ATLAS/ICESat-2 L2A Normalized Relative Backscatter Profiles, Version 6

USER GUIDE

How to Cite These Data

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

Palm, S. P., Y. Yang, U. C. Herzfeld, and D. W. Hancock III. 2023. *ATLAS/ICESat-2 L2A Normalized Relative Backscatter Profiles, Version 6*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/ATLAS/ATL04.006. [Date Accessed].

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FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/ATL04

National Snow and Ice Data Center

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1 DATA DESCRIPTION

1.1 Parameters

Normalized relative backscatter (NRB) profiles of the atmosphere.

1.2 File Information

1.2.1 Format

Data are provided as HDF5 formatted files.

1.2.2 ATLAS/ICESat-2 Description

NOTE: The following brief description of the Ice, Cloud and land Elevation Satellite-2 (ICESat-2) observatory and Advanced Topographic Laser Altimeter System (ATLAS) instrument is provided to help users better understand the file naming conventions, internal structure of data files, and other details referenced by this user guide. The ATL04 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 | V6, https://doi.org/10.5067/H975R4YYVIT6).

The ICESat-2 observatory utilizes a photon-counting lidar (the ATLAS instrument) and ancillary systems (GPS, star cameras, and ground processing) to measure the time a photon takes to travel from ATLAS to Earth and back again and determine the reflected photon's geodetic latitude and longitude. Laser pulses from ATLAS illuminate three left/right pairs of spots on the surface that trace out six approximately 14 m wide ground tracks as ICESat-2 orbits Earth. Each ground track is numbered according to the laser spot number that generates it, with ground track 1L (GT1L) on the far left and ground track 3R (GT3R) on the far right. Left/right spots within each pair are approximately 90 m apart in the across-track direction and 2.5 km in the along-track direction. ATL04 is organized by ground track, with ground tracks 1L and 1R forming pair one, ground tracks 2L and 2R forming pair two, and ground tracks 3L and 3R forming pair three. Each pair also has a Pair Track—an imaginary line halfway between the actual location of the left and right beams (see Figure 1). Pair tracks are approximately 3 km apart in the across-track direction.

The beams within each pair have different transmit energies—so-called weak and strong beams—with an energy ratio between them of approximately 1:4. The mapping between the strong and weak beams of ATLAS, and their relative position 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 (see Figure , left). In this orientation, the weak beams lead the strong beams and a weak beam is on the left edge of the beam pattern. In the backward orientation, ATLAS travels along the -x coordinate, in the instrument reference frame, with the strong beams leading the weak beams and a strong beam on the left edge of the beam pattern (see **Error! Reference source not found.**). The first yaw flip was performed on 28 December 2018, placing the spacecraft into the backward orientation. ATL04 reports the spacecraft orientation in the `sc_orient` parameter stored in the `/orbit_info/` data group (see section 1.2.4 Data Groups). In addition, the current spacecraft orientation, as well as a history of previous yaw flips, is available in the ICESat-2 Major Activities tracking document (`.xlsx`).

The Reference Ground Track (RGT) refers to the imaginary track on Earth at which a specified unit vector within the observatory is pointed. During nominal operating conditions onboard software aims the laser beams so that the RGT is between ground tracks 2L and 2R (i.e., coincident with Pair Track 2). The ICESat-2 mission acquires data along 1,387 different RGTs. Each RGT is targeted in the polar regions once every 91 days to allow elevation changes to be detected. 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, for example in ATL02 file names, by appending the two-digit cycle number (cc) to the RGT number, e.g., 0001cc to 1387cc.

