ATLAS/ICESat-2 L3A Sea Ice Freeboard, Version 6

USER GUIDE

How to Cite These Data

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

Kwok, R., A. Petty, G. Cunningham, T. Markus, D. W. Hancock III, A. Ivanoff, J. Wimert, M. Bagnardi, N. Kurtz and the ICESat-2 Science Team. 2023. *ATLAS/ICESat-2 L3A Sea Ice Freeboard, Version 6*. [Indicate subset used]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. https://doi.org/10.5067/ATLAS/ATL10.006. [Date Accessed].

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National Snow and Ice Data Center

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1 DATA DESCRIPTION

1.1 Parameters

Sea ice freeboard, calculated using three different approaches, plus leads used to establish the reference sea surface.

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 ATL10 data product is described in detail in the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) Project Algorithm Theoretical Basis Document (ATBD) for Sea Ice Products (ATBD for ATL07/10/20/21 | V6, https://doi.org/10.5067/9VT7NJWOTV3I).

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. Higher level ATLAS/ICESat-2 data products (ATL03 and above) are 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 1, 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 Figure 1, right). The first yaw flip was performed on 28 December 2018, placing the spacecraft into the backward orientation. ATL10 reports the spacecraft orientation in the `sc_orient` parameter stored in the `/orbit_info/` data group (see Section 1.2.4 Data Groups). 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.

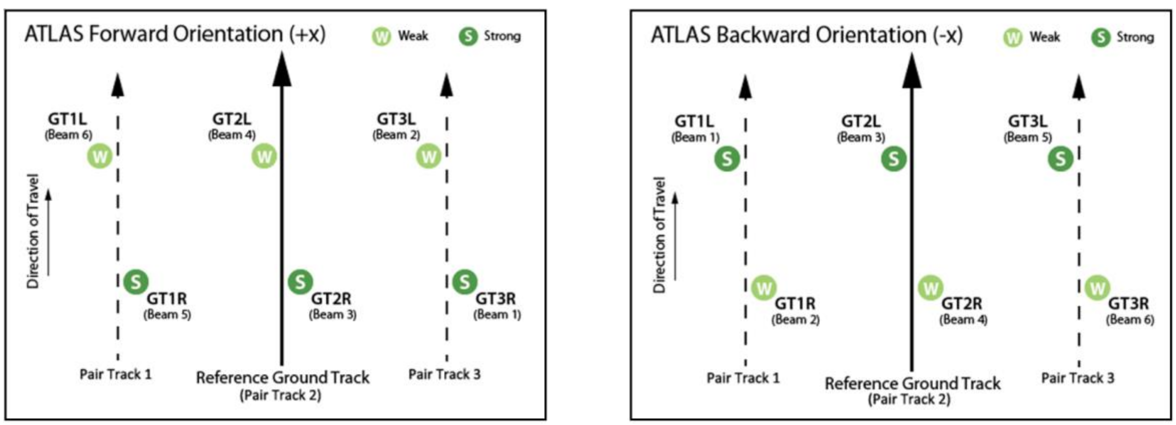

Figure 1. Spot and ground track (GT) naming convention with ATLAS oriented in the forward (instrument coordinate +x) direction and backward (instrument coordinate -x) direction.

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.

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.

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.

