# ATLAS/ICESat-2 L3A Calibrated Backscatter Profiles and Atmospheric Layer Characteristics, Version 7

## USER GUIDE

**How to Cite These Data**

As a condition of using these data, you must include a citation:

Palm, S. P., Yang, Y., Herzfeld, U. C., Hancock III, D. W., Barbieri, K. A., Wimert, J., & the ICESat-2 Science Team. (2025). *ATLAS/ICESat-2 L3A Calibrated Backscatter Profiles and Atmospheric Layer Characteristics* (ATL09, Version 7). [Data set]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/ATLAS/ATL09.007 [Date Accessed].

FOR QUESTIONS ABOUT THESE DATA, CONTACT NSIDC@NSIDC.ORG

FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/ATL09

National Snow and Ice Data Center

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# 1 DATA DESCRIPTION

The ATL09 data product is described in detail in the ICESat-2 Algorithm Theoretical Basis Document for the Atmosphere, Part I: Level 2 and 3 Data Products (ATBD for ATL04/09, V7 | https://doi.org/10.5067/2Z50X3MKTVCE) and Part II: Detection of Atmospheric Layers and Surface Using a Density-Dimension Algorithm (ATL04/09 ATBD Part II, V6 | https://doi.org/10.5067/CP08GNGYS4YJ ; V7 is forthcoming).

## 1.1 Summary

ATL09 contains calibrated, attenuated backscatter profiles (CAB), layer-integrated attenuated backscatter, blowing snow, and other parameters including cloud and aerosol layer height and atmospheric characteristics. The data were acquired by the Advanced Topographic Laser Altimeter System (ATLAS) instrument on board the ICESat-2 observatory.

## 1.2 File Information

### 1.2.1 Format

Data are provided as HDF5-formatted files.

### 1.2.2 File Naming Convention

Data files utilize the following naming convention:

`ATL09_[yyyymmdd][hhmmss]_[ttttccss]_[vvv_rr].h5`

Example:

`ATL09_20200813233552_07580801_007_01.h5`

The following table describes the file naming convention variables:

Table 1. File Naming Convention Variables and Descriptions

| Variable | Description |
|---|---|
| ATL09 | ATLAS/ICESat-2 L3A Calibrated Backscatter Profiles and Atmospheric Layer Characteristics data product |
| yyyymmdd | Year, month, and day of data acquisition |
| hhmmss | Hour, minute, and second of data acquisition (UTC) |
| tttt | Reference Ground Track (RGT). The ICESat-2 mission has 1,387 RGTs, numbered from 0001 to 1387. |

| Variable | Description |
|---|---|
| cc | Cycle number. Each of the 1387 RGTs is targeted in the polar regions once every 91 days. The cycle number tracks the number of 91-day periods that have elapsed since ICESat-2 entered the science orbit. |
| ss | Region number, always "01" for ATL09.[1] |
| vvv_rr | Version and revision number.[2] |

[1] Some ATLAS/ICESat-2 products (e.g., ATL03) are provided as files that span 1/14th of an orbit. As such, these products' file names specify a segment number that ranges from 01 to 14. Because ATL09 data files span one full orbit, the segment number is always set to 01.

[2] Occasionally, NSIDC receives reprocessed granules from our data provider. These granules have the same file name as the original (i.e., date, time, ground track, cycle, and region number), but the revision number has been incremented. Although NSIDC deletes the superseded granule, the process can take several days. If you encounter multiple granules with the same file name, please use the granule with the highest revision number.

Each data file has a corresponding XML file that contains additional science metadata. XML metadata files have the same name as their corresponding `.h5` file, but with `.xml` appended.

### 1.2.3 File Contents

A complete list of all ATL09 parameters is available in the ATL09 Data Dictionary.

ATL09 data are provided as granules (files) that span one orbit (i.e., one RGT). Within data files, similar variables such as science data, instrument parameters, orbit information, and metadata are grouped together according to the HDF model. ATL09 data files contain the top-level groups shown in the following figure:

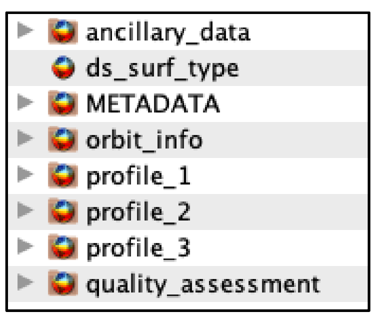


Figure 1. ATL09 top-level data groups.

The following sections summarize the structure and primary variables of interest in ATL09 data files. Additional details are available in "Section 4.2 | L3 Outputs" of the ATL04/09 ATBD Part I.

#### 1.2.3.1 ancillary_data

Ancillary information such as product and instrument characteristics and processing constants.

#### 1.2.3.2 ds_surf_type

This parameter, stored at the top level alongside the data groups, is a dimension scale variable indexing the surface type array (`/profile_[x]/surf_type`).

#### 1.2.3.3 METADATA

ISO19115 structured summary metadata for the granule, including content that describes the required geospatial information. The version(s) of the input files are included in the file name attribute under the `Lineage` group.

#### 1.2.3.4 orbit_info

Parameters that are constant for a granule, such as the RGT number, cycle number, and spacecraft orientation (`sc_orient`).

