Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) Project

Algorithm Theoretical Basis Document (ATBD) for Mean Inland Surface Water Data

ATL22 Release 003

April 28, 2023

by

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Abstract

This document describes the theoretical basis of the algorithms employed in the derivation and processing of the ATL22 Mean Inland Surface Water Data products for ICESat-2, Version 3. These level L3B data products are reported at the mean transect rate for each ICESat-2 water body crossing, using output from the L3A ATL13 Ver 6 Along Track Inland Water Body Data product. The ATL22 ATBD includes descriptions of the input and output data products and product parameters, detailed algorithm steps required for computing the mean of those products, a summary of other ancillary ICESat-2 products required in the processing, and a calibration and validation plan.

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*Note:

The companion continuous ATL13 Level 3A along track products are published as a separate product as described in Chapter 1 below.

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CM Foreword

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Preface

This document is the L3B Algorithm Theoretical Basis Document for the ATL22 Version 2 Mean Inland Surface Water Data products processing implemented at the ICESat-2 Science Investigator-led Processing System (SIPS). The SIPS supports the ATLAS (Advance Topographic Laser Altimeter System) instrument on the ICESat-2 Spacecraft and encompasses the ATLAS Science Algorithm Software (ASAS) and the Scheduling and Data Management System (SDMS). The science algorithm software produces Level 0 through Level 3A&B standard data products as well as the associated product quality assessments and metadata information.

The ICESat-2 Science Team, in support of the ICESat-2 Project Science Office (PSO), assumes responsibility for this document and updates it, as required, as algorithms are refined or to meet the needs of the ICESat-2 SIPS. Reviews of this document are performed when appropriate and as needed updates to this document are made. Changes to this document will be made by complete revision.

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Change History Log

Revision Level	Description of Change	SCoRe No.	Date Approved
1.0	**ATL22 Version 001** (Not published) Derived from ATL13 ATBD Ver 4		August 31, 2021
2.0	**ATL22 Version 002** Derived from ATL13 ATBD Ver 5		
3.0	**ATL22 Version 003** Derived from ATL13 ATBD Ver 6		March 10 2023
	The mean values of all parameters improved from previous ATL22 Rel 002 by filtering ATL13 input heights using histogram analysis that excluded outliers (E.g., land, islands).		

List of TBDs/TBRs

Item No.	Location	Summary	Ind./Org.	Due Date

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1.0 INTRODUCTION

1.1 Summary

This ICESat-2 L3B Algorithm Theoretical Basis Document (ATBD) describes the initial release of the ICESat-2 **Mean Inland Surface Water Data product or ATL22 Ver 3**. Its principal products include, for each of the ICESat-2's six beams over a water body transect, the mean surface water height, mean surface height standard deviation, and mean ATLAS 532nm attenuation coefficient, reported at the center of the beam transect. Additional products including the beginning and end of the transect, transect length, and center of transect are also reported.

ATL22 Ver 3 is a derivative of the continuous **L3A ATL13 Ver 6 Along Track Inland Surface Water Data** product which has been published since May 2019 and continues to be published as a separate ATBD (E.g. See Jasinski et al, 2023a; 2023b). ATL13 contains the high resolution, along track inland water surface profiles derived from analysis of the geolocated photon clouds from the ATL03 product. By contrast, ATL22 computes the mean surface water quantities directly from ATL13 products with no additional photon analysis. The two data products, ATL22 and ATL13, can be used in conjunction as they include the same orbit and water body nomenclature independent of the version. Both sets of products and all subsequent versions of those products always reprocess the full record of ICESat-2 observations from the beginning of acquisition in October 2018 to present.

The complete documentation of the ATL22 product including the most recent version of this ATL22 ATBD, Data Product Known Issues, and data acquisition, is available at the NSIDC link https://nsidc.org/data/atl22.

The frequency of water body crossings depends on the intersection of the ATL13/22 water body mask and ICESat-2's orbital pattern that is characterized by the latitude-dependent observation scenario. For high latitude polar regions, mission requirements require that ICESat-2 repeats observations along the precisely established reference tracks, similar to ICESat-1. However, for all lower latitudes, ICESat-2 does not repeat during the first two years but rather implements a systematic off-pointing mapping scenario. The frequency of observing a water body therefore depends also on its size and geographic location.

1.2 Justification of the ATL22 Mean Surface Water Products

The importance and justification of the L3A ICESat-2 Inland Surface Water Products have been aptly described in Section 1.2 of the ATL13 ATBD. Here, ATL22 has been developed as a higher level (L3B) more convenient alternative to ATL13 for hydrologists, water resources engineers, and other discipline scientists and applied science users who only require the mean surface water products across the water body such as water surface height. The computation of the mean crossing products directly from the ATL13 products can be cumbersome due to the non-repeat nature of the orbits and the irregular shape of the water bodies.

The mean ATL22 Inland Surface Water products offer several important applications. For instance, the estimation of river discharge usually requires the overall slope or mean water elevation at the upper and lower boundaries of a river reach. Differencing the ATL22 mean heights between two ICESat-2 beams for a single overpass, as well as the channel center, provides that measure. Similarly, storage change in a lake or reservoir is usually estimated on the basis of the mean elevation difference between two crossing dates. The ATL22 mean elevation centered at the middle of a reservoir transect more accurately provides that height, compared to in situ measurements near the shore that may be affected by wind setup. An additional important ATL22 product is the crossing length distances whose computation can be hindered by uncertainty in the exact beginning and end of the ATL13 water entry and exit locations. Finally, the ATL22 products continue to offer valuable data especially in remote areas such as high latitude boreal zones in North America and Eurasia where in situ data measurements are sparse or non-existent. They further serve as a high resolution calibration source for other radar altimeters, that generally perform poorly in ice covered lakes, and as an accurate calibration source for the upcoming SWOT mission.

The difference between the mean ATL22 products and the long-standing ATL13 products is schematically illustrated in Figure 1-1 below. In Figure 1a, the reporting scales of the ATL13 products are short segment lengths with a minimum number of signal photons (E.g., Short segments, 100 signal photon default). By contrast in Figure 1b, the reporting scale of ATL22 mean products is a single value for the entire transect.

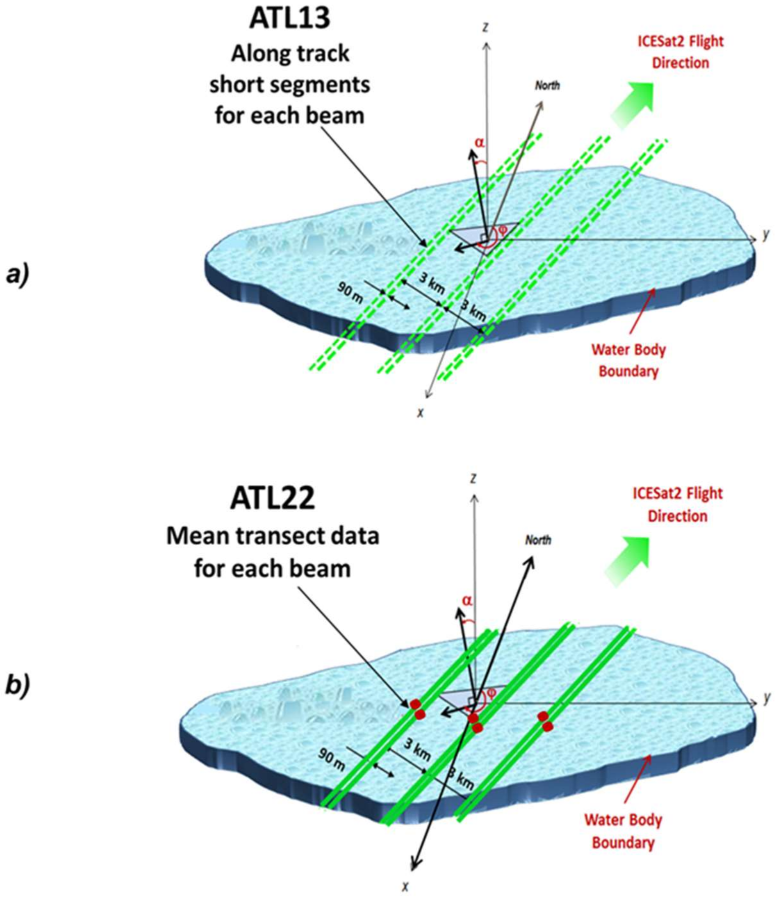


Figure 1-1. Schematic comparison of ATL13 and ATL22 data products. a) ATL13 short-segment, Along Track Inland Surface Water Data products are reported at variable segment lengths of 75-100 signal photons based on water body type, or about 30-100m, b) ATL22 Mean Inland Surface Water Data products report a single mean located at the center of each observed transect (red dots). Estimated vertical error is < 5 cm per transect and is dependent on transect length.