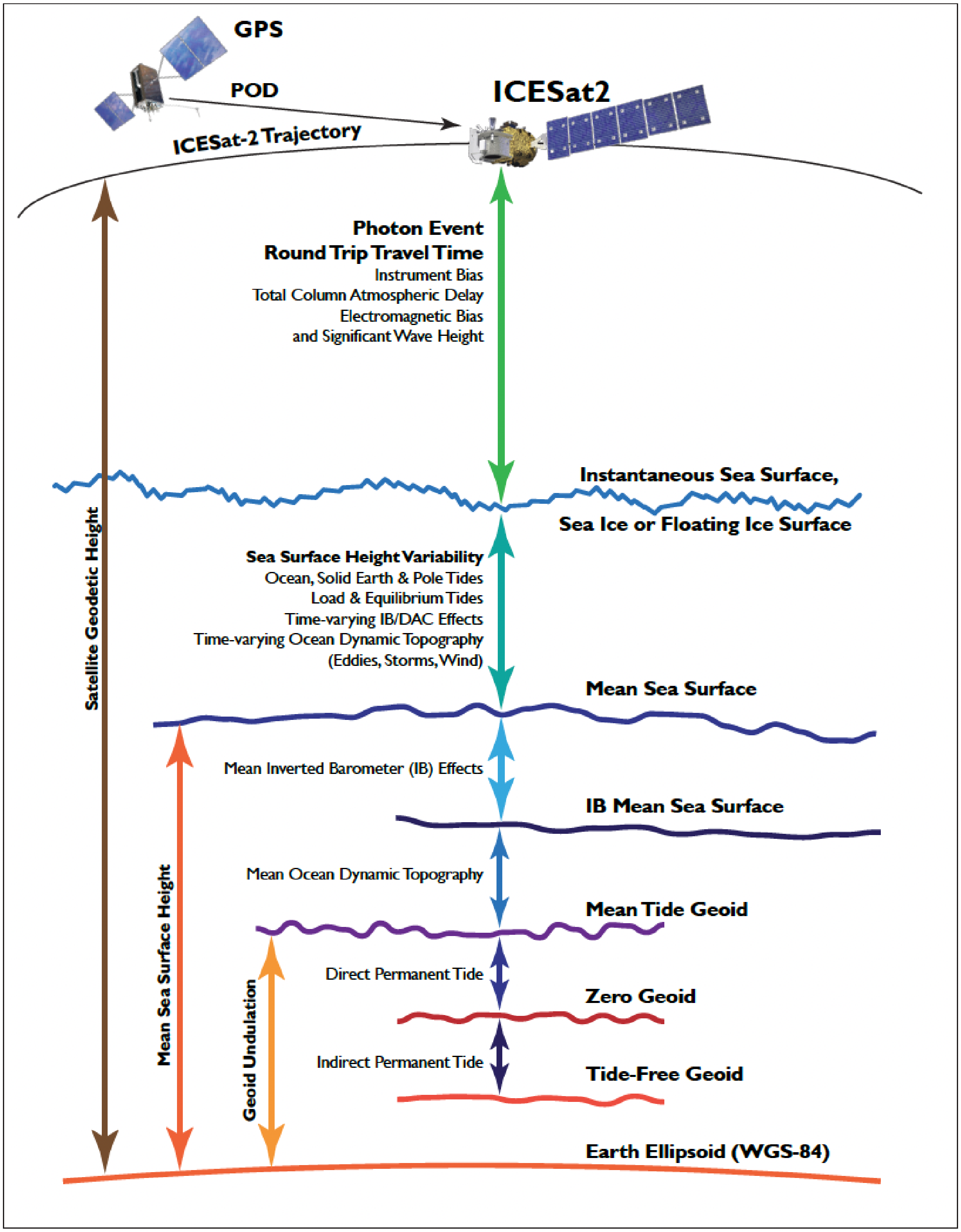

Figure 2. Geophysical corrections used in satellite altimetry. Taken from *ICESat-2 Data Comparison User's Guide for Rel006* available on the ATL03 data set landing page.

Table 1. Geophysical Corrections for ICESat-2 Products by Surface Type

ICESat-2 Products	Geophysical Corrections[1]
Photon-level Product (ATL03)	Ocean loading Solid Earth tide Solid Earth & ocean pole tide
Land Ice, Land, and Inland Water (ATL06, ATL08, and ATL13)	No additional corrections
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 Dynamic atmospheric correction (IB + wind effects)

[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 File Contents

Data files (granules) contain the sea ice retrievals (freeboard) for one of ATLAS's 1,387 orbits, provided as separate files for Northern Hemisphere and Southern Hemisphere overpasses. Sixteen granules are available per hemisphere per day.

