ATLAS/ICESat-2 L3A Ocean Surface Height, Version 6

USER GUIDE

How to Cite These Data

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

Morison, J. H., D. W. Hancock III, S. Dickinson, J. Robbins, L. Roberts, R. Kwok, S. P. Palm, B. Smith, M. F. Jasinski, and the ICESat-2 Science Team. 2023. *ATLAS/ICESat-2 L3A Ocean Surface Height, 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/ATL12.006. [Date Accessed].

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National Snow and Ice Data Center

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1 DATA DESCRIPTION

1.1 Parameters

Along-track sea surface height of the global open ocean, including the ice-free seasonal ice zone and near-coast regions. Estimates of height distributions, significant wave height, sea state bias, and 10 m heights are also provided.

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 ATL12 data product is described in detail in the Ice, Cloud, and land Elevation Satellite-2 Project Algorithm Theoretical Basis Document (ATBD) for Ocean Surface Height (ATL12 ATBD, V06 | https://doi.org/10.5067/E5JD7G9RZNUI).

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 , 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. ATL12 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).

NOTE: ATL12 includes data from strong beams only. In general, ICESat-2 only downlinks strong beam data over the ocean. Weak beam data are only downlinked in ocean regions that overlap with ice cover or land buffer zones.

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.

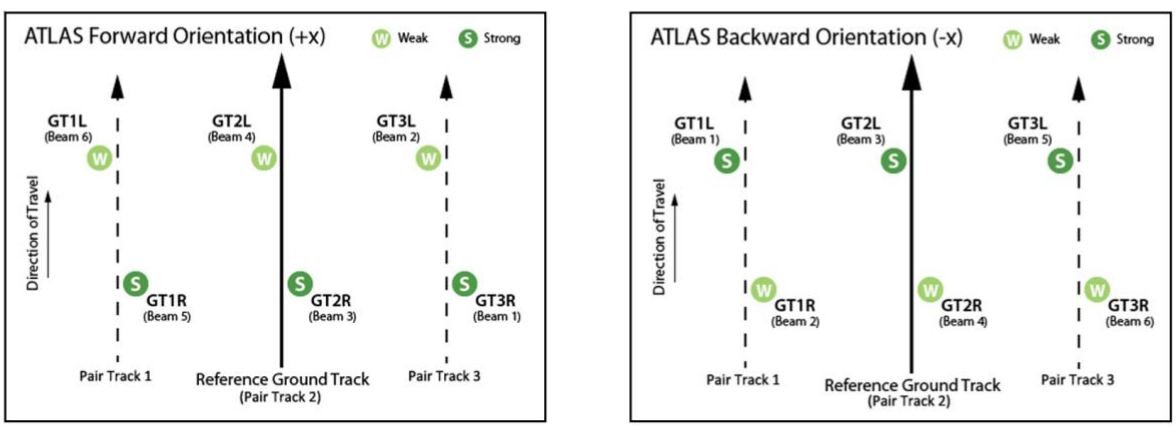

Figure 1. Spot and ground track (GT) naming convention with ATLAS oriented in the forward (instrument coordinate +x) direction and backward (instrument coordinate -x) direction.

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.