1.3 Evolution of the ATL13 and ATL22 Inland Surface Water Data Products

The Inland Surface Water Data products are continually being updated to include new features and capability. Table 1-1 summaries the evolving features of progression of the data product through ATL13 Version 006 and the newest ATL22 Version 3. The list of all specific products associated with the latest ATL22 version is provided in Table 5.2.

ATL13/22 Version	Release Date	Water Body Types (Number of unique IDs)	Description and Principal/Added Features
ATL13v1	May 2019	Lakes & reservoirs > 10 km^2 (19,634)	- Continuous, along track surface water products including subsurface attenuation and supporting data. - reported at short segment length - Employs GLWD (Lehner & Doll 2004)
ATL13v2	Nov 2019	Lakes & reservoirs ≥ 10 km^2 (19,800) Estuaries, bays, and near shore 7 km buffer (~3500)	- Employs HydroLAKES (Messager & Lehner, 2016) - Adds transitional waters; Named Marine Water Bodies (ESRI) GSHHG Shoreline (Wessel et al, 1996) - Adds significant wave height - coarse bathymetry algorithm - Adds dynamic shore finding
ATL13v3	Mar 2020	Lakes & reservoirs ≥ 0.1 km^2 (~1,400,000) Estuaries, bays, and near shore buffer (7 km) (~3500) Rivers ≥ ~50-100 m wide (10,300)	- Adds river mask using GRWL (Allen and Pavelsky, 2018) - Adds wind speed for all crossings - Adds Ice on/off flag from multi-sensor NOAA product - Corrects first photon bias error - Adds cloud confidence flag
ATL13v4/v5	Apr/Nov 2021	All above water bodies	- Improves photon classification - Improves accuracy of existing data products - Reports additional products
ATL22v2	Dec 2021	All water bodies	- Mean surface water and supporting products including crossing length - Reported for each transect (uninterrupted water crossing)
ATL13v6	Aug 2023	All water bodies	- Improves accuracy of surface products by eliminating anomalous photons - Improves accuracy of subsurface attenuation coefficient deconvolution scheme - Reports additional quality flags
ATL22v3	Aug 2023	All water bodies	- Improves mean surface water product estimates removing anomalies

Table 1-1 Evolution of principal features of ATL13 and ATL22 Inland Surface Water Product Releases

2.0 BACKGROUND

2.1 Summary of ICESat-2 ATLAS Instrument

NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) mission is the second of the ICESat laser altimetry missions launch in September 2018. ICESat-2 carries an improved Advanced Topographic Laser Altimeter System (ATLAS) consisting of a low energy, micropulse, multibeam, high-resolution photon-counting laser altimeter possessing three pairs of beams. Each pair, separated by about 90 m, consists of a high energy (~100 mJ) beam and a low energy (25 mJ) beam each with an approximately 11 m footprint. Pairs of beams are separated by about 3 km. An instrument pulse rate of 10kHz and a nominal ground speed of ~7000m/s allow observations about every 70 cm. ATLAS can be oriented forward or backward, which changes the relative position of the weak and strong beams. A schematic of the backward orientation is shown in Figure 2-1.

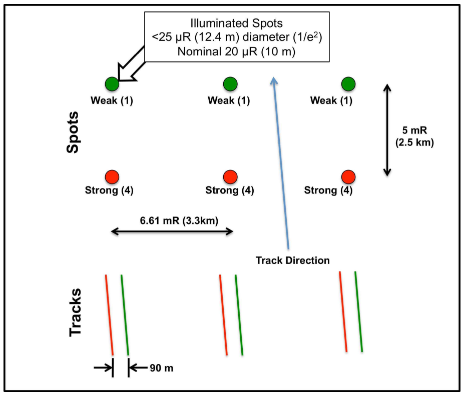


Figure 2-1 ICESat-2 ATLAS six-beam configuration oriented backward.

2.2 ICESat-2 Orbit Configuration

ICESat-2's orbits at 496 km in a non-sun-sync, 92° inclination. Orbiting is configured in a 91 day repeat cycle with an approximately 30 day subcycle. An additional unique feature of ICESat-2 is its two orbit scenarios as shown in Figure 2-2 below. Above approximately +/-65 deg latitude, ATLAS operates in a repeat track mode over designated reference tracks similar to ICESat in order to obtain continuous time series of ice sheet change along those tracks. Below +/- 65 deg, however, ICESat-2 systematically off-points left or right off the reference tracks in subsequent orbits, in order to conduct a two-year global mapping of vegetation. Additional scheduled off-pointing also is often planned to observe targets of opportunity and calibration/validation sites.

The frequency of water body crossings depends on the intersection of the ATL13/22 water body mask and ICESat-2's orbital pattern that is characterized by a dual, latitude dependent observation strategy. For high latitude polar regions, mission requirements require that ICESat-2 repeats observations along the precisely established reference tracks, similar to ICESat-1. However, for all lower latitudes, ICESat-2 does not repeat during the first two years but rather implements a systematic off-pointing mapping scenario. The frequency of observing a water body therefore depends also on its size and geographic location.

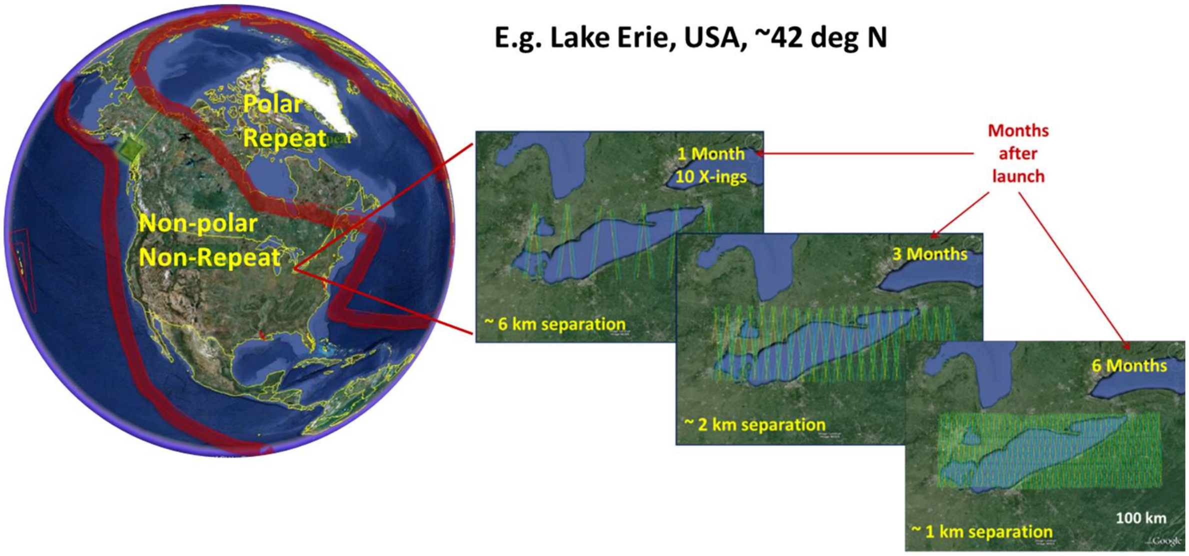


Figure 2-2 ICESat-2 off-pointing sampling scheme over land. E.g. Lake Erie, U.S. (Jasinski, Stoll, Gao and Parrish AGU, 2019).