1.2.4 Data Groups

Within data files, similar variables such as science data, instrument parameters, and metadata are grouped together according to the HDF model. ATL10 data files contain the top-level groups shown in Figure 3.

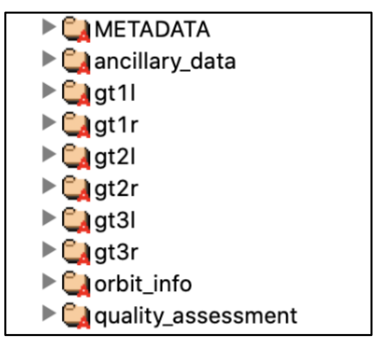

Figure 1. ATL10 top-level data groups shown in HDFView.

The following sections summarize the structure and primary variables of interest in ATL10 data files. Additional details are available in "Section 5.2 | Output of Freeboard Estimation Algorithm" and Appendix A of the ATBD for ATL07/10/20/21. The ATL10 Data Dictionary contains a complete list of all ATL10 parameters.

1.2.4.1 METADATA

ISO19115 structured summary metadata.

1.2.4.2 ancillary_data

Information ancillary to the data product such as product and instrument characteristics and processing constants.

1.2.4.3 gt1l–gt3r

Six ground track groups (gt1l–gt3r), each with /`freeboard_segment`/, /`leads`/, and /`reference_surface_section`/ subgroups:

- `/freeboard_segment/` contains the freeboard estimate and associated height segment parameters for the specified ground track. Data within this group are stored at the variable segment rate. Parameters include freeboard height for the beam (`beam_fb_height`); acquisition time, latitude and longitude, and distance from the equator to the segment center (`seg_dist_x`); plus, quality indicators for the freeboard estimate.
- `/leads/` contains parameters associated with the leads (sea surface height segments) used to compute the reference sea surface and local freeboard. Parameters include acquisition times, latitudes and longitudes, lengths, heights, standard deviations, and the number and indices of height segments used as leads.
- /`reference_surface_section`/ contains reference sea surface and mean freeboard.

1.2.4.4 orbit_info

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

1.2.4.5 quality_assessment

Quality assessment data for the granule as a whole, including a pass/fail flag and a failure reason indicator.

1.2.5 Naming Convention

Data files utilize the following naming convention:

```
ATL10-[HH]_[yyyymmdd][hhmmss]_[ttttccss]_[vvv_rr].h5
```

Examples:

```
ATL10-02_20181014062057_02390101_006_01.h5
ATL10-02_20181014062057_02390101_006_01.h5
```

The following table describes the file naming convention variables:

Table 2. File Naming Convention Variables and Descriptions

Variable	Description
ATL10	ATLAS/ICESat-2 L3A Sea Ice Freeboard product
HH	Hemisphere code. Northern Hemisphere = 01, Southern Hemisphere = 02
yyyymmdd	Year, month, and day of data acquisition for the given RGT
hhmmss	ICESat-2 data acquisition start time, hour, minute, and second (UTC) for the given RGT (not the start of ATL07 data production)
tttt	Reference Ground Track number. The ICESat-2 mission has 1,387 RGTs, numbered from 0001 to 1387.
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	Segment number. Not used for ATL10. Always 01.
vvv_rr	Version and revision number*

*NOTE: 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 superceded granule, the process can take several days. As such, 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.

1.2.6 Browse Files

Browse files are provided as JPGs that contain images 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.

1.3 Spatial Information

1.3.1 Coverage

Spatial coverage includes regions in the ice-covered oceans of the Northern and Southern Hemispheres that have > 50% sea ice concentration and lie > 25 km away from the coast.

1.3.2 Resolution

The ATLAS instrument transmits laser pulses at 10 kHz. At the nominal ICESat-2 orbit altitude of 500 km, this yields approximately one transmitted laser pulse every 0.7 meters along ground tracks. Note, however, that the number of photons that return to the telescope depends on surface reflectivity and cloud cover (which obscures ATLAS's view of Earth). As such, the spatial resolution varies.