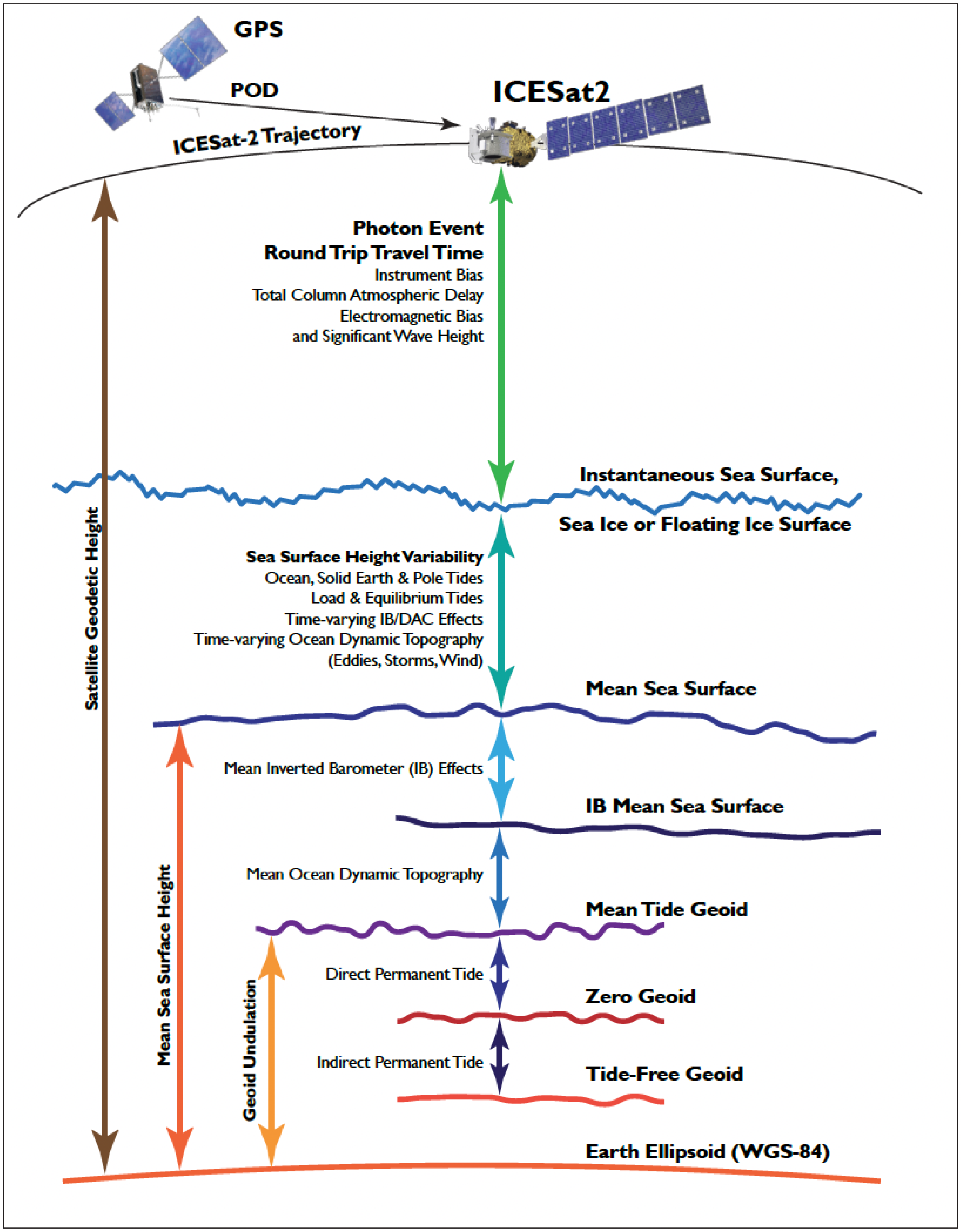

Figure 2. Geophysical corrections used in satellite altimetry. Taken from *ICESat-2 Data Comparison User's Guide for Rel006* available on the ATL03 data set landing page.

Table 1. Geophysical Corrections 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 File Contents

ATL12 data represent surface height at a given point on the ocean at a given time. Data files (granules) contain surface heights acquired during four consecutive orbits, plus parameters needed to assess the quality of the height estimates and to interpret and aggregate the estimates over greater distances. Over purely ocean regions, ATL12 includes data from strong beams only. However, over ocean regions that overlap ice cover and land marginal zones, weak beam data are also downlinked, processed identically to strong beam data, and output in addition to the strong beam results.

ATL12 processing is designed for open ocean conditions and includes a sea state bias calculation. However, processing is applied to the world ocean, including ice-covered regions reported by the ATLAS/ICESat-2 sea ice height and freeboard products ATL07 and ATL10. In these regions, the statistical parameters reported by ATL12 are valid for the mixed ocean/ice-covered and ice-free surface, however, mean heights include the average sea ice freeboard.