3.0 INLAND WATER PRODUCTS

3.1 Conceptualization of ATLAS observed inland water altimetry

The ATL22 product is computed from previously developed ATL13 surface and subsurface water products reported at the short segment rate. The ATBD of these along track products, include surface water height statistics, beam attenuation, and potential bottom elevation, among many others (Jasinski et al., ATL13 ATBD Ver 6, 2023).

3.2 Definition of ATL13/22 Inland Water Body

An ATL13/22 inland water body is defined as a contiguous continental water body of the following types: lakes and reservoirs greater than about 0.1km^2, rivers greater than about 50-100m wide, transitional water including estuaries and bays, and a near-shore 7km buffer. In aggregate, the number of water bodies defined above is globally about 1.5 million. In ATL13/22, each water body is defined by a unique ID using publicly available masks and datasets. The project endeavors to include the most accurate and updated mask available, which also serves the advantage of being consistent with developments within future missions such as the Surface Water Ocean Topography (SWOT) mission.

3.3 Definition of ATL13/22 Inland Surface Water Body Transect

ATL13/22 water bodies are identified by a set of polygons in shape-file format. An ICESat-2 transect is any portion of an ICESat-2 beam crossing over a single water body that is interrupted by land, say due to islands, bays, or peninsulas. An ICESat-2 crossing with no land interruptions would have a single transect. An ICESat-2 crossing with a single island would have two transects. It is possible that an island interrupting one beam is not in the path of another beam. Therefore, each of the six ICESat-2 beams may have a different number and/or location of transects on that particular crossing.

For ATL13/22 non-land portion of the coastal buffer shapes that abut the adjacent ocean or river (See for example, Figure 3-2), and for the upstream and downstream sides of the river reaches shape that abut another reach, there is no land on the sides. In these cases, the transect is defined as the distance between the shape edge and the land.

3.4 The ATL03 Inland Water Mask (Flag)

In order to facilitate processing of data over only land and near coastal regions that possess water bodies, two types of hydrologic masks are created: i) an ATL03 Inland Water Mask, and ii) an ATL13 Inland Water Body Mask.

The ATL13 Inland Surface Water team worked with the ATL03 team to construct a gridded water mask of 0.1 km^2 that flags whether or not one or more water bodies exist in that grid. Water bodies include lakes, reservoirs, impoundments, and permafrost. The purpose of this fixed “Inland Water Mask”, shown as the shaded regions in Fig 3-1, is one of efficiency. The implementation of the ATL22 algorithm draws only on ICESat-2 observations that have been flagged as falling within an AT03 Inland Water Mask.

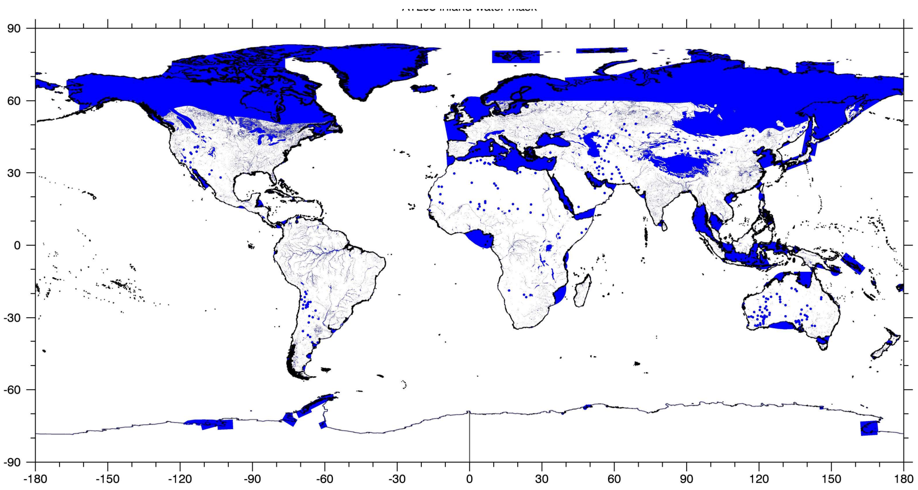


Figure 3-1 ATL03 Inland Water Mask (gridded, non-contiguous).

The ATL03 Inland Water Mask is further described in ATL13.

3.5 ATL13/22 Inland Surface Water Mask (Shape File)

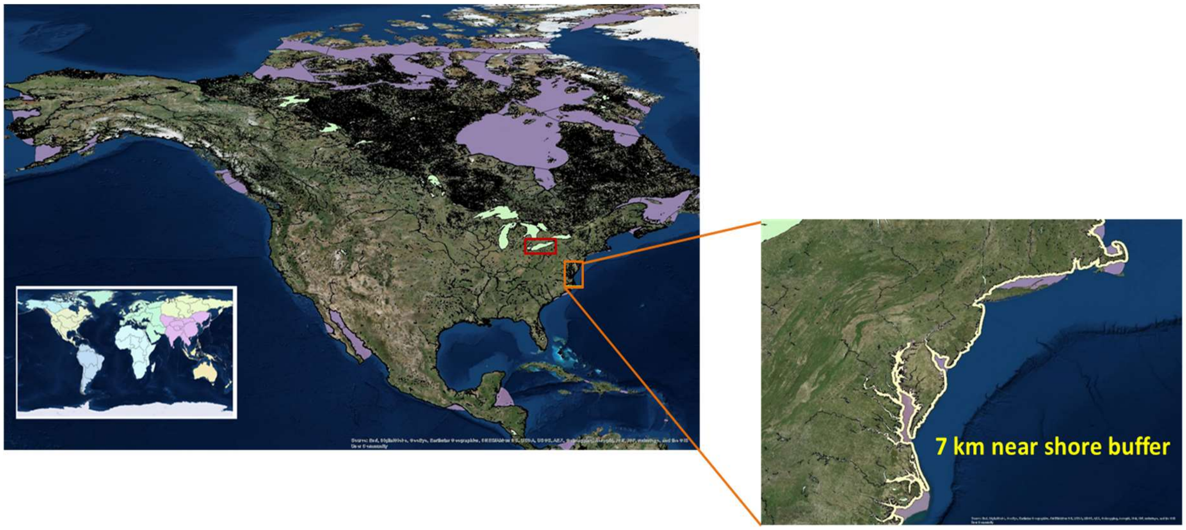


Figure 3-2 ATL13/22 Inland Surface Water Mask for North America Shape file (Jasinski, Stoll, Gao and Parrish, AGU, 2019).

The ATL13/22 Inland Surface Water Mask shown in Figure 3-2 is used to organize the ATLAS data used for inland water calculations and hydrologic data products in a logical manner. It consists of polygons that represent principally the outline of entire large river basins and some adjacent intervening area. Each polygon contains all the lakes and rivers within that river basin. Archiving data products in this manner eliminates the problem of having to store ATLAS inland water data products of contiguous lake and rivers within different files. The regional basins are: 1= Northern North America; 2 = Southern North America; 3- Greenland; 4 = South America; 5 = Africa; 6 = Europe; 7 = Northern Asia; 8 = Southern Asia; 9 = Australia & Oceania; 10 = Antarctica. Details are provided in the ATL13 ATBD.

It is estimated that the multi-beam ATL13/22 ICESat-2 coverage contains potentially over 1.4 million water bodies, allowing the overpass of about 650 lakes $\geq 100\text{km}^2$, of which 50% are in Canada, and 25% in Eurasia. For lakes $\geq 10\text{km}^2$, the estimate is about 19,300 lakes. With 75-100 photon along-track aggregation there is the potential to record heights of the more numerous smaller impoundments ($> 1\text{-}5\ \text{km}^2$) which number in tens of thousands. Height accuracy will depend on aggregation level and water state but is expected to be about 10cm for the strong beam.