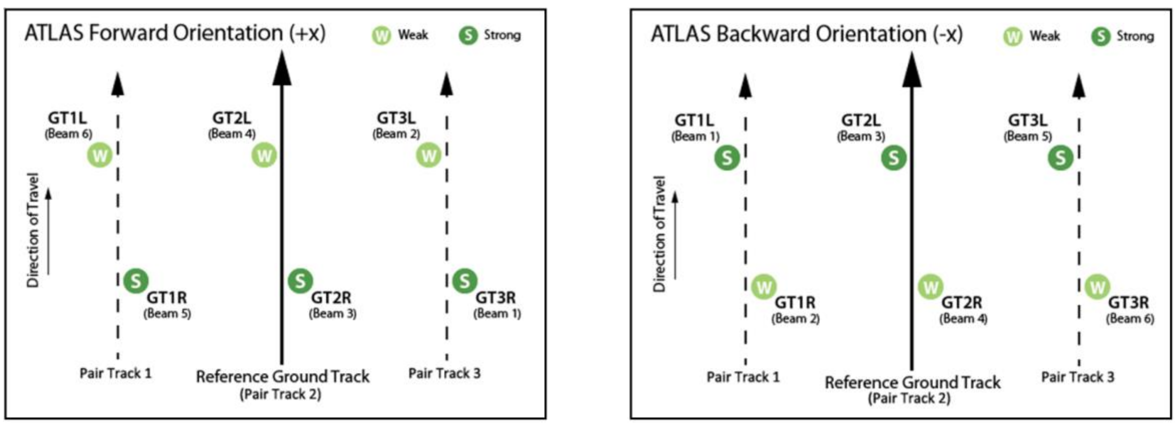

Figure 1. Spot and ground track (GT) naming convention with ATLAS oriented in the forward (instrument coordinate +x) direction and backward (instrument coordinate -x) direction.

NOTE: ICESat-2 reference ground tracks with dates and times can be downloaded as KMZ files from NASA's ICESat-2 | Technical Specs page below the Orbit and Coverage table.

Under normal operating conditions, data are not collected along the RGT; however, during spacecraft slews, or off-pointing, some ground tracks may intersect the RGT. Off-pointing refers to a series of plans over the mid-latitudes that have been designed to facilitate a global ground and canopy height data product with approximately 2 km track spacing. Off-pointing began on 1 August 2019 with RGT 518, after the ATLAS/ICESat-2 PPD and POD solutions had been adequately resolved and the instrument had pointed directly at the reference ground track for at least a full 91 days (1,387 orbits).

Users should note that sometimes, for various reasons, the spacecraft pointing may lead to ICESat-2 data collected offset at some distance from the RGTs instead of along the nominal RGT. Although not along the nominal RGT, the geolocation information and data quality for these data are not degraded. As an example, from 14 October 2018 and 30 March 2019, the spacecraft pointing control was not yet optimized. To identify such time periods, refer to the ICESat-2 Major Activities file.

Unlike ATLAS-derived altimetry, which utilizes both weak and strong beams, atmospheric profiles are generated from strong beams only: beams 1, 3, and 5. The ATL04 product contains three corresponding atmospheric profiles numbered 1, 2, and 3 from left to right relative to the direction of spacecraft travel. Note, however, that the instrument orientation determines which beam corresponds to which profile. With ATLAS in the forward spacecraft orientation (+x), beam 1 lies to the left of the nadir ground track (profile 1), beam 3 lies along the nadir track (profile 2), and beam 5 is to the right (profile 3). The backward orientation reverses the locations on the ground of beams 1 and 5 (beam 3 remains in the center regardless of orientation), with beam 5 to the left of nadir (profile 1) and beam 1 (profile 3) to the right.

Various reference systems and dynamic processes, or geophysical corrections, occur during an ATLAS/ICESat-2 measurement (Figure 2). Table 1 lists the corrections needed for each surface type and ICESat-2 product. For example, to determine an estimate of the mean sea surface, several well-modeled, time-varying effects must be accounted for.