#### 1.2.3.5 profile_[x]

The `profile_1`, `profile_2`, and `profile_3` data groups each contain three subgroups:

**`/bckgrd_atlas/`**
ATLAS 50-shot background data and derivations

**`/high_rate/`**
Parameters related to CAB at 25 Hz, including CAB profiles (`cab_prof`) from -1 to 20 km for the leftmost, center, and rightmost ground tracks (strong beams) with respect to the satellite direction of motion; latitudes and longitudes; parameters related to the background calculation; blowing snow layer characteristics; cloud characteristics; atmospheric layer characteristics; and high-, medium-, and low-confidence signal photon counts and statistics (from ATL03 processing).

**`/low_rate/`**
Parameters related to atmospheric characteristics at 1 Hz, including low-resolution blowing snow layer characteristics and atmospheric layer characteristics (pressure, specific humidity, temperature, total column liquid water and cloud ice, and component winds).

#### 1.2.3.6 quality_assessment

Quality assessment (QA) data for the granule overall, plus summary QA data. QA parameters include statistical metrics for each profile related to CAB and Apparent Surface Reflectance (ASR); cloud detection results; column optical depth (COD); surface detection; and ocean surface reflectance.

### 1.2.4 Browse Files

Browse files are provided as JPGs designed to quickly assess the location and quality of each granule's data. Browse files utilize the same naming convention as their corresponding data file but with "`_BRW`" and descriptive keywords appended.

A list of available images is shown in **Error! Reference source not found.**, and an example is shown in Figure 2.

Table 2. Images Available as Browse

| Image | Description |
| --- | --- |
| `cloud_flag_atm_on_map` | Number of layers found from the backscatter profile using the DDA layer finder |
| `cloud_flag_asr_on_map` | Cloud flag (probability) from ASR |
| `msw_flag_on_map (default 2)` | Multiple scattering warning flag |
| `layer_flag_on_map` | Consolidated cloud flag |
| `layer_heights` | Layer heights |
| `cab_profile` | CAB profile |
| `cloud_flag_asr_on_cab` | Cloud flag (probability) from ASR |
| `layer_flag_on_cab` | Layer flag on CAB profile |
| `layer_heights_on_cab (default 1)` | Layer heights on CAB profile |
| `apparent_surf_reflec` | ASR |
| `column_od_asr` | Optical depth from ASR |
| `ocean_surf_reflec` | Ocean surface reflectance |

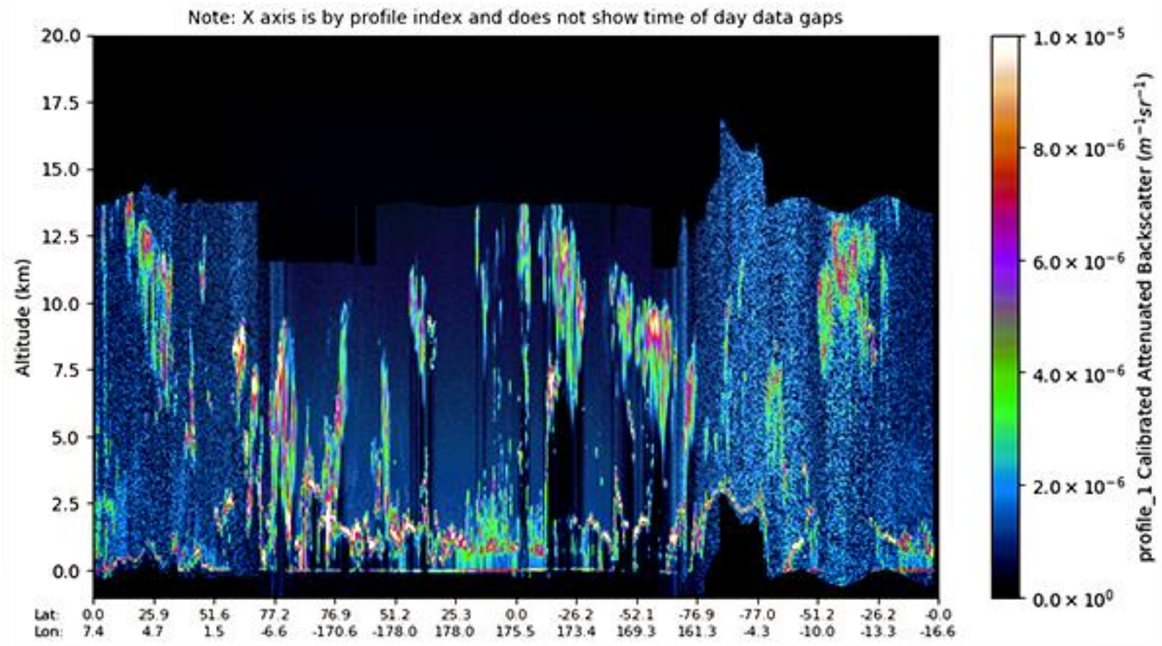


Figure 2. Sample browse image (`cab_profile`) showing Calibrated Attenuated Backscatter.

## 1.3 Spatial Information

### 1.3.1 Coverage

Spatial coverage is nearly global (approximately 88° N to 88° S).

### 1.3.2 Resolution

The atmospheric profiles consist of 30 m bins in a 14 km tall column, where the top is nominally 13.75 km above and the bottom is -0.25 km below the local value of the digital elevation model (DEM) (see "pulse aliasing" in Section 1 of the ATL04/09 ATBD). After summing 400 shots, the three strong beams are downlinked to produce three 25 Hz profiles with a 280 m along-track resolution. This 14 km CAB profile is placed in a 21 km (700 bin) frame with respect to the ellipsoid such that bin 1 is 20.0 km above the ellipsoid and bin 700 is -1.0 km below the ellipsoid. All bins outside (above and below) of the 14 km profile are set to invalid.