1.2.4 Data Groups

Within data files, similar variables such as science data, instrument parameters, altimetry data, and metadata are grouped together according to the HDF model. ATL12 data files contain the top-level groups shown in Figure 1:

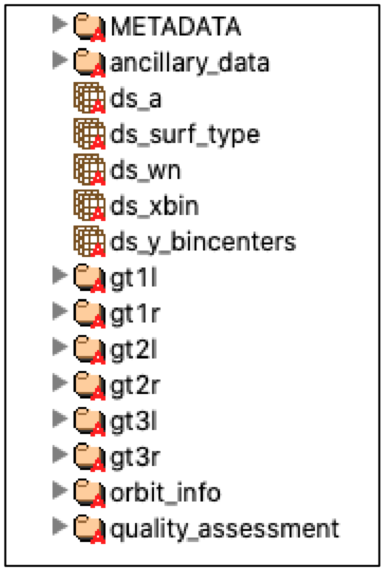

Figure 1. ATL12 data groups shown in HDFView.

1.2.4.1 METADATA

ISO19115 structured summary metadata for the granule, including content that describes the required geospatial information.

1.2.4.2 ancillary_data

Information that is ancillary to the data product. This may include product and instrument characteristics and/or processing constants.

1.2.4.3 gt1l–gt3r

Six ground track groups (gt1l–gt3r) that contain the per-beam data parameters (within the `/ssh_segments` subgroup) for the specified ATLAS ground track. Mean latitude, longitude, and time, plus duration of the segment, are stored at the top level of `/ssh_segments`. The sea surface height distribution and fit parameters are stored in the `/heights` subgroup. Quality and corrections to the sea surface heights are stored in `/stats`. Key parameters include:

- sea surface height (stored in /heights/h); variance (`/heights/h_var`); skewness (`/heights/h_skewness`); kurtosis (`/heights/h_kurtosis`)
- significant wave height[1] (`/heights/swh`)
- sea state bias (`/heights/bin_ssbias`); not valid for ice-covered water
- segment length (`/heights/length_seg`)
- total number of photons (`/stats/n_ttl_photon`) and number of surface photons (`/stats/n_photons`) in the segment

- percentage of non-open ocean included in the segment (`/stats/surf_type_prcnt`. See Spatial Information for details).

For a complete list of output parameters, see "Section 5.5 | Output Parameters" in the ATBD for ATL12 or the ATL12 Data Dictionary.

1.2.4.4 orbit_info

Orbit parameters that are constant for a granule, such as the RGT number and cycle and the 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.

1.2.4.6 Dimension Scales

Three HDF5 dimension scales are stored at the top level alongside the data groups—`ds_a`, `ds_surf_type`, `ds_y_bins`, and `ds_y_bincenters`. These dimension scales index the surface type and y-histogram bin and center values, respectively.

1.2.5 Naming Convention

`ATL12_[yyyymmdd][hhmmss]_[ttttccss]_[vvv_rr].h5`

Example:

`ATL12_20181014031222_02370101_006_01.h5`

The following table describes the file naming convention variables:

Table 2. File Naming Convention Variables and Descriptions

Variable	Description
`ATL12`	ATLAS/ICESat-2 L3A Ocean Surface Height product
`yyyymmdd`	Year, month, and day of data acquisition
`hhmmss`	Data acquisition start time, hour, minute, and second (UTC)
`tttt`	Four-digit RGT number of the first of four tracks in the granule. The ICESat-2 mission has 1,387 RGTs, numbered from 0001 to 1387.
`cc`	Cycle Number. 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 ATL12. Always 01.[1]

Variable	Description
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 ATL12 data files span four full orbits, the segment number is always 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.