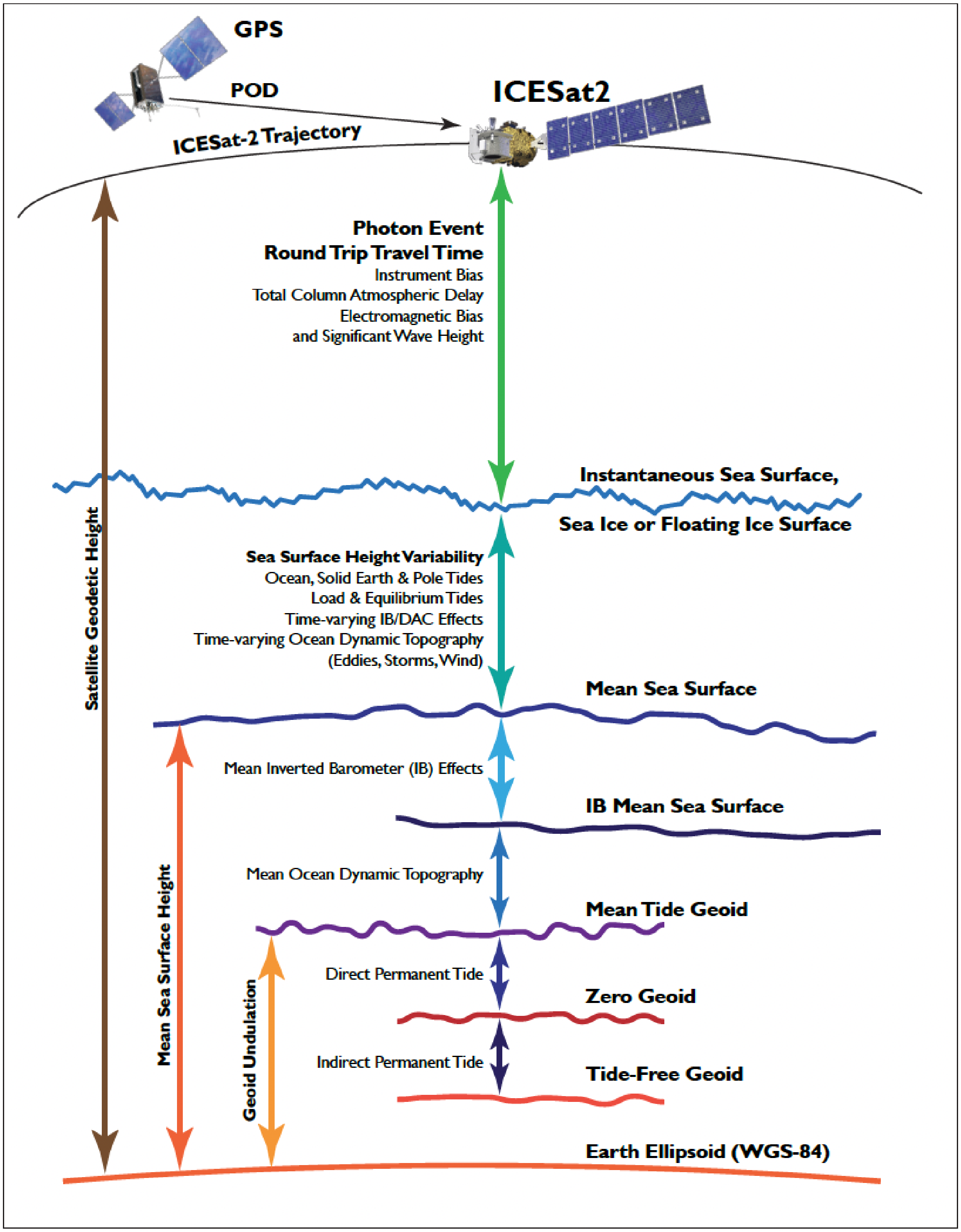

Figure 2. Geophysical corrections used in satellite altimetry. Taken from *ICESat-2 Data Comparison User's Guide for Rel006* available on the ATL03 data set landing page.

Table 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 Solid Earth tide Solid Earth pole tide Ocean pole tide Total column atmospheric range-delay
Land Ice, Land, and Inland Water (ATL06, ATL08, and ATL13)	*No corrections beyond ATL03*
Sea Ice (ATL07 and ATL10)	Referenced to mean sea surface Ocean tide Long period equilibrium ocean tide Inverted barometer (IB)
Ocean (ATL12)	Ocean tide Long period equilibrium ocean tide

[1]For details, see Section 5 of the *ICESat-2 Data Comparison User's Guide for Rel006* available on the ATL03 data set landing page.