### 1.3.3 Geolocation

World Geodetic System 1984 (EPSG 4326)

## 1.4 Temporal Information

### 1.4.1 Coverage

Temporal coverage is 14 October 2018 through the most current processing.

Satellite maneuvers, data downlink issues, and other events can introduce data gaps into the ICESat-2 products. Users can download and consult a regularly updated list of data gaps (`.xlsx`) in the lower-level ATL03 product.

> Note: Temporal updates to the product are made available to users a few times per year. The addition of these new files is not reflected in the Version History section of the user guide.

### 1.4.2 Resolution

ICESat-2 flies along each of its 1,387 Reference Ground Tracks (RGT) once every 91 days (i.e., the orbit has a 91-day repeat cycle). During many repeat cycles, the beam pattern is shifted from the previous cycle's pointing pattern a variable amount in the cross-track direction during parts of each orbit to increase the density of spatial coverage.

# 2 DATA ACQUISITION AND PROCESSING

## 2.1 Background

The primary mission objective for the ICESat-2 atmospheric data is to produce a cloud/no cloud flag and to generalize the intensity of multiple scattering of the laser pulse due to clouds, fog, and blowing snow. Multiple scattering of the laser beam can cause significant error in the estimation of surface height (i.e., the surface appears lower). ATL09 contains a multiple scattering flag that indicates the magnitude (if any) of multiple scattering for each profile. The flag is based on the height and integrated backscatter of the lowest layer detected. The resulting profiles and flags are passed to and used by higher-level products to characterize the atmosphere. A secondary objective is to gather measurements of the vertical distribution of clouds and aerosols and their properties.

## 2.2 Acquisition

To acquire high-resolution altimetry measurements, ATLAS uses a high repetition rate laser (10 KHz). Each laser pulse is separated by only 30 km in the vertical. Thus, when a pulse (pulse 1) strikes the ground, the laser pulse right after it (pulse 2) is at 30 km altitude. When the ground return from pulse 1 reaches 15 km altitude (on its way back to the satellite), laser pulse 2 is at 15 km also (but travelling downward). The atmospheric return from pulse 2 (from 15 km altitude) travels back to the receiver at the same time as the ground return from pulse 1. If a cloud was present at 15 km, then its scattering signature would appear at the position of the ground return. If a cloud was present at 16 km, then it would appear 1 km above the surface in the 14 km atmospheric profile. This "folding" occurs throughout the atmospheric column.

In general, the atmospheric scattering that is recorded by the instrument at height H (km) is the sum of the scattering at height H, H+15, H-15, H+30, H-30, H+45, H-45, etc.

## 2.3 Processing

### 2.3.1 Inputs

The following inputs are used to generate the ATL09 product:

- The current and previous ATL04 granule
- NOAA Global Multisensor Automated Snow/Ice Cover Map
- Surface albedo (see Section 4.6.2, ATL04/09 ATBD Part I)

Algorithm adjustable parameters that are read in and used by the ATL09 algorithm are listed in Table 4.2 of the ATL04/09 ATBD Part I.

### 2.3.2 Calibrated Attenuated Backscatter

The current calibration method computes ~60 calibration constants continuously around the orbit, independently for each granule. This process may result in a slight (but unnoticeable) calibration jump from the end of one granule to the beginning of the next. Profiles that occur at and between the first and last calibration values use a linear least squares fit to the calibration points in the current granule to assign a calibration value at any time (one-second resolution). Thus, the CAB computation is a function of time. See "Section 4.3 | Calibrated, Attenuated Backscatter Profiles" in the ATL04/09 ATBD Part I.

### 2.3.3 Layer Heights

The Density-Dimension Algorithm (DDA) is applied to the three strong beams to detect layer heights. The product stores a maximum of ten layers, along with a layer confidence flag, a layer attribute flag, and a cloud flag. The DDA retrieves layer heights at the resolution of the measurement (30 m vertical and 280 m horizontal). See "Section 2 | Mathematical Concepts of the Density-Dimension Algorithm" and "Section 3 | Algorithm Steps and Pseudocode: Density-Dimension Algorithm for ATLAS Atmosphere Data" in the ATL04/09 ATBD Part II.

### 2.3.4 Cloud/Aerosol Discrimination

Layers of particulates within the observed atmospheric volume can be located using the atmospheric lidar data. The layers are considered clouds where the particles are condensed water (liquid or ice) or aerosols where the particles are other liquid or solid substances that do not undergo phase changes in the atmosphere. The attenuated backscatter coefficient, layer altitude, and relative humidity determine the layer type. See "Section 4.5 | Cloud/Aerosol Discrimination" in the ATL04/09 ATBD Part I.

### 2.3.5 Blowing Snow

The blowing snow module outputs five parameters: blowing snow height, optical depth of the layer, blowing snow confidence flag, blowing snow intensity, and blowing snow polar stratospheric clouds (PSC) flag. The blowing snow detection algorithm is invoked over any surface determined to be snow, ice sheet, or sea ice. See "Section 4.6 | Blowing Snow" in the ATL04/09 ATBD Part I.