4.0 ALGORITHM THEORY

4.1 Overall Approach

This section describes the necessary steps used to process relevant ATL13 outputs into ATL22 transect mean quantities and other supporting parameters. Users interested in the derivation of the ATL13 products are referred to Jasinski, et al. (2023).

4.2 Computation of Mean Products

ATL22 takes advantage of the high resolution ATL13 along-track products to produce transect-level output for utilization when the study of more granular data is unnecessary. The ATL22 transect-rate output files for each of six beams are produced on an approximate 24-hour basis, with four ATL13 granules utilized as input.

Mean surface water products are computed as follows: The mean ellipsoidal height, mean orthometric height, and mean subsurface attention of a given beam transect are computed as the arithmetic mean of the respective ATL13 segment-rate output. The mean is computed over all non-anomalous ATL13 short segments in a transect and reported at a single index location for each beam in the transect based on the latitude and longitude of each segment. Transect-level representations of latitude, longitude, and time for each ATL22 transect are computed based on the short segment index photon location within the transect that is closest to the arithmetic means of the corresponding ATL13 data sets, with mean transect time also provided in UTC format. The length of a transect is defined as the distance between the start and end latitudes and longitudes of the first and last ATL13 observed segments in the ATL22 transect, respectively.

Prior to estimating the mean, short segments are filtered based on a histogramming of ATL13 heights in order to exclude outliers (E.g., land) from mean calculations.

The mean standard deviation of the transect water surface for each beam is calculated as the square root of the sum of the squares of the short segment standard deviations divided by the number of segments. The reporting position is the same as for the other mean products in the transect. (For ATL22 release 003, the standard deviation output for rivers is marked as invalid pending further development).

In order to allow a user to conveniently understand the lineage of ATL22 products, a number of attributes from the ATL13 source data are conveyed as ATL22 output describing the water body to which the transect belongs. Each ATL22 transect, having been derived from ATL13 output from a single water body, can be described similarly in ATL22 output and its input outlined for source tracing and higher resolution ATL13 data access. For each ATL22 transect, the ATL13 granule name is provided that was utilized as input (/metadata/lineage), as well as the unique reference identification number (atl13_gran_ndx) for the water body to which the transect belongs, the water body region, and the water body type.

In order to further facilitate the use of ATL22 output in concert with the higher resolution ATL13 data, ATL22 transect output contains indices directing a user to the start and end rows (transect_start_sseg_idx and transect_end_sseg_idx) of ATL13 input arrays upon which the ATL22 products are based. Thus, the exact set of input used to compute the output for a given transect can be traced within the lineage, reference, and transect identifying values of an ATL13 product array by considering the start and end index values provided by ATL22. The name and description of the input products including the start and end latitude and longitude locations are provided in Table 5-1. The names and descriptions of the ATL22 output products are provided in Table 5-2.

Additional information that is useful in understanding the robustness of a given transect in the ATL22 output is provided as counts of the shorter ATL13-defined segments that construct the transect. The count of non-anomalous short segments, long segments, and very long segments as defined in ATL13 processing are provided as ATL22 output.

Three examples of ATL22 output are provided in Section 6, a single lake and two global images.

4.3 Data Product Precision and Evaluation

The Inland Water Data Product quality relies on the precision of the ATL03 georeferenced photons and associated products which are evaluated prior to their use within ATL13. The plan offered for evaluating ATL13 ATBD data products is presented in Section 4.9.2, Jasinski et al., 2023) and is also provided here.

4.3.1 ICESat-2 Precision

The precision of the ICESat-2 retrieval is estimated from root mean square of five error sources:

- i) Radial orbit error, RO_{RMS}
- ii) Tropospheric delay error, TD_{RMS}
- iii) Forward scattering error, FS_{RMS}
- iv) Geolocation Knowledge uncertainty, GK_{RMS}
- v) ATLAS ranging precision per photon, σ_{RMS}.

Actual rms error for each source are obtained from ATL03. The current default values are RO_{RMS} = 4.0 cm, TD_{RMS} = 3 cm, FS_{RMS} = 3 cm, GK_{RMS} <0.5 cm (over water) and σ_{RMS} =

24.0 cm. For 100 photon short segments, the ranging precision is estimated as $\sigma_{RMS100} = \sigma_{RMS}/(100^{1/2}) = 24/(100)^{1/2} = 2.4$ cm.

The overall ensemble error per 100 inland water photons is estimated as

$$\begin{aligned}\sigma_{ICESat2} &= \sqrt{[RO_{RMS}^2 + TD_{RMS}^2 + FS_{RMS}^2 + GK_{RMS}^2 + \sigma_{100\,shots}^2]} \\ &= \sqrt{37.25} = 6.1 \text{ cm} \qquad (4.1)\end{aligned}$$

This precision error is updated as post-launch ATLAS data sets are evaluated.

Previously analyzed MABEL data (Jasinski et al., 2016) scale well with the anticipated ATLAS observations. Results indicate a MABEL water return rate of 0.36 to 2.90 (photon events per meter (pe/m) depending on surface and atmospheric conditions. The ranging precision for a 100 shot segment would vary from 2.0 to 5.0 cm, respectively.

4.3.2 **Data Product Evaluation**

A plan for evaluating the Inland Water Data Product was formulated during the development of ATL13 by using principally existing publicly available data from relevant U.S. agencies, university researchers, and other various organizations. Data product quality is achieved through monitoring, assessment, and validation at various levels of effort depending on available resources. The overall approach for ATL22 is i) to compare ATL22 data products with *in situ* data and satellite radar altimetry where available, ii) evaluate several components of the ATL22 algorithm through threshold monitoring with model diagnostics, and iii) conduct in situ validation and calibration when resources are available or synergistic field opportunities arise. Evaluation can be conducted over all ATL22 Inland Water Body types including lakes, reservoirs, rivers, estuaries and near shore coasts. Sites are located primarily in the US and North America, but also at several international sites. Every effort is made to be aware of other sponsored field programs by NASA and other agencies.

4.3.2.1 Monitoring Activities

Monitoring refers to active and continuous evaluation of ICESat-2 data-product parameters, primarily through data visualizations and threshold monitoring. Monitoring can occur through comparison of ATL22 time series data plots with other independent data. Time series can be evaluated with respect to mean water surface segment heights, variances, slopes, significant wave height, subsurface attenuation, presence of ice, and identifiable bottom location, as a function of water body type, location, water clarity and prevailing meteorological conditions. For the Inland Water Data Product, monitoring occurs principally by leveraging off existing databases supported by numerous organizations in the US and internationally, including radar altimetry missions. Principal sources include:

a) Reservoir and lake elevations based on satellite radar altimetry from Jason 3, Sentinel 3A and 3B sensors and compiled at online archives. Example online data bases include:

- i) Center for Topographic Studies of the Ocean and Hydrosphere (CTOH) data
  - http://ctoh.legos.obs-mip.fr/data
- ii) HYDROWEB (Theia, LEGOS, other international)
  - http://hydroweb.theia-land.fr
- iii) Global Reservoir and Dam Database (GWSP)
  - http://globaldamwatch.org/grand/
- iv) G-REALM (USDA)
  - https://ipad.fas.usda.gov/cropexplorer/global_reservoir
- v) Global River Database
  - http://gaia.geosci.unc.edu/rivers/
- vi) River and Lakes (ESA) (historical data)
  - http://altimetry.esa.int/riverlake/shared/main.html
- vii) Database for Hydrological Time Series of Inland Waters (DAHITI)
  - https://dahiti.dgfi.tum.de/en/
- viii) Global Water Monitor
  - https://blueice.gsfc.nasa.gov/gwm/lake/Index

b) *In situ* water level gauges primarily at reservoirs, lakes, and other water bodies monitored by the: i) US Geological Survey (USGS), ii) National Oceanic and Atmospheric Administration (NOAA), iii) Bureau of Land Management (BLM), and iv) US Army Corps of Engineers (USACE). Although there are hundreds of available sites, the principal water bodies being considered include Lake Fort Peck, MT; Lake Mead, NV; all Great Lakes; Lake Tahoe, CA; Chesapeake Bay; Lake Teshekpuk and Toolik Lake, AK; Lake Issyk-Kul, Kyrgyzstan; water bodies within the Mississippi, Connecticut, and Yukon River basins. All these water bodies are well gaged by the USGS, NSF, or other US agencies with accessible online data. Analyses will include evaluation mainly of root mean square error, bias, and mean absolute error. Databases include:

i) NOAA Great Lakes Environmental Research laboratory

https://www.glerl.noaa.gov/data/wlevels/levels.html#observations

ii) Lake Levels (GWSP)

http://www.lakelevels.info

iii) Lakes Online

http://www.lakesonline.com/

vi) USGS National Water Information System

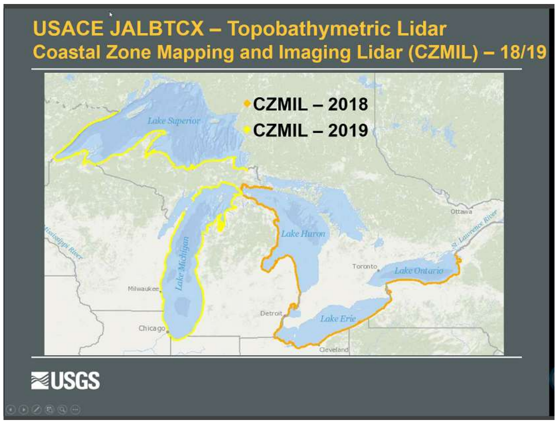
https://waterdata.usgs.gov/nwis

4.3.2.2 Assessment and Validation Activities

Assessment refers to a single post-launch evaluation of ICESat-2 data-product accuracy and/or precision, generally against in situ data. ‘Validation’ refers to an aggregate of post-launch ‘assessments’ to determine global ICESat-2 accuracy or precision. Instruments required are those that observe water surface height statistics, wind speed and direction, and basic water quality constituents that affect optical transmission and turbidity such as mineral particles, dissolved organic carbon and chlorophyll, among others.

Several opportunities are available with the following programs:

a) United States Great Lakes and near shore transitional zones. Field experiments are planned in collaboration with the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) mission performs operations, research, and development in airborne lidar bathymetry to support the coastal mapping and charting requirements of the US Army Corps of Engineers (USACE), the US Naval Meteorology and Oceanography Command, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geologic Survey (USGS). JALBTCX executes survey operations worldwide using the Coastal Zone Mapping and Imaging Lidar (CZMIL) system and other industry-based coastal mapping and charting systems. CZMIL is integrated with an ITRES CASI-1500 hyperspectral imager and a true-color digital camera. CZMIL collects 10-kHz lidar data concurrent with 5-cm digital true-color and 48-band hyperspectral imagery. JALBTCX research and development supports and leverages work in government, industry, and academics to advance airborne lidar and coastal mapping and charting technology and applications. An example of planned JALBTCX coverage in 2018 and 2019 is shown below.

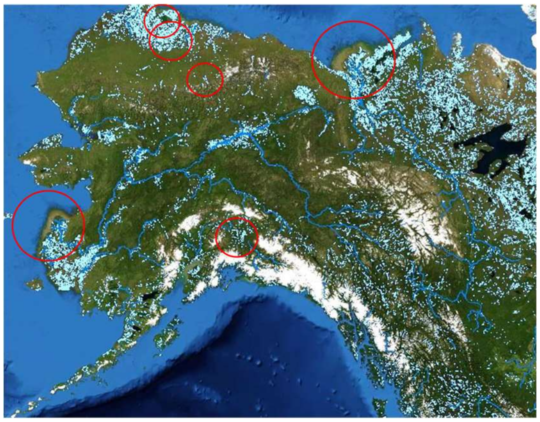


USACE JALBTCX – Topobathymetric Lidar
Coastal Zone Mapping and Imaging Lidar (CZMIL) – 18/19

● CZMIL – 2018
● CZMIL – 2019

b) <u>Alaska Sites</u>

ATL13 has collaborated with researchers from the Alaska USGS, the University of Alaska, Fairbanks, and NASA GSFC, for in situ monitoring during overflights. Sites include NSF sponsored Lakes Teshekpuk and Inigot, Toolik Lake; and the Yukon River and the Mackenzie River deltas as shown below. Participation in NASA GSFC field experiments at the mouths of the Yukon River and the near-shore region off Northern Alaska to the Mackenzie River mouth are currently under consideration.



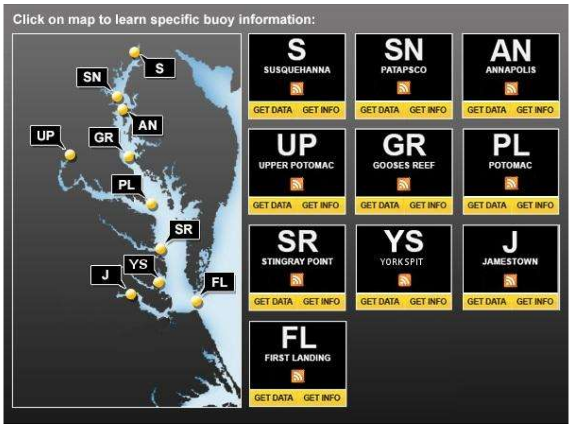
c) <u>Mid-Latitude Lakes and Reservoirs</u>

Assessment sites include collaboration a several sites with various groups including the Great Lakes (JALBTCX, Illinois State geological Survey), Lakes Mead (US Bureau of Reclamation), Lake Fort Peck (USACE), Lake Tahoe and the Great Lakes. For the Great Lakes, ATL13 is collaborating with efforts to measure Great Lakes surface water conditions at the locations shown below.

d) <u>Transitional Water Bodies (Estuaries, Bays, Near Shore Coasts)</u>

Principal areas would include the Chesapeake Bay, and the estuaries of the Mississippi/Atchafalaya River deltas, Everglades, Mackenzie River, and Yukon River, together with the near shore regions surrounding the East and West coast of the continental U.S. and Northern Alaska.

Collaboration with personnel from NOAA STAR for in situ measurements was implemented.


Click on map to learn specific buoy information:

4.3.2.3 Calibration Activities and Measurements

Data product calibration consists of the application of post-launch ‘assessments’ or ‘validations’ to either ICESat-2 instrument settings, or to future data releases, in an effort to improve measurement accuracy and/or precision. Necessary measurements for validation include the following:

i) Meteorology: Wind speed and direction, optical depth, cloud cover

ii) Water Surface Physical Properties: GPS, wave height statistics, temperature, water depth

iii) Subsurface Radiative Properties: Upwelling and downwelling radiance, at 532 nm.

iv) Water Inherent Optical Properties: subsurface attenuation, suspended particulate matter, CDOM, Chlorophyll, temperature, salinity, turbidity (NTU) and Secchi Depth.

5.0 ALGORITHM IMPLEMENTATION

5.1 Outline of Procedure

The overall procedure is to process global inland water body transects on a regular basis based on the ATL22 processing interval. The algorithm analyzes all transects of one water body before proceeding to the next. Mean data products are computed for all the new transects observed for that water body since the previous processing period.