1.2.3 Naming Convention

ATL04 data are provided as granules (files) that span one orbit (i.e., one RGT). Data files utilize the following naming convention, as described in Table 2:

```
ATL04_[yyyymmdd][hhmmss]_[ttttccss]_[vvv_rr].h5
```

Example:

```
ATL04_20181014044639_02380101_006_01.h5
```

Table 2. File Naming Convention Variables and Descriptions

Variable	Description
ATL04	ATLAS/ICESat-2 L2A Normalized Relative Backscatter Profiles
yyyymmdd	Year, month, and day of data acquisition
hhmmss	Hour, minute, and second of data acquisition (UTC)
tttt	Reference Ground Track. The ICESat-2 mission has 1,387 RGTs, numbered from 0001 to 1387.
cc	Cycle number. Each of the 1,387 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	Segment number; always "01" for ATL04/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 ATL04 and ATL09 data files span one full orbit, the segment number is set to 01.

[2] From time to time, 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 segment 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.

1.2.4 Data Groups

Within data files, similar variables such as science data, instrument parameters, orbit information, and metadata are grouped together according to the HDF model. ATL04 data files contain the top-level groups shown in the following figure:

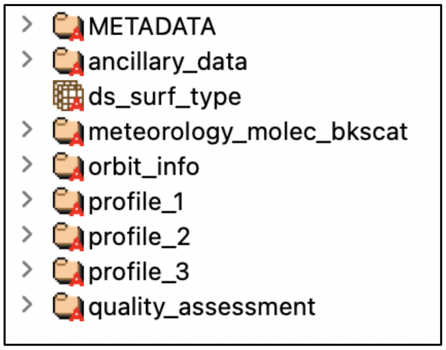

Figure 3. Top-level data groups as shown in HDFView.

The following sections summarize the contents of the data groups shown in Figure 3. Additional details are available in "Section 3.2 | L2A Outputs" of the ATL04 ATBD. For a complete list of all ATL04 parameters, see the ATL04 Data Dictionary.

1.2.4.1 METADATA

ISO19115 structured summary metadata.

1.2.4.2 ancillary_data

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

1.2.4.3 meteorology_molec_bkscat

Sampled GEOS-5 FP-IT meteorological model data and molecular backscatter. Data are created from time/locations of the center profile (profile 2) and stored at a 1 Hz rate.

1.2.4.4 orbit_info

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

1.2.4.5 profile_[x]

The `profile_1`, `profile_2`, and `profile_3` groups contain the NRB profiles (`profile_[x]/nrb_profile`) of the leftmost, center, and rightmost ground tracks (with respect to the satellite direction of motion). The `profile_[x]` data groups also contain a number of other key parameters, including the following:

- Latitudes and longitudes (WGS 84, top of the atmosphere histogram) of the profiles
- The ellipsoidal height at the top of the atmospheric range window (`atm_tw_top`) and its bin number within the vertically aligned frame (`nrb_top_bin`)
- Surface type (`surf_type`)
- Solar background (photons per bin) computed using three methods (`backg_method1`, `backg_method2`, `backg_method1`)
- Counts of low-, medium-, and high-confidence signal photons for each NRB (`sig_count_low`, `sig_count_med`, `sig_count_hi`)
- Descriptive statistics (mean and standard deviation) for the low, medium, and high-confidence signal photon heights

1.2.4.6 quality assessment

QA data for the granule, plus summary QA data. These include statistical metrics for each profile related to background computations, the calibration constant computation, and surface detection.

1.2.4.7 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`).

1.2.5 Browse Files

Browse files are JPG images designed to quickly assess the location and quality of each granule's data. A list of images is shown in Table , and an example is shown in Figure 4.

Table 3. Images Available as Browse Files

Parameter	Description
Background1	Plot of computed background using method 1
Background2	Plot of computed background using method 2
Background3	Plot of computed background using method 3
Cal_c	Plot of calculated calibration constants
groundtrack	Plot of satellite ground track on a global map
Nrb_profile	Image of NRB (see Figure)
Solar_elevation	Plot of solar elevation
Surface_sig	Plot of the magnitude of the surface return (photons)