Freeboard is estimated from ATL07 sea ice height segments that vary in length depending on the distance over which approximately 150 signal photons are accumulated and the availability of a reference sea surface. The along-track length of these input height segments is stored in `gt[x]/freeboard_segment/heights/height_segment_length_seg`.

1.3.3 Geolocation

Points on Earth are presented as geodetic latitude, longitude, and height above the ellipsoid using the WGS 84 geographic coordinate system (ITRF2014 Reference Frame). The following table contains details about WGS 84:

Table 3. 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	WGS 84
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
Reference	https://epsg.io/4326

For information about ITRF2014, see the International Terrestrial Reference Frame | ITRF2014 webpage.

1.4 Temporal Information

1.4.1 Coverage

14 October 2018 to present

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).

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

2 DATA ACQUISITION AND PROCESSING

2.1 Background

The ATLAS/ICESat-2 sea ice products are derived from geolocated, time-tagged photon heights plus other parameters passed to them by the ATLAS/ICESat-2 L2A Global Geolocated Photon Data (ATL03) product. The following figure illustrates the suite of ICESat-2 data products:

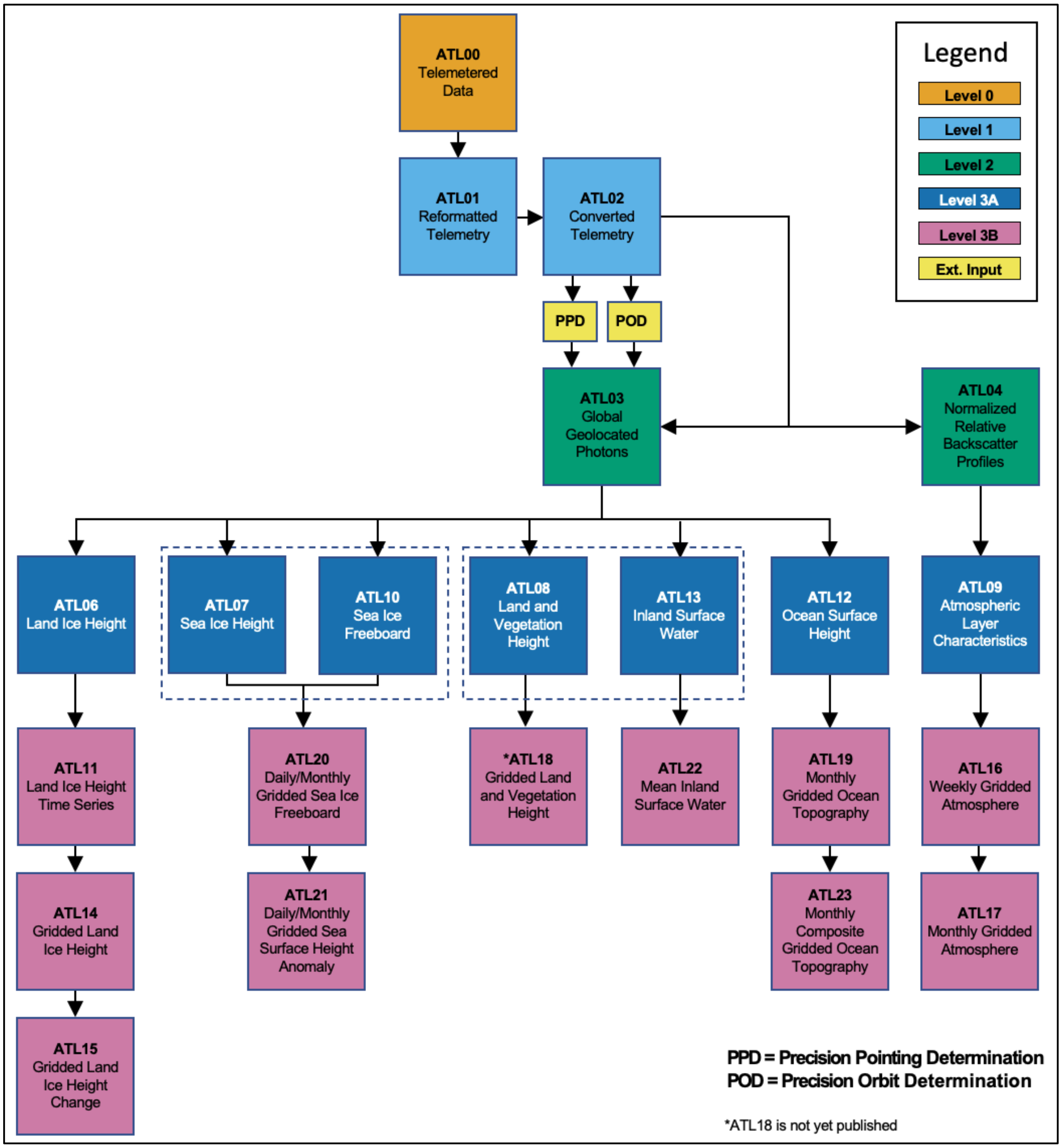

Figure 2. ICESat-2 data processing flow. The ATL01 algorithm reformats and unpacks the Level 0 data and converts it into engineering units. ATL02 processing converts the ATL01 data to science units and applies instrument corrections. The Precision Pointing Determination (PPD) and Precision Orbit Determination (POD) solutions compute the pointing vector and position of the ICESat-2 observatory as a function of time. ATL03 acts as the bridge between the lower-level, instrumentation-specific products and the higher-level, surface-specific products.

NOTE: The following description briefly outlines the inputs, product coverage, and approach used to generate the ATL10 product. ATL10 is derived predominantly from ATL07, the ATLAS/ICESat-2 L3A Sea Ice Height product. Users seeking a detailed description of how ATL10 along-track freeboard is generated should consult "Section 4 | Algorithm Description: ATL07" and "Section 5 | Algorithm Description: ATL10" of the ATBD for ATL07/10/20/21.