5.2 ATL22 Input Variables and Parameters

Table 5-2 Input Variables for ATL22 Mean Inland Surface Water Algorithm

Name	Description	Units	ATLxx/Other Source
atl13_lineage	Names of ATL13 granules utilized as input into ATL22 granule.	unitless	ATL13/METADATA/Lineage/ATL13/fileName
atl13refid	Unique aggregate reference number for each shape in the ATL13 Inland Water Body Mask, where digit 1 = type, digit 2 = size, digit 3 = source, and digits 4-10 = shape id	unitless	ATL13/gtx/atl13refid
transect_id	Transect within a water body to which the short segment rate output belongs.	unitless	ATL13/gtx/transect_id
inland_water_body_id	Identifying signature of an individual inland water body. Each body of water is represented by a unique numeric value.	unitless	ATL13/gtx/inland_water_body_id
inland_water_body_region	ATL13-created shapefile representing relevant bodies of water over which to implement the ATL13 water surface finding algorithm only within a region of processing interest.	unitless	ATL13/gtx/inland_water_body_region

Name	Description	Units	ATLxx/Other Source
inland_water_body_type	Type of Inland Water Body, where 1=Lake, 2=Known Reservoir, 3=(Reserved for future use), 4=Ephemeral Water, 5=River, 6=Estuary or Bay, 7=Coastal Water, 8=Reserved, 9=Reserved	unitless	ATL13/gtx/inland_water_body_type
s_seg1	Short segment size, operationally used as unit length over which to identify water surface height anomalies such as islands, bridges, etc.	unitless	ATL13/ancillary_data/inland_water/s_seg1
l_surf	Long segment size, operationally used as unit length over which to detrend the water surface, characterize the surface, and deconvolve the instrument pulse and subsurface effects from the water surface response.	unitless	ATL13/ancillary_data/inland_water/l_surf
l_sub	Long segment size, operationally used as unit length over which to characterize the subsurface, and deconvolve the instrument pulse and subsurface effects from the water surface response.	unitless	ATL13/ancillary_data/inland_water/l_sub
segment_lat	Latitude of reporting location for all short segment statistics.	degrees	ATL13/gtx/segment_lat
segment_lon	Longitude of reporting location for all short segment statistics.	degrees	ATL13/gtx/segment_lon

Name	**Description**	**Units**	**ATLxx/Other Source**
delta_time	Number of GPS seconds since the ATLAS SDP epoch. The ATLAS Standard Data Products (SDP) epoch offset is defined within /ancillary_data/atlas_sdp_gps_epoch as the number of GPS seconds between the GPS epoch (1980-01-06T00:00:00.000000Z UTC) and the ATLAS SDP epoch. By adding the offset contained within atlas_sdp_gps_epoch to delta time parameters, the time in gps_seconds relative to the GPS epoch can be computed.	seconds	ATL13/gtx/delta_time
sseg_start_lat	Latitude at which the short segment begins. May be a signal or non-signal photon.	degrees	ATL13/gtx/sseg_start_lat
sseg_start_lon	Longitude at which the short segment begins. May be a signal or non-signal photon.	degrees	ATL13/gtx/sseg_start_lon
sseg_end_lat	Latitude at which the short segment ends. May be a signal or non-signal photon.	degrees	ATL13/gtx/sseg_end_lat
sseg_end_lon	Longitude at which the short segment ends. May be a signal or non-signal photon.	degrees	ATL13/gtx/sseg_end_lon
ht_water_surf	Water surface height, reported for each short segment (default length = approximately 100 signal photons) with reference to WGS84 ellipsoid	meters	ATL13/gtx/ht_water_surf
ht_ortho	Orthometric height EGM2008 converted from ellipsoidal height.	meters	ATL13/gtx/ht_ortho
subsurface_attenuation	Subsurface attenuation coefficient.	unitless	ATL13/gtx/subsurface_attenuation

Name	Description	Units	ATLxx/Other Source
stdev_water_surf	Standard deviation of water surface, calculated over long segments with result reported at each short segment location tag contained within.	meters	ATL13/gtx/stdev_water_surf

Table 5-3 Parameters Needed to Drive the Algorithm

Name	Var Type	Description	Default*
ht_ortho_bin_size	R*4	Bin size by which to histogram ATL13 ht_ortho values.	0.025 m
threshold_include	R*4	Minimum threshold fraction bin count relative to the mode for its member short segments to be included in ATL22 mean calculations.	0.20

Table 5-4 Intermediate Variables

Name	Units	Description	Section
H_ht_ortho		Binned histogram of ATL13 ht_ortho values on the transect.	5.2.2
ht_ortho_mode_count	N/A	Count of ht_ortho values contained in the histogram mode.	5.2.2
include_flag	N/A	Flag indicating whether or not an ATL13 output short segment shall be included in ATL22 mean computations.	5.2.2

5.3 PROCESSING PROCEDURE

5.3.1 **Input ATTRIBUTES**

The ATL22 transect-rate output is produced on an approximate 24-hour basis, with four ATL13 granules utilized as input. In order to allow a user to conveniently understand the lineage of ATL22 products, a number of attributes from the ATL13 source data are conveyed as ATL22 output.

For each transect, include ***atl13_gran_ndx*** equal to the index value of the ATL13 granule listed in ***atl13_lineage*** upon which the ATL22 transect computations are based. Each transect in the ATL22 output, being derived from ATL13 products of a single water body, can be described similarly in ATL22. For each transect, include as ATL22 output ***atl13refid***, ***transect_id***, ***inland_water_body_id, inland_water_body_region,*** and ***inland_water_body_type*** of its ATL13 input.

In order to facilitate the use of ATL22 output in concert with the higher resolution ATL13 data, ATL22 contains indices directing a user to the start and end rows of ATL13 input upon which the ATL22 products are based. These output variables are ***transect_start_sseg_idx*** and ***transect_end_sseg_idx***, defined as the first and last row in the ATL13 output variable arrays used in each ATL22 transect computation, identified by matching values of ***atl13_gran_ndx***, ***atl13refid*** and ***transect_id***.

Once the start and end of the ATL13 array for a given water body transect have been identified, it is also possible to compute as product output ***transect_sseg_cnt***, the number of ATL13 short segments contributing to the ATL22 transect. The ATL22 output also includes the number of long and very long segments, as defined in ATL13. These segment counts are derived for each transect from ATL13 ancillary data, where ***transect_lseg_cnt*** = ***l_surf*** / ***s_seg1*** and ***transect_lseg2_cnt*** = ***l_sub*** / ***s_seg1***.

5.3.2 **TRANSECT DEFINITION**

Because ATL22 output is produced at the transect rate, it is necessary to compute spatial and temporal definitions for each transect based on its ATL13 source short segment input.

ATL13 short segment heights of certain body types are further tested for the likelihood that they are part of the water surface before inclusion in ATL22 mean calculations. For a given transect of ***inland_water_body_type*** = [1,2,5,6,7], histogram the ***transect_sseg_cnt*** ATL13 heights, ***ht_ortho*** as ***H_ht_ortho***, in bins of ***ht_ortho_bin_size*** width. Identify the bin (or bins) in ***H_ht_ortho*** with the largest count, and set that count as ***ht_ortho_mode_count***. Test each bin in the histogram where if the bin count equals or exceeds ***threshold_include* * *ht_ortho_mode_count***, each ATL13 sseg represented in the bin receives ***include_flag*** = 1, and if bin count is less than ***threshold_include* **ht_ortho_mode_count, include_flag*** =0.

The count of short segments that pass the filtering, where ***include_flag*** = 1, is set as ***transect_sseg_cnt_filtered***.

Compute as output product variables ***transect_mean_lat***, ***transect_mean_lon***, and ***transect_mean_time*** by computing the mean of all short segments' ***segment_lat***, ***segment_lon***, and ***delta_time***, respectively where ***include_flag***=1. The ATL22 output also includes ***transect_mean_time_utc***, a conversion of ***transect_mean_time*** to UTC time.

Of the ATL13 input segments that comprise the ATL22 transect, identify the ***segment_lat***, ***segment_lon***, and ***delta_time*** nearest ***transect_mean_lat***, ***transect_mean_long***, and ***transect_mean_time***, respectively, and designate them on the ATL22 product as ***transect_lat***, ***transect_lon***, and ***transect_time***.

Define the start and end locations of an ATL22 transect, where ***transect_start_lat*** and ***transect_start_lon*** are equal to ***sseg_start_lat*** and ***sseg_start_lon*** of the first ATL13 segment in the ATL22 transect where ***include_flag***=1. Similarly, ***transect_end_lat*** and ***transect_end_lon*** are defined on ATL22 output by ***sseg_end_lat*** and ***sseg_end_lon*** of the final ATL13 segment in the ATL22 transect where ***include_flag***=1. ATL22 transect start and end times, ***transect_start_time*** and ***transect_end_time***, are defined by the ATL13 ***delta_time*** of the first and last short segment in the ATL22 transect where ***include_flag***=1, respectively.