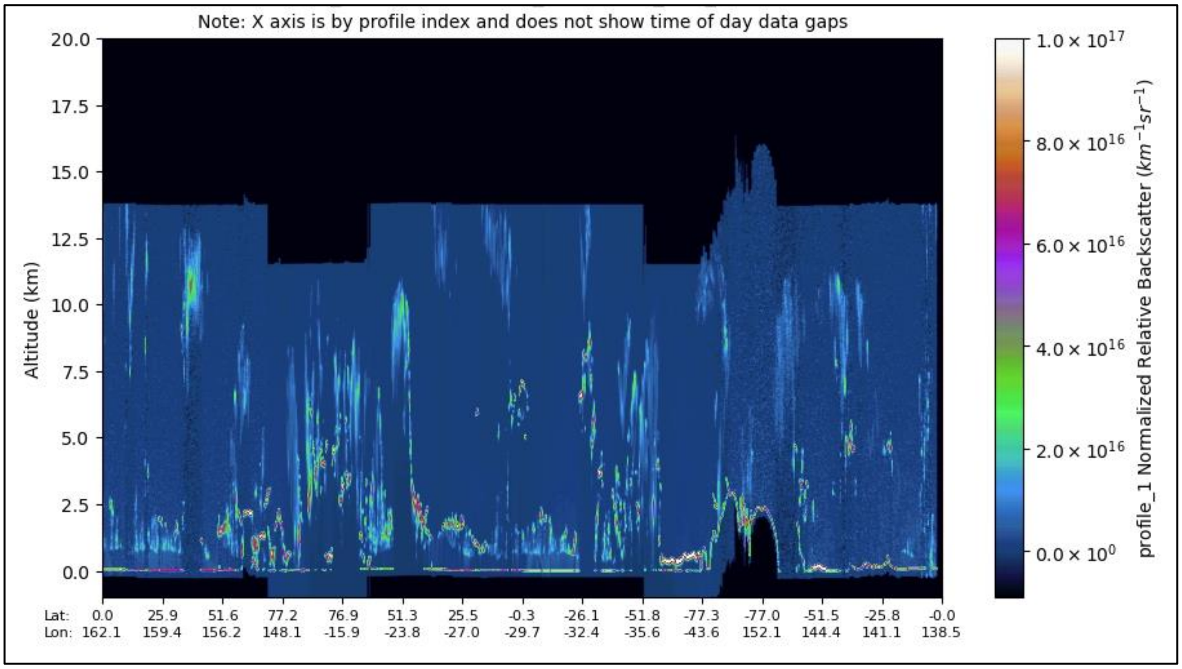

Figure 4. Sample browse image (nrb_profile) showing normalized relative backscatter.

Browse files utilize the same naming convention as their corresponding data file but with "_BRW" and descriptive keywords appended.

1.3 Spatial Information

1.3.1 Coverage

The ICESat-2 mission acquires data along 1,387 RGTs.

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.

1.3.3 Geolocation

The following tables provide information for geolocating this data set.

Table 4. Geolocation Details

Geographic coordinate system	WGS 84
Projected coordinate system	N/A
Longitude of true origin	Prime Meridian, Greenwich
Latitude of true origin	N/A
Scale factor at longitude of true origin	N/A
Datum	World Geodetic System 1984
Ellipsoid/spheroid	WGS 84
Units	degree
False easting	N/A
False northing	N/A
EPSG code	4326
PROJ4 string	+proj=longlat +datum=WGS84 +no_defs +type=crs
Reference	https://epsg.io/4326

1.4 Temporal Information

1.4.1 Coverage

14 October 2018 to present

Note that satellite maneuvers, data downlink issues, and other events can introduce data gaps into the ICESat-2 suite of products. ATL03 acts as the bridge between the lower-level, instrumentation-specific data and the higher-level products. On the data set landing page under Documentation, users can download and consult a regularly updated list of ATL03 data gaps (`.xlsx`).

1.4.2 Resolution

Each of ICESat-2's 1,387 RGTs is targeted in the polar regions once every 91 days (i.e., the satellite has a 91-day repeat cycle).

2 DATA ACQUISITION AND PROCESSING

2.1 Background

ATL04 consists of NRB profiles, calculated 532 nm calibration coefficients, plus other ancillary parameters. The NRB profiles are created by subtracting the solar background photons from raw photon counts (passed from ATL02), multiplying by the square of the range from the satellite to the return height, and normalizing by the laser energy. These profiles are passed to and used by higher-level products to characterize the atmosphere. Figure illustrates the suite of ICESat-2 data products and their connections.