2.2 Acquisition

Along-track, sea ice freeboard is estimated for every sea ice height segment computed in ATL07. These segments are passed to ATL10 along with available sea surface height segments (leads) that are flagged by ATL07 as suitable for establishing a local, reference sea surface height that can be used to compute freeboard. The along-track length of the ATL07 sea ice segments is determined by the distance over which approximately 150 signal photons are accumulated, which changes with varying surface types up to a maximum of 150 meters. Cloudy conditions are identified using parameters input from ATL09 (ATLAS/ICESat-2 L3A Calibrated Backscatter Profiles and Atmospheric Layer Characteristics), and height estimates are not produced for segments contaminated by clouds.

2.3 Processing

2.3.1 Product Coverage

The marginal ice zone is defined as that part of the ice cover with < 15% ice concentration determined from daily ice concentration fields from satellite passive microwave brightness temperatures (AMSR-E/AMSR2 Unified L3 Daily 12.5 km Brightness Temperatures, Sea Ice Concentration, Motion & Snow Depth Polar Grids, Version 1). Returns with ice concentrations < 15% are not processed in ATL07/10.

NOTE: If AMSR2 data are not available within one day of the ICESat-2 granule, then Near-Real-Time NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 2 data are used instead.

2.3.2 Freeboard Estimation

The ATL10 product computes along-track sea ice freeboards at two scales.

First, data are provided at the individual height/freeboard segment rate using height retrievals from the collection of 150 signal photons along the tracks of each beam. The average track lengths are ~20 m for strong beams and ~60 m for weak beams. The single-beam freeboard data are contained in the `gt[x]/freeboard_segment/` group.

Second, averaged freeboards at the reference scale of 10 km along-track for the entire freeboard swath based on a reference surface are computed as the weighted mean of all the lead heights within that freeboard swath.