5.3.3 **ALONG-TRACK PROCESSING**

ATL22 takes advantage of the high resolution ATL13 along-track products to produce transect-level output for utilization when the study of more granular data is unnecessary. The length of each transect, ***transect_length***, is computed as the distance between ***sseg_start_lat*** and ***sseg_start_lon*** of the first ATL13 segment in the ATL22 transect where ***include_flag***=1 and ***sseg_end_lat*** and ***sseg_end_lon*** of the final segment in the transect where ***include_flag***=1.

Ellipsoidal height, orthometric height, and subsurface attention of a given transect are the mean values of ***ht_water_surf***, ***ht_ortho***, and ***subsuface_attenuation*** for all short segments of valid output where ***include_flag***=1, and reported on ATL22 product output as ***transect_mean_ht_WGS84***, ***transect_mean_ht_ortho***, and ***transect_mean_subsurf_atten***.

The standard deviation of the transect water surface, ***transect_mean_stdev_water_surf***, is calculated as sqrt[sum(***stdev_water_surf***$_{1:transect\_sseg\_cnt}^{2}$)/***transect_sseg_cnt_filtered***], including only short segments with valid ***stdev_water_surf*** values and ***include_flag***=1. Pending further development of the product, the ***transect_mean_stdev_water_surf*** computation is then overwritten as ***invalid*** for all transects in ATL22 release 003 where ***inland_water_body_type* =** 5.

5.4 Mean Transect and Associated Output Products

The ATL22 transect-rate output is produced on an approximate 24-hour basis, with four ATL13 granules utilized as input. In order to allow a user to conveniently understand the lineage of ATL22 products, a number of attributes from the ATL13 source data are conveyed as ATL22 output. takes advantage of the high resolution ATL13 along-track products to produce transect-level output for utilization when the study of more granular data is unnecessary.

Table 5-5 Output Parameters for ATL22 Mean Inland Surface Water Algorithm

Name	Units	Description
atl13_gran_ndx	N/A	ATL13 granule index, indicating from which ATL13 granule in /METADATA/Lineage/ATL13/fileName an ATL22 transect product was derived.
atl13refid	N/A	Unique aggregate reference number for each shape in the ATL13 Inland Water Body Mask, where digit 1 = type, digit 2 = size, digit 3 = source, and digits 4-10 = shape id
transect_mean_lat	degrees	Mean latitude of the transect, calculated as mean of all filtered sseg latitudes in the transect.
transect_mean_lon	degrees	Mean longitude of the transect, calculated as mean of all filtered sseg longitude in the transect.
transect_mean_time	sec	Mean time of the transect, calculated as mean of all filtered sseg times in the transect.
transect_mean_time_utc	N/A	Mean time of the transect in UTC format YYYY-MM-DDTHH:MM:SS.SSSSSSZ.
transect_sseg_cnt	unitless	Number of non-anomalous short segments in the transect.

Name	Units	Description
transect_lseg_cnt	unitless	Number of complete long segments in the transect.
transect_lseg2_cnt	unitless	Number of complete very long segments in the transect.
transect_start_lat	degrees	Latitude of the transect start, determined by the latitude of the first photon in the first filtered short segment in the transect.
transect_start_lon	degrees	Longitude of the transect start, determined by the longitude of the first photon in the first filtered short segment in the transect.
transect_start_time	seconds	Time of the transect start, determined by the time of the index photon in the first filtered short segment in the transect.
transect_end_lat	degrees	Latitude of the transect end, determined by the latitude of the last photon in the last filtered short segment in the transect.
transect_end_lon	degrees	Longitude of the transect end, determined by the longitude of the last photon in the last filtered short segment in the transect.
transect_end_time	seconds	Time of the transect end, determined by the time of the index photon in the last filtered short segment in the transect.
transect_mean_ht_WGS84	meters	Mean geodetic height of the transect with respect to the WGS84 ellipsoid, determined as the mean of all filtered short segment height values in the transect.
transect_mean_ht_ortho	meters	Mean orthometric height of the transect with respect to the EGM2008 geoid, determined as the mean of all filtered short segment height values in the transect.
transect_mean_stdev_water_surf	meters	Mean standard deviation of the transect water surface, determined based on filtered short segments. (Deferred for rivers; populated with invalid values in rel003)

Name	Units	Description
transect_mean_subsurf_atten	m^{-1}	Mean subsurface attenuation (alpha) of the transect, determined as the mean of all filtered alphas along the transect.
transect_length	meters	Length of the transect, determined as the distance from the first filtered observed reference photon in the water body to the final filtered observed photon in the body.
transect_start_sseg_idx	unitless	Index of first entry in ATL13 short segment rate output data contributing to transect summary.
transect_end_sseg_idx	unitless	Index of final entry in ATL13 short segment rate output data contributing to transect summary.
transect_id	unitless	Transect within a water body to which the short segment rate output belongs.
inland_water_body_id	unitless	Identifying signature of an individual inland water body. Each body of water is represented by a unique numeric value.
inland_water_body_region	unitless	ATL13-created shapefile representing relevant bodies of water over which to implement the ATL13 water surface finding algorithm only within a region of processing interest.
inland_water_body_type	unitless	Type of Inland Water Body, where 1=Lake, 2=Known Reservoir, 3=(Reserved for future use), 4=Ephemeral Water, 5=River, 6=Estuary or Bay, 7=Coastal Water, 8=Reserved, 9=Reserved
transect_lat	degrees	Reporting latitude of transect statistics.
transect_lon	degrees	Reporting longitude of transect statistics.
transect_time	seconds	Reporting time of transect statistics.
transect_sseg_cnt_filtered	unitless	Number of filtered ATL13 non-anomalous short segments in the transect used in ATL22 mean product calculations.
err_slope_bdy	unitless	Error included in segment_slope_trk_bdy. (deferred)
err_aspect	rad	Error included in aspect reported. (deferred)

6.0 ATL22 SAMPLE PRODUCT RESULTS

6.1 Typical ATL22 Version 1 example for single water body

Three examples of ATL22 output are provided below. First, Figure 6.1 exhibits the ATL13 and ATL22 Version 1 surface height products in WGS84 datum for one beam (GTR2) of an ICESat-2 crossing over Eagle Lake, CA on October 19, 2018. Three ICESat-2 data products are plotted: i) the ATL03 georeferenced photons (green dots); ii) the ATL13 along track short segment water surface heights (yellow dashes), and iii) the ATL22 mean water heights (red dots). ATL22 results indicate that ICESat-2 crosses two transects defined by the inland water mask at this location in Eagle Lake and accurately estimates the mean water surface height between the well-defined river banks (See E.g. mean Latitudes ~40.635N and 40.672N).