### 2.3.6 Apparent Surface Reflectance

ASR is essentially the received laser pulse energy from the surface divided by the transmitted laser pulse energy, multiplied by the two-way atmospheric transmission. The ASR is modified by atmospheric transmission, which is not well known. Clouds and aerosols introduce further transmission loss such that ASR will always be less than the actual surface reflectance. For ATL09, the ratio of the ASR to the actual surface reflectance is used as a relative measure of two-way atmospheric transmission and COD. A low two-way transmission (< ~0.6) indicates the likely presence of clouds. See "Section 4.7 | Apparent Surface Reflectance (ASR)" in the ATL04/09 ATBD Part I.

### 2.3.7 Ocean Surface Reflectivity

Over water, the surface reflectance is computed from surface wind speed. High wind speed results in a rougher ocean surface, thereby scattering the laser pulse in all directions as it strikes the surface and reducing the direct-backscatter surface signal measured by ATLAS. Conversely, low wind speed results in smaller waves and a smoother sea surface, which increases the backscattered signal to the receiver. See "Section 4.8 | Ocean (or Open Water) Surface Reflectivity" in the ATL04/09 ATBD Part I.

### 2.3.8 Total Column Optical Depth

The total atmosphere transmission and column particulate optical depth is computed from the ratio of the ASR (the ratio of the returned surface energy to the transmitted) to the true surface reflectance (best known over water where it is a function of wind speed). Over land, prior ICESat-2 measurements of ASR for clear-only profiles are used to determine the true surface reflectance. These values of surface reflectance over land are not as accurate as those determined over water; thus, the resulting COD is also not as accurate over land.

Further, the surface return cannot be zero, implying that the computation is limited to cases where the overlying cloud and aerosol have a combined depth of less than ~3. See "Section 4.9 | Total Column Optical Depth Using ASR" in the ATL04/09 ATBD Part I.

## 2.4 Quality, Errors, and Limitations

In addition to browse files that contain various plots for assessing data quality, several parameters can be computed to assess overall quality:

- The average and standard deviation of the ratio of calibrated backscatter to molecular backscatter between 11 and 13.5 km (or top of profile) for all data poleward of 60º N/S
- The min, max, and average number of cloud layers detected from the DDA algorithm
- Percent clouds as detected by the DDA algorithm and from the ASR method
- Min, max, average, and standard deviation of ASR (`apparent_surf_reflec`); min, max, and average of the ocean surface reflectance (`ocean_surf_reflec`); and the total column optical depth (`column_od_asr`)
- Percent of time ground was detected

The composite POD/PPD flag indicates the quality of input geolocation products per ATL03 segment. This flag is useful for determining when ocean scans occurred, as well as other calibration activities. See "Section 6.0 | Quality Assessment" and "Section 7.0 | Product Quality Parameters" in the ATL04/09 ATBD Part I.

# 3 VERSION HISTORY

Table 3. Version History Summary

| Version | Date | Description of Changes |
|---|---|---|
| 7.0 | 26 Aug 2025 | • Addition of a new L3A cloud folding algorithm to better detect and flag instances when clouds above 15 km are folded down to the lower few km of the profile.<br>• Detection and flagging of layers that are wholly below ground and thus folded.<br>• Detection and flagging of folded layers that straddle ground.<br>• Setting the layer_attr parameter to a value of 11 when a layer is determined to be folded from above 15 km.<br>• Changes to the structure of the layer detection algorithm (DDA) to enable execution of N passes of the DDA.<br>• Improved thin layer detection. |
| 6.1 | 1 May 2024 | Data from 13 Nov 2022 to 26 Oct 2023 were reprocessed using ITRF2014 (replacing ITRF2020) for consistency across the entire data set. |

| Version | Date | Description of Changes |
|---|---|---|
| 5.0<br>(retire) | 11 Jan 2024 | Data access was removed for v5.0. Data coverage was 13 Oct 2018 to 13 Oct 2022. |
| 6.0 | 18 May 2023 | • Modified blowing snow detection algorithm to reduce false positive detections often seen in daylight.<br>• Added and modified the blowing snow confidence values (bsnow_con) to include new descriptions and changed the parameter from a one-byte to a two-byte integer value. See Table 4.<br>• Added four values to the layer attribute parameter (layer_attr). See Section 2.2.2.<br>• Added a new parameter called clear air precipitation top height (cap_h) that denotes the top height of clear air precipitation that reached the ground.<br>• Replaced the ANC32 surface reflectance map (now based on three years of ICESat-2 surface reflectance measurements instead of two) to fill in gaps.<br>• Changed bs_quartile to bs_quantile in ATL09 and related code.<br>• Modified code to use density matrix 1 instead of density matrix 2 when computing layer densities.<br>• Implemented a third pass of the density dimension algorithm to reduce the effect of noise in creating false layers.<br>• Updated the ANC45 cloud/aerosol discrimination table to increase the accuracy of detected layers. |
| 4.0<br>(retire) | 13 Jun 2022 | Data access was removed for v4.0. Data coverage was 13 Oct 2018 to 15 Jul 2021. |
| 3.0<br>(retire) | 25 Jan 2022 | Data access was removed for v3.0. Data coverage was 13 Oct 2018 to 11 Nov 2020. |
| 5.0 | 29 Nov 2021 | • Added new routine process_blow_snow_dens to compute blowing snow height and diamond dust heights based on methods defined in the DDA ATBD. bsnow_h_dens now has valid values when the DDA detects blowing snow<br>• Added constants bs_quartile, bs_gap, bs_bin_thresh, dd_min_top_bin, dd_bin_thresh, bs_thresh_sens, bs_thresh_bias, bs_downsample, bs_thresh_seg_len to ATL09<br>• Added parameters bsnow_dens_flag, ddust_htop_dens, ddust_hbot_dens<br>• Added parameter podppd_flag, which provides identification of ATLAS data in nominal geolocation quality status or a degraded quality. podppd_flag =0 means geolocation is in reference ground track pointing with normal quality. podppd_flag =4 means geolocation is in around-the-world scan or ocean scan with normal quality. Other values are degraded quality<br>• Set Fill Value to 127 for snow_ice on ATL09<br>• DDA processing is now done on same solar elevation sub-chunks (day, night, twilight) rather than using the first solar elevation per processing chunk<br>• Added check on invalid aclr_true and raised limit of aclr_clim to prevent errors<br>• Changed dead time correction algorithm used to correct the surface signal magnitude. This should improve the accuracy of the parameter surface_sig. This improved ASR accuracy<br>• Replaced ANC32 surface reflectance map based on GOME with one generated from actual ICESat-2 ASR measurements in clear (no cloud or aerosol layers) conditions. This should increase the accuracy of ASR-based cloud detection and column optical depth measurements. |
| 2.0<br>(retire) | 21 May 2021 | Data access was removed for v2.0. Data coverage was 13 Oct 2018 to 15 Nov 2019. |