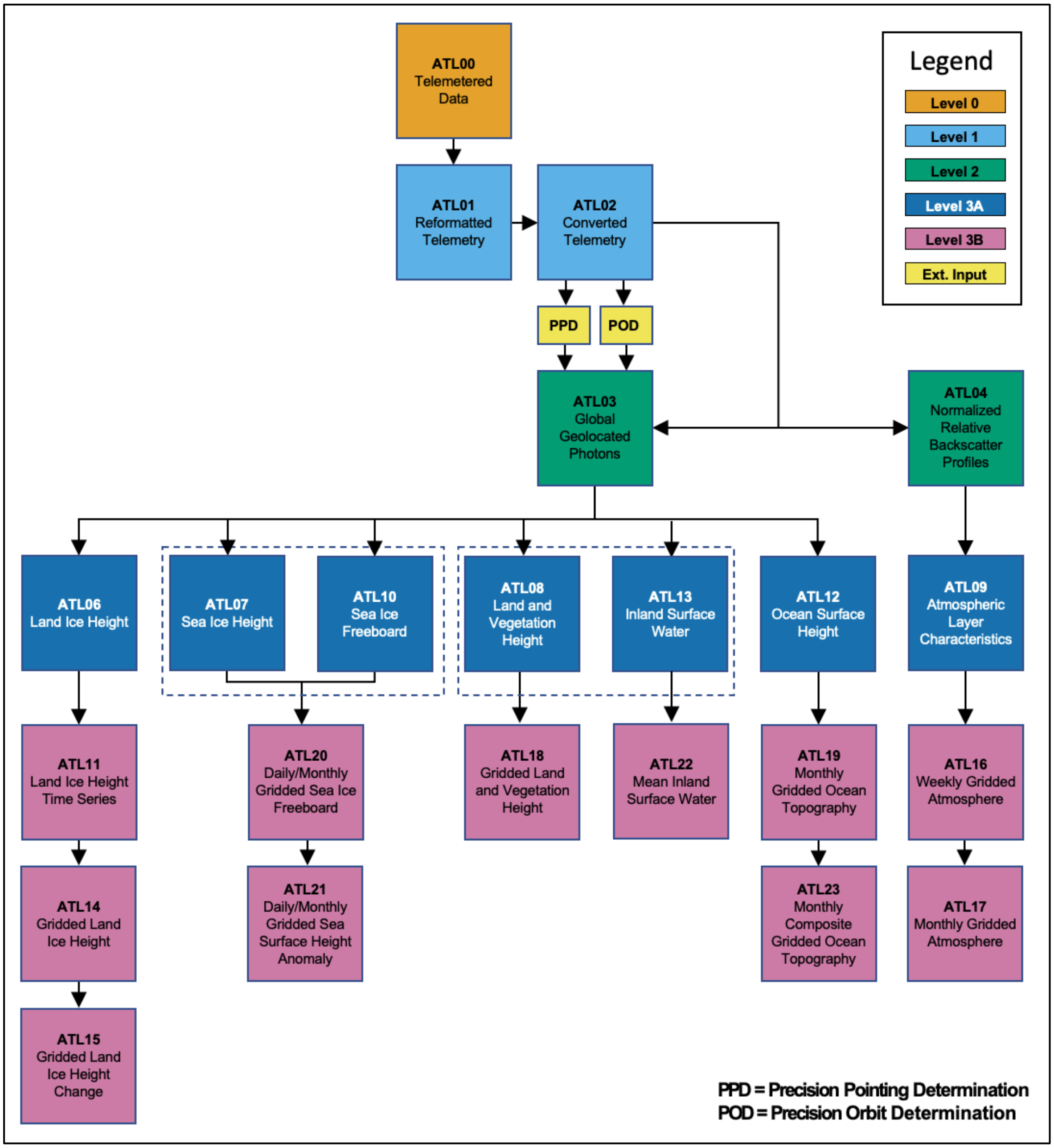

Figure 5. ICESat-2 data processing flow. ATL02 processing converts the ATL01 data to science units and applies instrument corrections. The Precision Pointing Determination (PPD) and Precision Orbit Determination (POD) solutions compute the pointing vector and position of the ICESat-2 observatory.