1.2.6 Browse File

Browse files are provided as JPGs that contain images designed to quickly assess the location and quality of each granule's data. Browse images (for strong beams) show each segment's mean sea surface height, standard deviation of the height distribution, significant wave height, skewness of the height distribution, kurtosis of the height distribution, and 2-Gaussian fit parameters. 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 spans the world ocean surface from approximately 88° N latitude to 88° S. Each granule contains data obtained during four consecutive ATLAS orbit tracks.

Static surface masks (land ice, sea ice, land, and ocean) are applied to ATL03 to reduce the volume of data that a surface-specific along-track data product is required to process. The ocean surface mask directs the ATL12 algorithm to consider data from only those areas of interest.

NOTE: The ocean mask overlaps with all the other surface types in buffer zones up to 20 km wide. As such, ATL12 data may include data collected over low-lying land surfaces which lie close enough to sea level to fall within ±15 m of the geoid. Examples include sea ice surfaces in marginal sea ice zones and low-lying islands. To determine how much non-open ocean is included in any given ocean segment, users can check the `gt[x]/ssh_segments/stats/surf_type_prcnt` output variable.

1.3.2 Resolution

Heights over the sea surface are defined for ocean segments that vary in both length and spacing along the ground track; this strategy is necessary to ensure photon counts are high enough to adequately characterize sea surface heights given the inherently low and variable reflectance of open ocean surfaces.

In general, one photon reflects back to ATLAS from the ocean surface per laser pulse—0.7 m of along-track distance—or approximately 100 photons in a segment length of about 70 m. In practice, the adaptive algorithm outputs heights at length scales between 70 m and 7 km, depending on conditions and assuming clear skies.

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

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

1.4 Temporal Information

1.4.1 Coverage

13 October 2018 to present

1.4.2 Resolution

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

2 DATA ACQUISITION AND PROCESSING

2.1 Background

The ATL12 product contains sea surface heights at varying length scales, plus other descriptive parameters. These data are derived from geolocated, time-tagged photon heights passed to ATL12, along with other parameters, from the ATLAS/ICESat-2 L2A Global Geolocated Photon Data (ATL03) product. The following figure illustrates the suite of ICESat-2 data products:

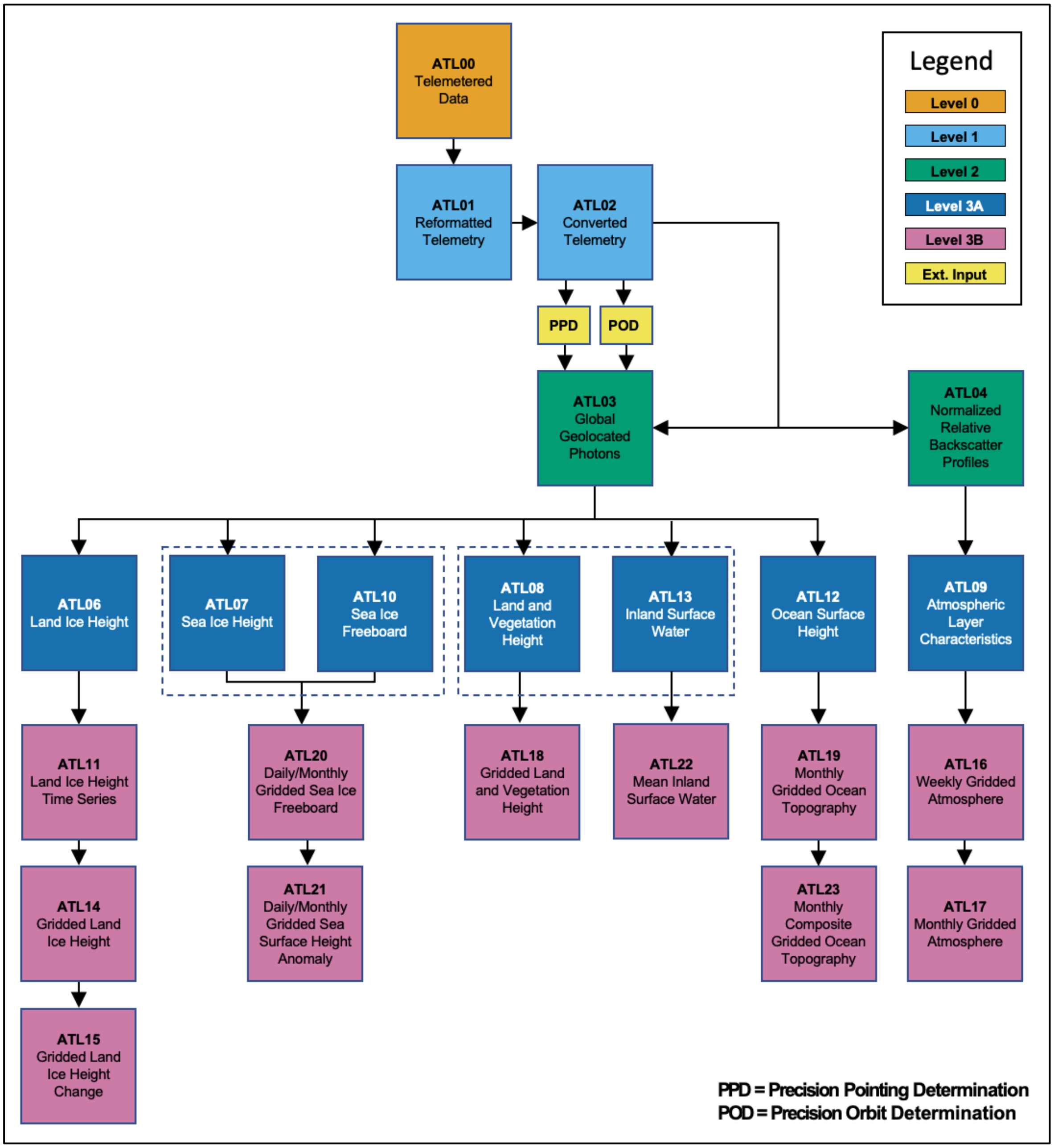

Figure 2. ICESat-2 data processing flow. The ATL01 algorithm reformats and unpacks the Level 0 data and converts it into engineering units. ATL02 processing converts the ATL01 data to science units and applies instrument corrections. The Precision Pointing Determination (PPD) and Precision Orbit Determination (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.

The following sections briefly describe the approach used to generate the sea surface heights and descriptive statistics reported by the ATL12 data product. The approach is detailed in "Section 4 | Algorithm Theory" and "Section 5.0 | Algorithm Implementation" in the ATBD for ATL12.

2.2 Acquisition

Sea surface heights are determined primarily from ATL03 geolocated photon heights. These inputs consist of low-, medium-, and high-confidence signal photons over open ocean combined with a buffer of photons that lie within ±15 m of the EGM2008 geoid. For a complete list of inputs to ATL12, see "Section 5.2 | Input Parameters" in the ATBD for ATL12.

2.3 Processing

Because the sea surface is in constant motion, surface finding requires searching ATL03 photon heights for a representative sea surface height distribution. The algorithm treats every ATL03 photon height passed as input to ATL12 as an individual surface-height point measurement, spaced on average less than one meter apart, but with an x-y location uncertainty on the order of 10 m. Figure 3 shows ATL03 photon heights collected over 7 km of ocean surface. Note that the dense cloud of surface-reflected photons clearly stands out from the noise photons above and below.