| Version | Date | Description of Changes |
|---|---|---|
| 4.0 | 13 Apr 2021 | • Erroneous blowing snow detection was fixed by using an updated ANC30 (NOAA snow/ice maps) file<br>• Added new control parameters demtol1 and demtold2 to ATL09 to set the search radius for DDA ground finding<br>• Added low-rate segment_id; this is copied from the profile2 1Hz MET data on ATL04<br>• Modified blow_snow to accommodate the new surface signal changes<br>• Replaced DDA constant layer_sep with the new constant min_layer_sep<br>• Changed default values for phi_ocean and asl_cal_factor used in the production of ATL09<br>• Changed snow_age constant value<br>• Changed the low rate blowing snow implementation to select the profiles used based on windspeed and proper relation to the time of low-rate data<br>• Fixed the computation error in total column optical depth to take the cosine of tilt_angle in radians rather than degrees<br>• Implemented the portion of the ATL09 ATBD that identifies surface returns based on density<br>• Implemented a replacement algorithm for Cloud/Aerosol Determination (use new ANC45 table)<br>• Implemented detected ground as a layer when computing density algorithm cloud layer confidence<br>• Improved the algorithm that removes ground surface from cloud layers<br>• Added 400 shots to the theoretical background equation<br>• Removed unused constant grd_search_width and added new constant min_layer_sep<br>• Remove references to GMTED in dem_h and dem_flag. |
| 1.0 (retire) | 3 Jun 2020 | Data access was removed for v1.0. Data coverage was 13 Oct 2018 to 9 Jan 2019. |
| 3.0 | 5 May 2020 | • A new parameter (lr_bsnow_fac) was added to the equation used to compute blowing snow. The algorithm detects blowing snow at two rates—high (25 Hz) and low (1 Hz)—however, the optimal threshold for low rate detection was found to be different (lower) than for high rate detection. The new parameter adjusts the low rate detection threshold and improves retrievals. The new parameter's nominal value of 0.5 is adjustable.<br>• Low-rate blowing snow height (bsnow_h) is now computed as intended. In prior versions, this parameter was computed as just the average of the high rate detections. The algorithm now averages the 25 Hz, high rate, calibrated attenuated backscatter profiles and then searches the profile for blowing snow<br>• The value for the high rate blowing snow threshold constant (bs_thresh_scale) was changed from 10.0 to 20.0 to reduce blowing snow detections<br>• A new parameter (asr_cloud_probability) was added that contains the probability of the occurrence of clouds (0 to 100) based on the magnitude of the ASR<br>• A new parameter for blowing snow intensity (bsnow_intensity) was added to the product; it is defined as the average scattering ratio within the blowing snow layer, multiplied by the 10 m level wind speed.<br>• The product was updated to accommodate the new pass-through constant (alpha) that was added to ATL04<br>• The single scaling constant phi, used to define a threshold in the ASR cloud detection algorithm, was replaced by two constants: phi_land and phi_ocean. These scaling parameters allow for different thresholds over land and ocean, to |

| Version | Date | Description of Changes |
|---|---|---|
| | | address ongoing analyses that indicate the algorithm was reporting too many clouds over land and too few over ocean.<br>• Areas masked out in ATL04 due to dense clouds were not being properly masked out in ATL09. This bug was corrected.<br>• The cloud_det_layer_thick parameter was removed. |
| 2.0 | 24 Oct 2019 | • Replaced the binary cloud_flag_asr parameter with cloud_conf_flag_asr (0-5) in the routine that computes layer_flag. This new parameter combines ASR cloud detection and DDA cloud detection into a single, consolidated confidence flag<br>• Corrected several issues related to units in the ATL09 documentation and product template.<br>• Added a layer_conf_dens parameter which indicates the confidence associated with the corresponding layer detection.<br>• Added constants phi_land and phi_ocean as adjustable (input) parameters in the algorithm that determines whether a cloud is present based on the measured ASR<br>• Modified the start bin in the blowing snow optical depth algorithm to mitigate a problem in v01 which led to unrealistically high values of optical depth.<br>• Fixed a bug in the surf_ht_dens_mod algorithm.<br>• Changed the nighttime QUANTILE1 to 0.97.<br>• Corrected an issue where an invalid density value could contaminate the computed value.<br>• Updated a hard-coded cloud thickness and separation value in v01 to allow the control file overrides to work correctly.<br>• Changed the default value for layer_conf to be invalid.<br>• Modified the surface height removal implemented in v01 to handle clouds at surfaces more than 300 m thick.<br>• Added blowing snow = invalid to the multiple scattering warning flag (msw_flag) criteria for msw_flag = 0. This change addresses logic in the MSW flag that did not treat blowing snow as a layer.<br>• Added a 700-bin relative humidity profile to the product (input from ATL04) to better discriminate between clouds and aerosols<br>• Modified the confidence limits for bs_conf in the blowing snow algorithm. |
| 1.0 | 28 May 2019 | Initial release |