NOTE: The freeboard swath values (`fbswath_fb_height`) are currently unavailable because the residual height biases between beams prevent an accurate estimation of sea ice freeboard from the combined beams. These swath freeboard data are planned for a future release.

The algorithm first finds the leads—collections of height segments flagged by ATL07 as sea surface—and then uses the leads to estimate the height of a reference surface for computing the local freeboard over a region of 10 km extent. The reference surface latitude, longitude, and time are determined by interpolating nearby available reference surfaces.

Freeboards are then calculated from the individual sea ice height segments, subtracting the sea surface reference height.

Erroneous reference surfaces are filtered out by identifying the conditions where the reference surface observations are near to land and/or in areas of low ice concentration (sea state influences the reference surface near the ice edge, resulting in surfaces that can be many tens of centimeters below the local mean sea surface). This filtering procedure is designed to use collections of reference surfaces within ATLAS sub-regions.

Further details about the filtering procedure are provided in Section 5 of the ATBD for ATL07/10/20/21 under the subsection "5.1.4 | Procedure to Filter and Fill Missing Surface Reference (`refsurf`) Estimates Along Track." For a list of parameters output by the freeboard algorithm, see "Section 5.2 | Output of Freeboard Estimation Algorithm" in the ATL07/10/20/21 ATBD.

2.4 Quality, Errors, and Limitations

Errors in height retrievals from photon counting lidars like ATLAS can arise from a variety of sources. For example:

- Sampling error: ATLAS height estimates are based on random point samplings of the surface height distribution;
- Background noise: sampled photons include some random outliers that are not from the surface;
- Misidentified photons: the retrieval algorithms do not always utilize the correct photons as surface photons when estimating surface height;
- Atmospheric forward scattering: photons traveling downward through a cloudy atmosphere may be scattered through small angles and yet still be reflected by the surface within the ATLAS field of view. As such, these photons will be delayed and produce an apparently lower surface;
- Subsurface scattering: photons may be scattered many times within ice or snow before returning to the detector and may underestimate surface heights.

- First-photon bias: this error, inherent to photon-counting detectors, may overestimate the mean detected photon height depending on signal strength.

For additional details, see "Section 2.2.5 | Potential Error Sources" in the ATL07/10/20/21 ATBD.

3 VERSION HISTORY

A summary of the version history is provided in Table 3, followed by a detailed list of changes for the current version.

Table 4. Version History Summary

Version	Release Date
V1	May 2019
V2	October 2019
V3	July 2020
V4	April 2021
V5	November 2021
V6	August 2023

Changes for Version 6 include:

- Added AMSR2 sea ice concentration (SIC) data as follows:
  1. Use AMSR2 by default (AMSR-E/AMSR2 Unified L3 Daily 12.5 km Brightness Temperatures, Sea Ice Concentration, Motion & Snow Depth Polar Grids, AU_SI12)
  2. Where AMSR2 is unavailable, use SSMI (NOAA/NSIDC Climate Data Record (CDR) of Passive Microwave Sea Ice Concentration, G02202)
  3. Where G02202 data are unavailable, use near-real-time SSMI data (Near-Real-Time NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, G10016)
- Removed interpolated reference surfaces with no sea ice segments.
- Updated the mean sea surface (MSS) variables description. Added mentions of the source of the MSS (which uses CryoSat-2 data) and clarified the use of the tide free system.
- Updated the ATL10 group structure. In V5, the main group contained mixed data rates. V6 creates three groups, one for each data rate. The three subgroups for each beam group (`gtx`) are `leads`, `reference_surface_section`, and `freeboard_segment`.
- Implemented land filtering. The introduction of uncorrected heights (which can be processed anywhere) caused many returns over land, so `distance_to_land` and bathymetry ancillary files were introduced for filtering purposes.

4 DOCUMENT INFORMATION

4.1 Publication Date

August 2023

4.2 Date Last Updated

August 2023