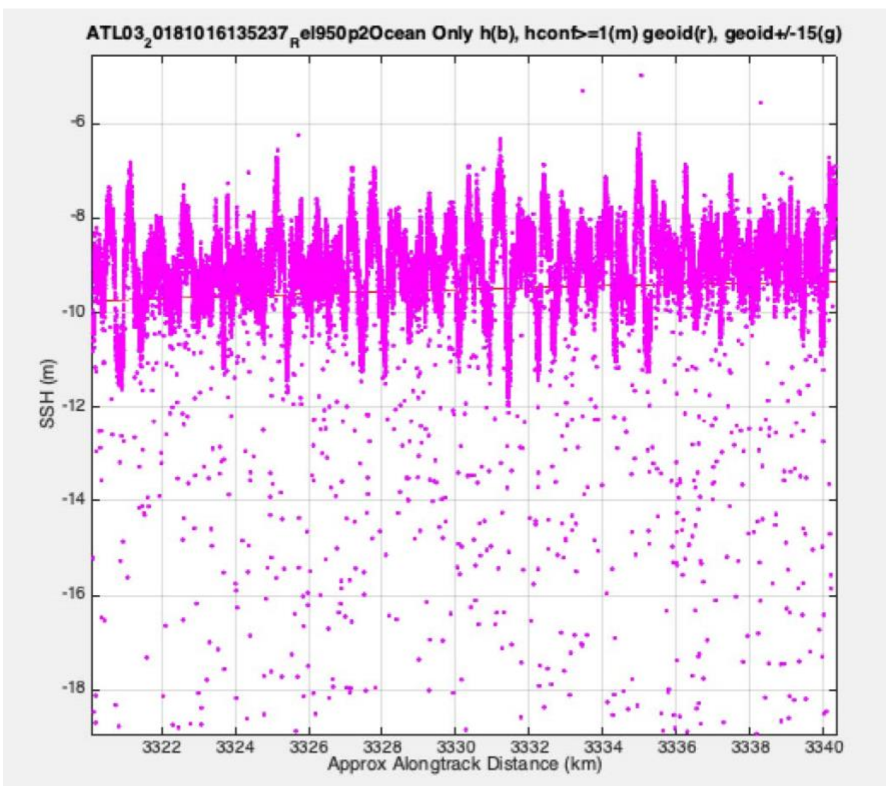

Figure 3. ATL03 photon heights (magenta) from 16 October 2018 over the Pacific Ocean. Waves in the dense photon cloud are apparent, as well as subsurface and atmospheric noise photons. Image from ATL12 Ocean Surface Height Release 004 Application Notes and Known Issues.

From the population of ATL03 input heights, the ATL12 algorithm accumulates photon returns that likely fall within the sea surface height distribution until it traverses 7 km of along-track distance or tallies 8,000 photons. The accumulated photons over the resulting ocean segment are then filtered to select heights in the histogram at levels above the background rate. After one iteration, a linear trend and average height are removed and then the data are filtered a second time (the trend and average height are retained and output with the ocean segment statistics).

The trimmed, detrended surface photon histogram is then 1) deconvolved with an ATLAS instrument impulse response histogram to produce a surface height distribution and 2) fit with a 2-Gaussian mixture model to produce the first four moments of the surface height distribution (see Figure 4).