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.

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 required by the ATL04 algorithm:

- Ground signal photon magnitude and width (ATL03)
- Raw strong beam atmosphere profiles (ATL02)
- Laboratory data relating signal magnitude and width to detector efficiency
- Meteorological data from the Global Modeling and Assimilation Office (GMAO)
- Ozone concentration (mixing ratio) from GMAO
- Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) 1 km x 1 km digital elevation model
- Surface type (International Geosphere–Biosphere Programme)
- Solar azimuth and zenith angle
- Range from Spacecraft to start of atmosphere profile (ATL02)
- Spacecraft altitude above WGS84 ellipsoid
- Pointing angles for each beam
- Laser energy for each of the 3 strong beams, time, and lat/lon
- Onboard 50 shot background (ATL02)
- 200 shot sum shift amount (ATL02)

A number of corrections are applied to the raw atmospheric profiles before being processed into the Level 2 product: removing the transmit echo pulse (TEP), applying a dead time correction, and compensating for shifting between major frames (see Section 2 of the ATL04 ATBD).

2.3.2 Outputs

ATL04 outputs include the following parameters:

- NRB profiles for each of the three strong beams at 25 Hz
- Background at 25 Hz
- Molecular backscatter profile from 20 km to 0 km, at 0.1 Hz, 30 m vertical resolution
- Calibration coefficients with time and location tags
- Molecular backscatter average used to compute the calibration coefficient
- NRB average used to compute the calibration coefficient
- Pressure, temperature from 30 km to 0 km, at 0.1 Hz, 30 m vertical resolution
- Range from spacecraft to start of atmospheric profile

- Pointing angles for each beam
- Laser energy, time, lat/lon
- Solar zenith and azimuth angle
- Surface type
- Surface 2 m wind velocity and temperature
- Wind velocity and temperature at 10 m height
- Onboard 50 shot background
- Meteorological data

For a list of ATL04 product parameters including variable names, see Table 3.1 in the ATL04 ATBD.

2.3.3 Normalized Relative Backscatter Computation

The following section briefly describes the approach used to compute NRB from ATLAS/ICESat-2 lidar data. For a complete description, see Section 3.3 of the ATL04 ATBD.

To compute NRB, three corrections are applied to the raw level-0 data: laser energy normalization, range square correction, and background subtraction. The lidar equation is:

$$S(z) = \frac{CE\beta(z)T^2(z)}{r^2} + p_b + p_d$$

In the equation above, S(z) is the measured raw signal (photons) at height z; r is the range from the spacecraft to the height z; C is the lidar system calibration coefficient; E is the laser energy; β(z) is the 180° backscatter coefficient at height z; T(z) is the one-way atmospheric transmission from the spacecraft to height z; p_b is the solar background; and p_d is the detector dark count rate.

NRB is then generated for each of the strong beams using:

$$NRB(z) = \frac{(S(z) - p_b - p_d)r^2}{E}$$

$$= C\beta(z)T^2(z)$$

For ICESat-2, determining p_b represents the biggest challenge in the equation above (both E and r are well known). In practice, p_b and p_d are lumped together and their sum called simply 'background'. At night, with no moon (and no effect from city lights), the background is simply p_d. During the day, the background is the sum of p_b and p_d.

The background computation would normally be performed using data below the ground; however, both molecular and cloud scattering may exist within this region due to range aliasing (i.e., the 10

KHz laser repetition rate). The background cannot be accurately computed because it is not possible to remove all atmospheric scattering from the profile; thus, alternate approaches are needed.

For the ATLAS/ICESat-2 atmospheric profiles, the ATL04 algorithm utilizes three methods to compute the background and stores each result in a separate variable. Briefly, methods 1 and 2 locate and remove any cloud layers in the data and then look for a minimum in the cloud-cleared profile. Although this minimum may be associated with a particulate-free area of the profile, it will still contain some molecular scattering. However, this scattering can be modeled and removed leaving only background. Methods 1 and 2 differ only in how clouds are removed. Method 3 applies a different approach by utilizing the onboard 50-shot background rate parameter from ATL03, converted to units of per 30 m atmospheric bin and averaged over the profile.