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# 5 DOCUMENT INFORMATION

## 5.1 Publication Date

August 2025

## 5.2 Date Last Updated

August 2025

# APPENDIX A – ICESAT-2/ATLAS DESCRIPTION

The ICESat-2 observatory utilizes a photon-counting lidar (the ATLAS instrument) and ancillary systems (GPS, star tracker cameras, and ground processing) to measure the round-trip time a photon takes to travel from ATLAS to Earth and back again. The time-of-flight, absolute time, spacecraft location and pointing are used to determine the reflected photon's geodetic height, latitude, and longitude.

The ATLAS instrument uses a single laser and a beam splitter to illuminate six different “spots” that each trace out a ~11 m wide track (Magruder et al., 2020) as ICESat-2 orbits Earth (Figure A - 1). Three of the spots are considered “strong” (spots 1, 3, and 5) and the other three “weak” (spots 2, 4, and 6). Three independent Photon Counting Electronics (PCEs) record the photons returned to the telescope, each for a single pair of strong/weak spots. PCE1 records spots 1 and 2; PCE2 records spots 3 and 4; and PCE3 records spots 5 and 6.

Higher-level ATLAS/ICESat-2 data products are organized by ground track (GT), with GT1L and GT1R forming pair one, GT2L and GT2R forming pair two, and GT3L and GT3R forming pair three. Each GT is numbered according to the relative location of the laser spot that generates it, with GT1L on the far left and GT3R on the far right. Left/right beams within each pair are approximately 90 m apart in the across-track direction and 2.5 km in the along-track direction.

The mapping between the strong and weak spots of ATLAS, and their relative positions on the ground, depends on the orientation (yaw) of the ICESat-2 observatory, which is changed approximately twice per year to maximize solar illumination of the solar panels. The forward orientation corresponds to ATLAS traveling along the +x coordinate in the ATLAS instrument reference frame (Figure A - 1, left), with the weak spots leading the strong spots. In the backward orientation, ATLAS travels along the -x coordinate in the instrument reference frame, with the strong spots leading the weak spots (Figure A - 1, right). Atmospheric profiles are generated from strong spots only, and the instrument orientation determines which GT label ("gtx") corresponds to which profile. The spacecraft orientation is tracked in the ICESat-2 Major Activities document (.xlsx).

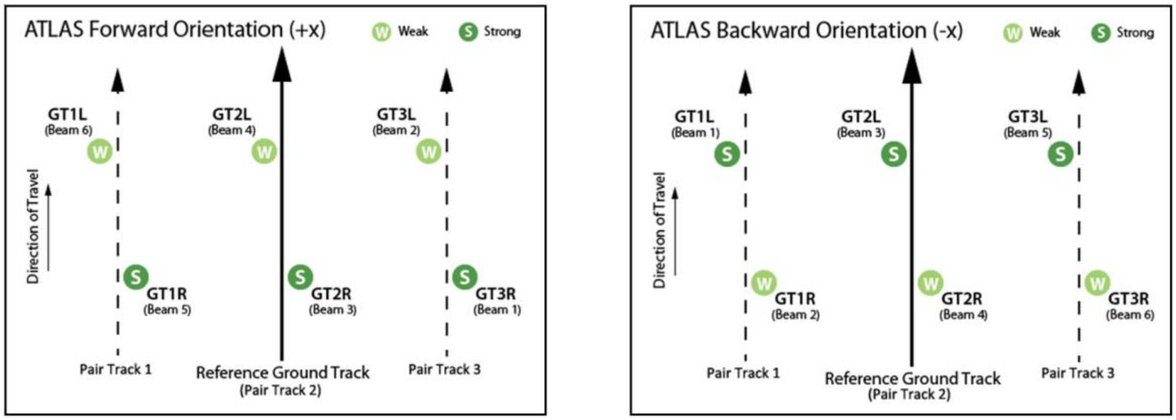


Figure A - 1. Spot and Ground Track (GT) naming convention.

The Reference Ground Track (RGT) is an imaginary track on Earth through the six-spot pattern that is used to point the observatory. 1,387 RGTs are sampled over the course of 91 days, allowing seasonal height changes to be detected. Onboard software aims the laser beams so that the RGT is between GT2L and GT2R (i.e., coincident with Pair Track 2). Nominal RGT pointing occurs over the oceans and polar regions and is periodically adjusted over vegetated land areas to broaden global coverage. Cycle numbers track the number of 91-day periods that have elapsed since the ICESat-2 observatory entered the science orbit. RGTs are uniquely identified by appending the two-digit cycle number (cc) to the RGT number.