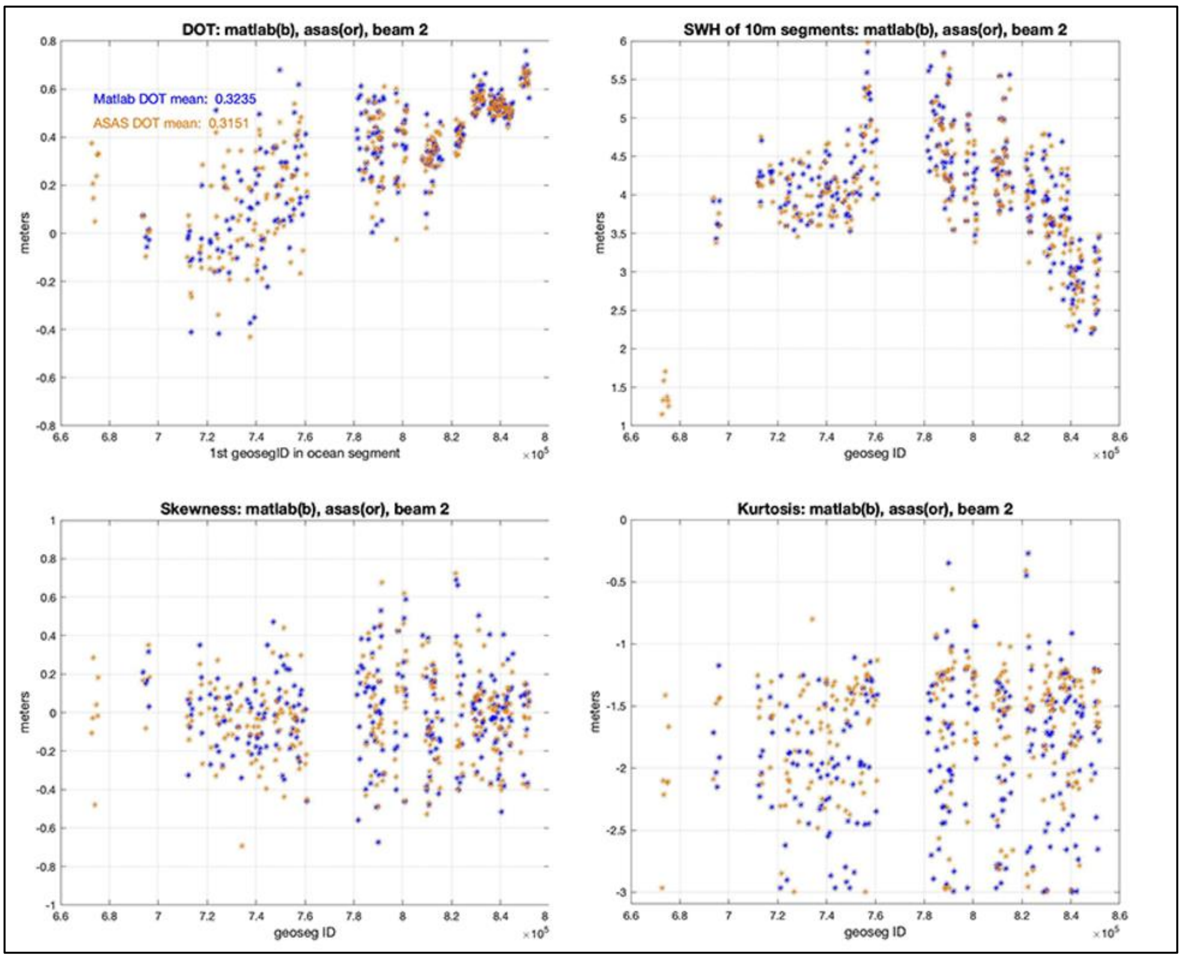

Figure 4. ATL12 ocean segment statistics. Upper left: Mean dynamic ocean topography (DOT) = SSH (moment 1) - geoid (EGM2008); upper right: significant wave height (SWH) = 4 x standard deviation (moment 2); lower left: skewness of sea surface height (moment 3); lower right: kurtosis of sea surface height (moment 4). Yellow DOTS are ATL12, Version 1 (revision 1) and blue dots are from ATL12 Science Team MATLAB developmental code applied to ATL03, which generally does not segment the data the same as ATL12. The agreement is better where segments are more closely matched.

Note that the impulse response function represents the height uncertainty associated with the lidar transmit pulse width and other instrumental factors.

In addition, the algorithm analyzes the spatial series of surface photon heights to characterize surface waves and to calculate the photon return rate and surface height correlation that constitutes the electromagnetic (EM) sea state bias (SSB) in the mean sea surface height. Thus, the ATL12 ocean product includes histograms and statistics of sea surface height over variable lengths.

2.4 Quality, Errors, and Limitations

Data quality metrics provided with the ATL12 product are listed in "Section 7.0 | Data Quality" in the ATBD for ATL12. In addition, users should consult "Section 9.0 | Constraints, Limitations, and Assumptions" in the ATBD for ATL12. This section summarizes the important factors that impact ATL12 coverage and quality and determine how the data should be interpreted and compared with other open ocean topography data sets.