The results of all three methods are stored within each `profile_[x]` data group in the `backg_method1`, `backg_method2`, and `backg_method3` variables. The background method that was used (1, 2, or 3) is stored in both ATL04 and ATL09 in the ancillary variable `backg_select` (`/ancillary_data/atmosphere/backg_select`).

All three methods are detailed in "Section 3.3.4 | Background Computation" in the ATL04 ATBD.

"Section 3.3 | NRB Computation" in the ATL04 ATBD provides complete descriptions about the theory and calculations used to determine NRB, including the molecular backscatter coefficient (Section 3.3.1); the molecular scattering folding correction (Section 3.3.2); ozone transmission (Section 3.3.3); and how the algorithm identifies the background (Section 3.3.4) and surface (Section 3.3.5) signals. "Section 3.3.6 | Vertical Height Adjustment" details the procedure used to put the raw atmospheric profiles into a constant height frame of reference.

2.3.4 Lidar Calibration

The theory behind the lidar calibration coefficient relates the power received by the detector to a physical quantity—the volume backscatter cross-section—which is primarily a function of the transmission of the system optics (transmitting and receiving), detector efficiency, geometric considerations, and the degree of alignment between the receiver field of view and the laser spot (boresite alignment). Because these factors can and do change with time in the typical lidar system and cannot easily be monitored, the lidar signal is calibrated continuously by comparing the measured signal to a reference target.

The atmosphere itself can act as a reference target so long as it is devoid of particulate scatterers (or the magnitude of particulate loading is known) and the density of the atmosphere is sufficiently well known. For instance, in the absence of large volcanic eruptions, the air in the lower and middle stratosphere is typically very clean. In these layers, the scattering consists only of molecular or Rayleigh scattering, which depends on only the pressure and temperature of the atmosphere. As such, the molecular backscatter cross section (i.e., the target) can be very accurately calculated in near real-time from National Center for Environmental Prediction (NCEP) or Goddard Modeling and Assimilation Office (GMAO) meteorological analyses or from short-range forecasts of temperature, pressure, and moisture fields.

"Section 3.3.7.1 | Theory" provides an introduction to the meaning and application of the lidar calibration coefficient. Users seeking details about how the calibration coefficient is computed by the ATLAS software can consult sections "3.3.7.2 | Calibration Algorithm using the Atmosphere" and "3.3.7.3 Calibration Algorithm using Surface Reflectance" in the ATL04 ATBD.

2.4 Quality, Errors, and Limitations

The browse file corresponding to each data granule contains a number of plots and images that can be used to assess the quality of ATL04 data. See Section 6.0 | Quality Assessment in the ATL04 ATBD for brief descriptions. In addition, QA parameters for each profile are stored in the top-level `quality_assesment/` data group, including statistical metrics that describe the background computations for all three methods, the calibration constant computation, and surface detection.

Potential sources of error and their magnitudes in the NRB computation are discussed in Section 3 of the ATL04 ATBD, particularly Sections 3.3.2.1 | Error Analysis of Molecular Contribution and 3.3.7.4 | Calibration Error and Confidence. Furthermore, errors and uncertainties in input sources, such as ATL02 and ATL03, can propagate into downstream products. Users interested in these error sources should consult the ATBDs for ATL02 and ATL03.

3 VERSION HISTORY

A summary of the version history is provided in Table 5.

Table 5. Version History Summary

Version	Release Date	Description
V1	May 2019	Initial release
V2	October 2019	Refer to V2 User Guide
V3	May 2020	Refer to V3 User Guide
V4	April 2021	Refer to V4 User Guide
V5	November 2021	Refer to V5 User Guide

V6	May 2023	• Added and modified alpha correction constants to improve calibration in the South Atlantic Anomaly (SAA) area. • Slightly modified the boundaries of the SAA box.
V6.1	May 2024	Data from 13 November 2022 to 26 October 2023 were reprocessed using ITRF2014 (replacing ITRF2020) for consistency across the entire data set.

4 REFERENCES

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5 DOCUMENT INFORMATION

5.1 Publication Date

May 2023

5.2 Date Last Updated

May 2024