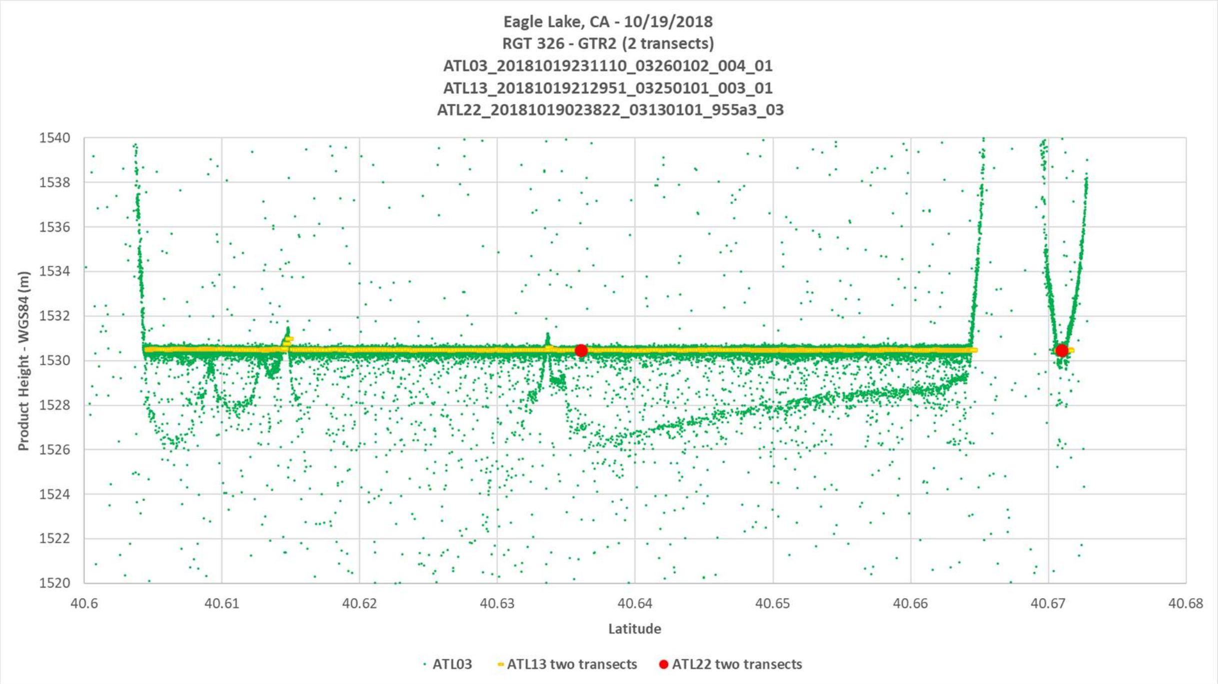


Figure 6-1 Typical example of ATL22 product (red dots) identifying two ICESat-2 transects over Eagle Lake on October 19, 2018.

6.2 Typical daily global summary of ATL22 transect length and mean orthometric height

Figures 6-2 and 6-3 show two ATL22 browse products for a 24 hour period. Figure 6-2 indicates the global mean water surface orthometric height for each water body transect that it crosses on October 18, 2019. The figure gives an indication of the density of products and the orbital pattern during that period. It can be seen that the higher elevations occur in the mountain region and in the interior of the continent, while lower elevations occur near the coast. The legend is plotted in log scale for convenience.

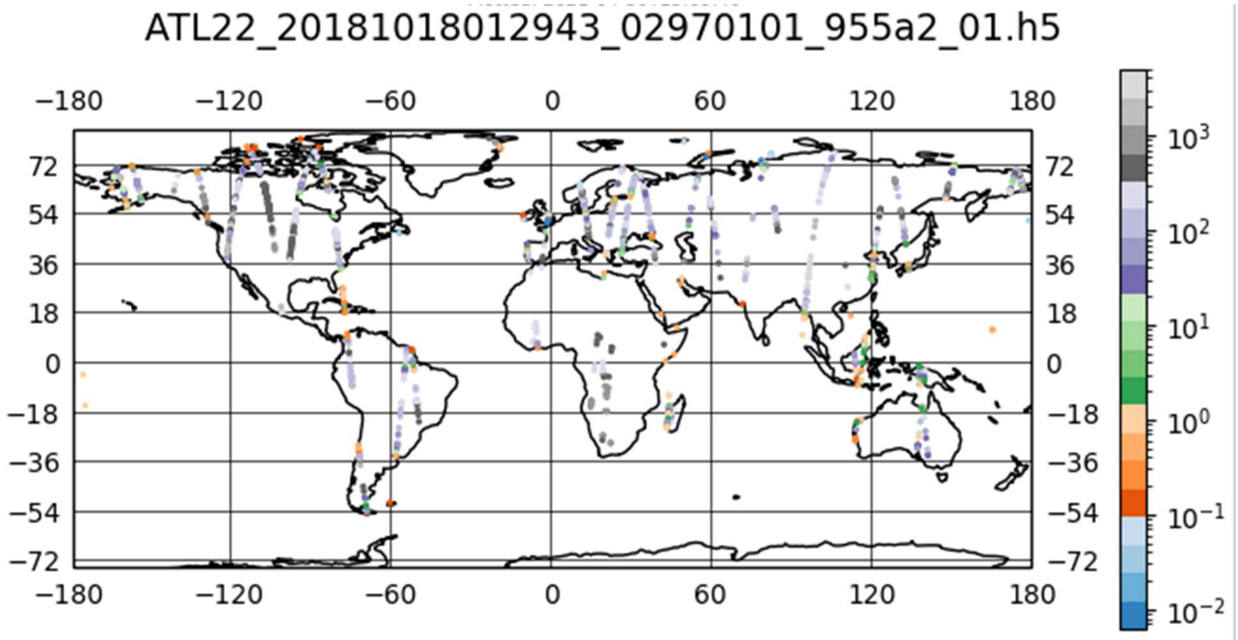


Figure 6-2 Typical ATL22 daily browse summary of transect mean orthometric height (EGM2008) for all global ICESat-2 crossings on October 18, 2019.

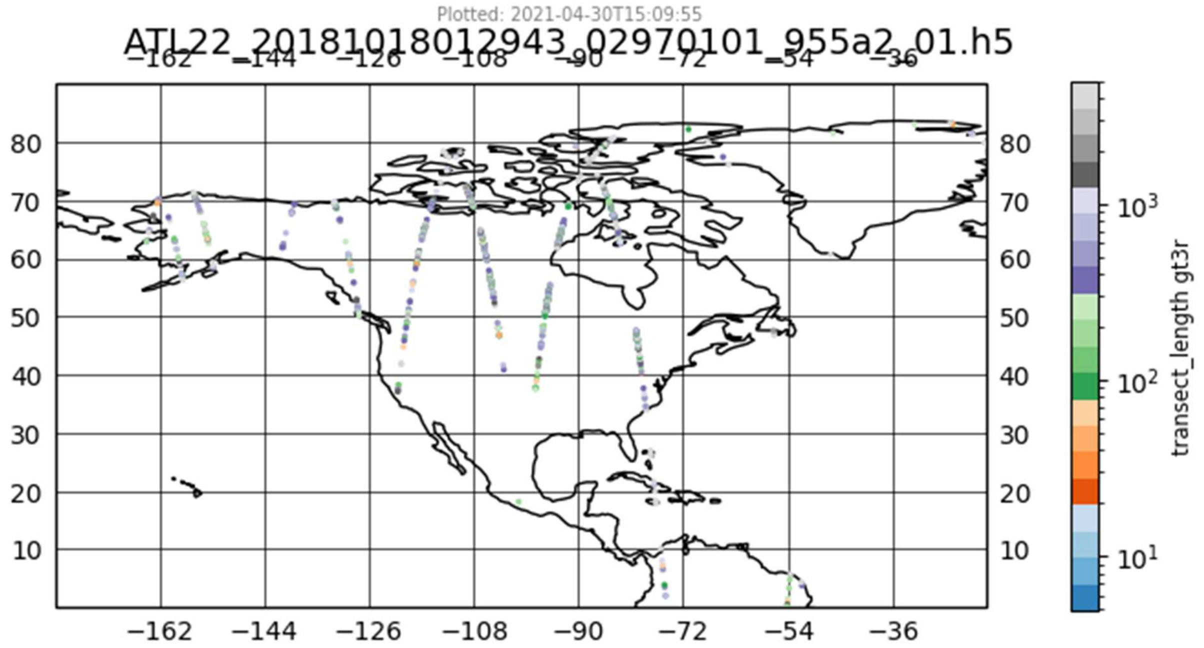


Figure 6-3 Typical ATL22 daily summary of transect length (m) for all North America ICESat-2 crossings on October 18, 2019.

Figure 6-3 shows the corresponding transect lengths associated with each of the heights shown in Figure 6-2 but zoomed in for North America. Greater transect lengths can be observed over the Great Lakes, whereas shorter lengths over smaller lakes are exhibited, for example, in interior of Alaska. Overall results from Figures 6-1, 6-2, and 6-3 demonstrate that the ATL22 height products and their mean locations are being calculated correctly together with their locations.

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