Over lower latitudes, the satellite points slightly off the RGT during most cycles to measure canopy and ground heights. Off-pointing began on 1 August 2019 with RGT 518 after the ATLAS/ICESat-2 Precision Pointing Determination (PPD) and Precision Orbit Determination (POD) solutions were adequately resolved, and the instrument had pointed directly at the RGT for at least a full 91 days (1,387 orbits).

NOTE: ICESat-2 RGTs with dates and times can be downloaded as KML files from NASA's ICESat-2 | Technical Specs page, below the Orbit and Coverage table. Pointing plans summarized by cycle and off-pointing angle are posted in the ICESat-2 Major Activities document.

The ATLAS data and data collected from ancillary systems are telemetered to the ground and processed into several data products (Figure A - 2). The ATL01 algorithm reformats and unpacks the Level 0 data and converts it into engineering units. ATL02 processing converts ATL01 data to science units, applies instrument corrections, and produces photon time-of-flight data. The PPD and POD solutions compute the pointing vector and position of the ICESat-2 observatory as a function of time. ATL02, PPD, and POD are used to produce the global geolocated photon data of ATL03 and the normalized relative backscatter profiles of ATL04, which are the base products for all higher-level data sets.

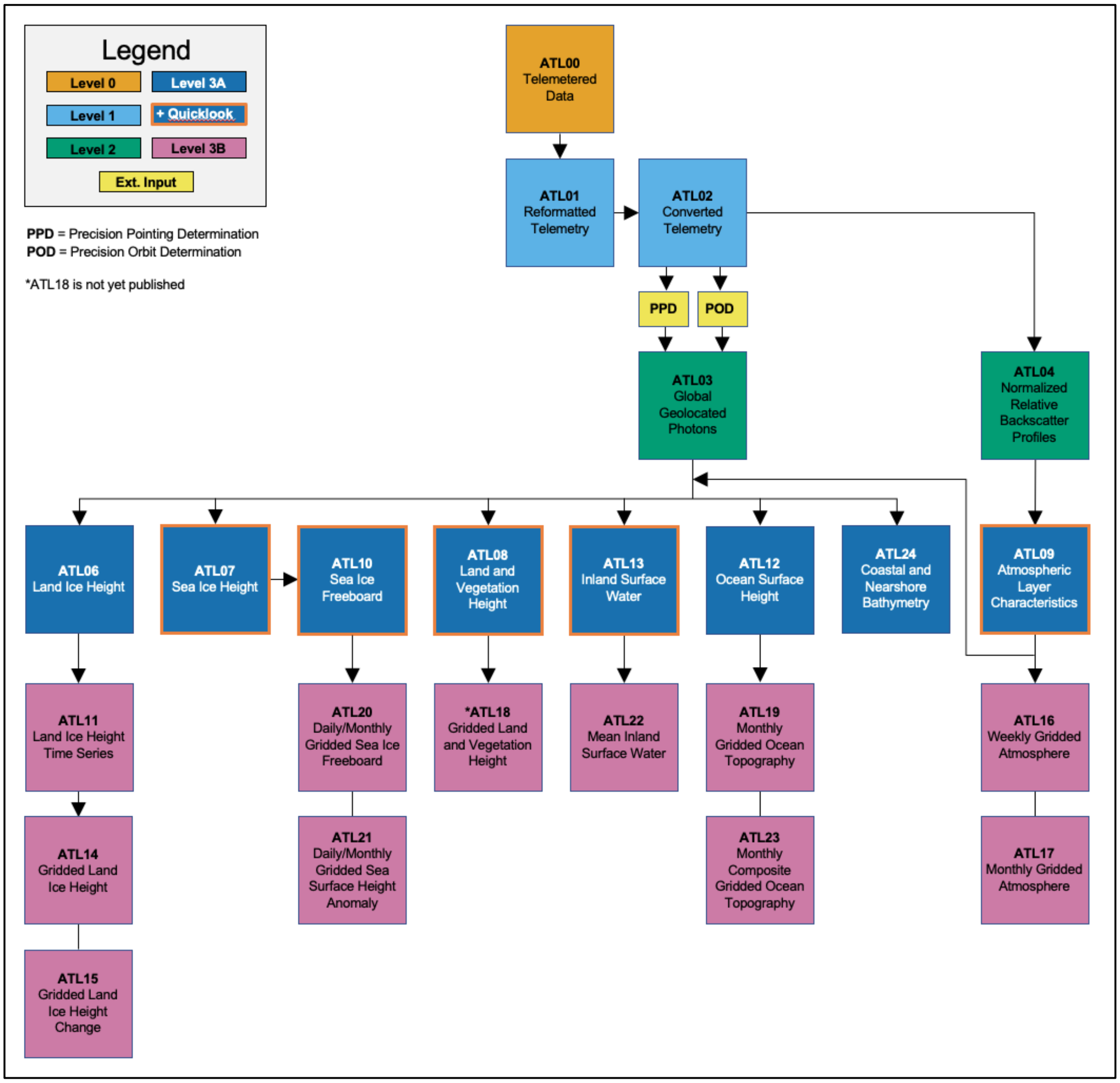


Figure A - 2. Schematic of ICESat-2 data processing and data products.