ATL12 aims to achieve standard errors in mean sea surface height of 1 cm or better under typical sea states. However, due its utilization of 532 nm (visible light range), the ATLAS sensor requires mostly clear skies to sample the ocean surface. Furthermore, the relatively low reflectance of the ocean surface requires greater along-track lengths to accumulate enough height measurements to meet the desired statistical significance.

Limitations in the current understanding of altimetric returns from the sea surface carry through to the ATL12 product. In particular, subsurface returns represent a significant concern because the ATLAS 532 nm laser penetrates water, and the higher subsurface density of photons apparent in Figure 3 may be due in part to subsurface scattering in the ocean. However, the ATL12 Science Team has noted similarly enhanced subsurface densities over clear, deep ocean waters (and even over land) where subsurface backscatter does not apply. At this time, the ICESat-2 Science Team believes that the subsurface noise level stems from forward scattering delays in the atmosphere. To eliminate subsurface returns masked by the true surface distribution, future releases will adopt a scheme that selects photons based on a histogram of height anomalies about a moving, 11 photon average of high confidence photon heights. This histogram is much narrower than the surface height histogram and has a more distinct negative-side noise tail that will facilitate deletion of subsurface returns under the surface wave crests.

In addition, the ATL12 Science Team has found larger ocean segment-to-segment variation in average DOT = SSH - Geoid (e.g., see Figure 4 upper left, ±0.1 to 0.3 m) than expected from instrumental factors. If each of the approximately 8,000 photon heights in an ocean segment was independent, even with a SWH = 2.5 m (t_h = 0.625 m), the uncertainty in estimates of the mean should be less than 1 cm. However, the height measurements over long ocean waves are not independent, and the degrees of freedom can approach the number of wavelengths in the ocean segment. To address this problem, future ATL12 releases will include harmonic analyses of surface height for each ocean segment and the option to use a zero wave-number amplitude to represent SSH. In addition, the spectral analysis will be used to derive measures of the effective number of degrees of freedom for each ocean segment. These measures will be output as an ATL12 parameter in order to optimally combine ATL12 ocean segment heights and produce the lowest uncertainties in the planned gridded SSH product (ATL19).

As this sea surface height product is being developed and evaluated on an ongoing basis, users should consult the most recent Known Issues document on the ATL12 data set landing page. This document will be updated with each new release.

3 VERSION HISTORY

A summary of the version history is provided in Table 4, followed by a detailed list of changes for the current version.

Table 4. Version History Summary

Version	Release Date	Description
V1	June 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	March 2022	Refer to V5 User Guide
V6	May 2023	See below
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.

Changes for Version 6 are as follows:

- Fixed an error in the surface type percentage calculation. Surface type percentage is based on the overlapping ATL03 surface type mask. The ocean surface type percentage now indicates 100% for all ocean segments. Other surface types properly indicate if the ATL03 mask for that type is fully, partially, or not overlapping the ocean segment. If there is an overlap (non-zero percent), then that surface-type-specific data product may contain results processed by the other algorithm; it does not indicate the ocean segment is contaminated by that surface type.
- Updated the ATL12 template. The min and max values for `htybin` were changed to ±20.0.
- Other improvements implemented since the last release:

- Added the earliest time for the granule (`delta_time`) to `/quality_assessment`.
- Added the average DOT for the granule (`dot_mean`) to `/quality_assessment`.
- Added the standard deviation of DOT for the granule (`dot_std`) to `/quality_assessment`.
- Added the mean DOT for each 10-degrees of latitude (`dot_mean_lat`) to `/quality_assessment`.
- Added the standard deviation of DOT for each 10-degrees of latitude (`dot_std_lat`) to `/quality_assessment`.
- Added the dimension scale for latitude bins center (`ds_lat_bincenters`) to `/quality_assessment`.
- The overall sigma and the mean DOT and its standard deviation for each 10 degrees of latitude are used for editing on ATL19 but not recorded. The best place for this summary data is in the ATL12 `quality_assessment` group.

4 DOCUMENT INFORMATION

4.1 Publication Date

May 2023

4.2 Date Last Updated

May 2024