1064 nm, all IFOVs)** – The uncertainty in the polarization gain ratio (PGR), computed using statistics of the PGR.
10. **Total Background and Variance (532 & 1064 nm, all IFOVs)** – The solar background counts and variance computed using the mean and variance of the total photon counts (perpendicular plus parallel) from the CATS vertical bins below the ground (-2.0 to 0.0 km).

11. **Perpendicular Background and Variance (532 & 1064 nm, all IFOVs)** – The solar background counts and variance computed using the mean and variance of perpendicular channel photon counts from the CATS vertical bins below the ground (-2.0 to 0.0 km).
12. **Laser Energy Average (532 & 1064 nm)** – The average laser energy from the laser shots accumulated to make a 20 Hz data profile (i.e. 250 shots for laser 2).
13. **Laser Energy Variance (532 & 1064 nm)** – The variance of the laser energy from the laser shots accumulated to make a 20 Hz data profile (i.e. 250 shots for laser 2).
14. **First Saturated Bin Index (532 & 1064 nm, all IFOVs)** – The bin number of the first saturated bin for each 20 Hz CATS data profile.
15. **Alpha Value (532 & 1064 nm, all IFOVs)** – Scaling factor used to correct CATS data for molecular folding resulting from the high repetition rate of the laser.

For version V2-06 of the CATS L1A and L1B products, an iterative computation of the alpha parameter is employed. A few hundred nighttime granules were used to derive a relationship between the below ground raw photon count (averaged for the granule) and the alpha parameter. This relationship was found to be a linear dependence. In V2-06 L1A processing this relationship was used to compute an initial value of alpha, which was then applied to the entire granule. The average NRB signal profile between 28 and 20 km is then computed for the granule, as is the average molecular profile. The slope of both of these profiles are computed and compared to each other. If the slopes differ by a pre-defined threshold, the value of alpha is adjusted and the whole granule is reprocessed. Alpha is adjusted based on the sign and magnitude of the slope difference. If, after processing the granule again, the slope difference is still greater than the threshold, the granule is quarantined (put in a holding directory). In the automated processing of over 5,000 granules, only about 50 had to be quarantined. For these files, the value of alpha will be determined manually to assure alpha is of the appropriate magnitude.

5.6 Time and Profile Parameters

The following parameters are reported in the Level 1B data product to identify each 20 Hz CATS record (profile).

1. **Profile UTC Date** - This is an HDF metadata field that defines the date (DDMMYYY) of each 20 Hz CATS record.
2. **Profile UTC Time** - This is an HDF metadata field that defines the time, in fraction of the day, of each 20 Hz CATS record.
3. **Profile ID** - This is an HDF metadata field that contains the ID number of each 20 Hz CATS record.
4. **Day Night Flag** - This is an HDF metadata field that identifies the illumination condition (day, night, twilight) of each 20 Hz CATS record. In L1B 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.

5.7 Ancillary Data

There are two ancillary data parameters, other than those already listed from GMAO and the ISS, in the CATS L1B 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.

5.8 Quality Flags

Depolarization Quality Flag

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 2-08 L1B 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 L1B 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 4. 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

Quality Control Flag

This is an unsigned 32-bit integer with each bit indicating a specific error condition, as defined by Table 2.

The first bit identifies profiles that suffer from erroneous values due to non-linear data system-detection issues. Bits 2-9 identify any missing data for a given wavelength or IFOV. Bits 10-13 identify profiles in which a large off-nadir angle was observed due to ISS motion. Large off-nadir angles change the vertical bin size and thus the vertical registration of the CATS data. Also, it can cause inaccuracies in the geolocation of all the CATS IFOV laser footprints as noted in bit 14. Bits 15-24 are used to identify granules with poor calibration performance and likely poor signal performance. Bits 25-27 represent profiles when the reported laser energy is below the expected energy. Finally, bit 28 identifies profiles where the signal is below a SNR threshold, likely do to poor alignment of the instrument telescope. Please note that this table was defined before launch, so 355 nm and AFOV flags were included before knowledge of the failure in the optical path of Mode 7.3.

CATS Quality Control Flag – Level 1B

Bits	QC Flag 1: Bit Interpretation
1	Non-Linear Mode 7.1 data system issue at 532 nm
2	532 nm parallel channel missing LFOV*
3	532 nm perpendicular channel missing LFOV*
4	1064 nm parallel channel missing LFOV*
5	1064 nm perpendicular channel missing LFOV*
6	532 nm parallel channel missing RFOV
7	532 nm perpendicular channel missing RFOV
8	1064 nm parallel channel missing RFOV
9	1064 nm perpendicular channel missing RFOV
10	Large off-nadir pointing angle, LFOV
11	Large off-nadir pointing angle, RFOV
12	Large off-nadir pointing angle, AFOV
13	Large off-nadir pointing angle, FFOV
14	Not geolocated (On-board Timing Algorithm)
15	Data below calibration threshold, 355 nm
16	Data below calibration threshold, 532 nm LFOV*
17	Data below calibration threshold, 532 nm RFOV
18	Data below calibration threshold, 1064 nm LFOV*

Bits	QC Flag 1: Bit Interpretation
19	Data below calibration threshold, 1064 nm RFOV
20	Historical calibration constant used, 355 nm
21	Historical calibration constant used, 532 nm LFOV*
22	Historical calibration constant used, 532 nm RFOV
23	Historical calibration constant used, 1064 nm LFOV*
24	Historical calibration constant used, 1064 nm RFOV
25	Single shot 532 laser energy below data quality threshold (low energy)
26	Single shot 1064 laser energy below data quality threshold (low energy)
27	Single shot 355 laser energy below data quality threshold (low energy)
28	Poor alignment suspected (low SNR at 532 nm)

*Used in Mode 7.2 (FFOV)

5.9 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
Ephemeris_Files_Used
GEOS_Version
GEOS_Files_Used

6.0 Data Release Versions

CATS Level 1B Data Product			
Night/Day Granules geolocated, calibrated lidar profiles			
Release Date	**Version**	**Data Date Range**	**Maturity Level**
June 2015	2.04	2/10/2015 to 3/21/2015 (Mode 7.1)	Provisional
August 2015	2.05	3/25/2015 to 8/1/2015 (Mode 7.2)	Provisional
February 2016	2.06	3/25/2015 to Present (All Modes)	Provisional/Validated Stage 1
June 2016	2.07	2/10/2015 to Present (All Modes)	Provisional/Validated Stage 1
July 2017	2.08	2/10/2015 to Present (All Modes)	Provisional-Validated Stage 2
Oct. 2018	3.00	2/10/2015 to 10/30/17 (All Modes)	Provisional-Validated Stage 2