In satellite altimetry, the reflection point of an emitted signal occurs on an instantaneous and often dynamic planetary surface (Figure A - 3). For ICESat-2, reflective surfaces include oceans, inland water bodies, solid ground, ice, vegetation, and manmade structures. Depending on the product and surface type, geophysical corrections are applied to measurements to account for various time-varying processes (Table A - 1). Upper-level products may undergo additional height corrections, including corrections for pulse shape and instrument characteristics. For more information, refer to the data product's ATBD.

Table A - 1. Geophysical Corrections Applied to ICESat-2 Products

| **ICESat-2 Products by Surface Type** | **Geophysical Corrections[1]** |
|---|---|
| Photon-level product (ATL03) (i.e., corrections applicable across all surface types) | Ocean loading<br>Solid Earth tide<br>Solid Earth pole tide<br>Ocean pole tide<br>Total column atmospheric delay |
| Land Ice, Land, and Inland Water (ATL06, ATL08, and ATL13) | *No geophysical corrections beyond ATL03* |
| Sea Ice (ATL07 and ATL10) | ATL03 corrections<br>Referenced to mean sea surface<br>Ocean tide<br>Long period equilibrium ocean tide<br>Dynamic atmosphere correction |
| Ocean (ATL12) | ATL03 corrections<br>Ocean tide<br>Long period equilibrium ocean tide |

[1]For details, see Section 5 of the *ICESat-2 Data Comparison User's Guide for Rel007* available on the ATL03 data set landing page.

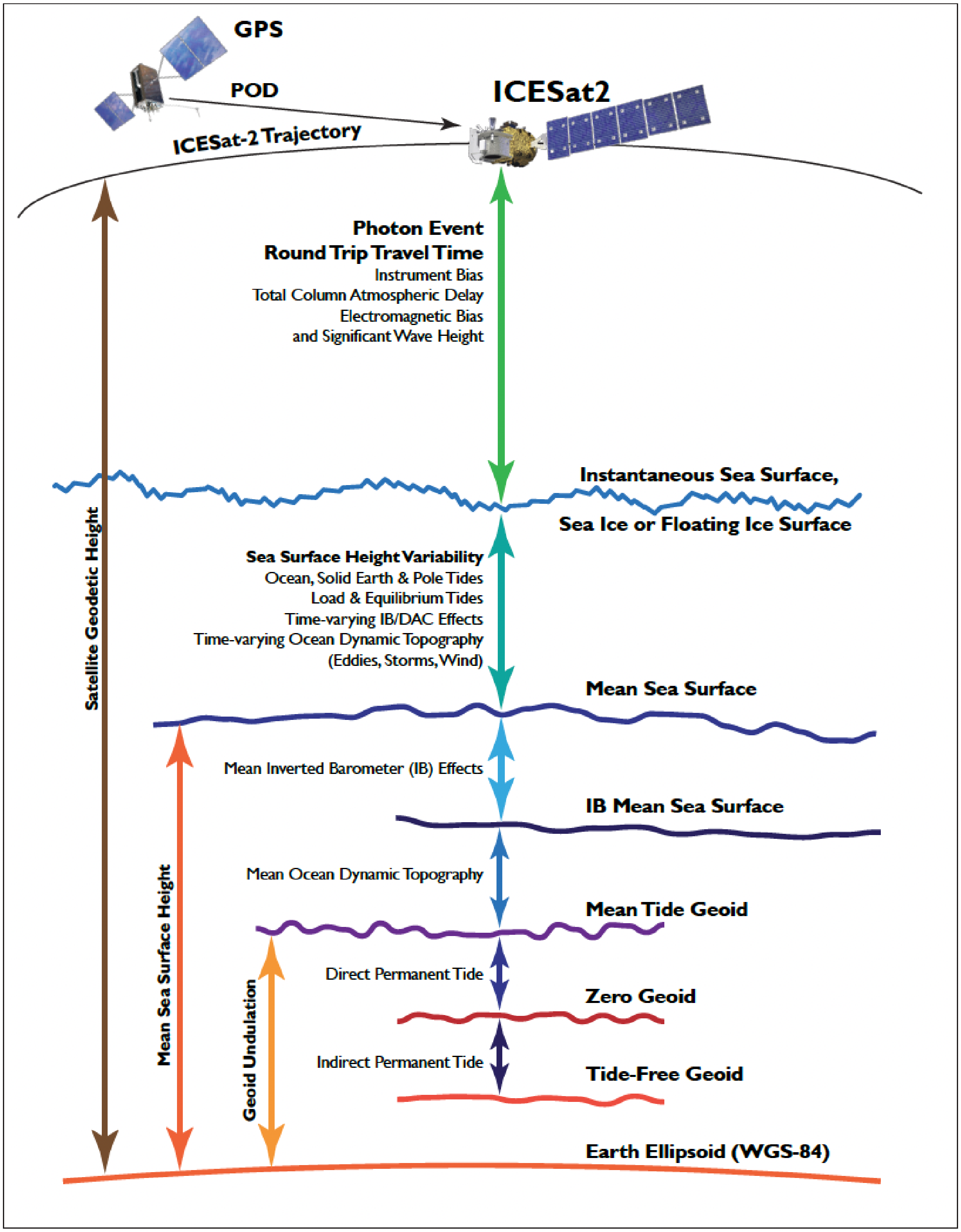


Figure A - 3. Geophysical corrections used in satellite altimetry (Source: *ICESat-2 Data Comparison User's Guide for Rel007,* available on the ATL03 data set landing page).