ICESat-2 L4 Along-Track Sea Ice Thickness, Version 1

USER GUIDE

How to Cite These Data

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

Petty, A. A., N. T. Kurtz, R. Kwok, T. Markus, and T. A. Neumann. 2021. *ICESat-2 L4 Along-Track Sea Ice Thickness, Version 1*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/JTI5YG3S6VAJ. [Date Accessed].

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

FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/IS2SITDAT4

National Snow and Ice Data Center

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1 DATA DESCRIPTION

1.1 Parameters

This data set reports daily, along-track winter Arctic sea ice thickness. Sea ice thickness is estimated using freeboard, the height of sea ice protruding above the water level, from Version 5 of the ATLAS/ICESat-2 L3A Sea Ice Freeboard data product (ATL10) and snow depth and density distribution from the NASA Eulerian Snow On Sea Ice Model (NESOSIM) version 1.1.

1.2 File Information

1.2.1 Format

Data are provided as NetCDF-4 (V4.4.1) formatted files.

NetCDF comprises a set of machine-independent data formats and software libraries that can be used to create, share, and access scientific data sets. NetCDF is developed and maintained by Unidata, a University Corporation for Atmospheric Research (UCAR)'s Community Program. For more information about NetCDF, visit the Unidata Network Common Data Form (NetCDF) website.

1.2.2 File Contents

All parameters and corresponding details of this data set are listed in Table 1.

Table 1. Parameter description

Name	Description	Units
`along_track_distance`	Along-track distance from start of ATL10 granule	km
`gps_seconds`	GPS time in seconds calculated from the ATL10 `delta_time` variable	s
`freeboard`	Sea ice freeboard from ATL10	m
`height_segment_id`	Height segment ID from ATL10	N/A
`ice_thickness`	Sea ice thickness from redistributed NESOSIM snow loading	m
`ice_thickness_unc`	Total sea ice thickness uncertainty	m
`ice_thickness_uncrandom`	Random sea ice thickness uncertainty	m

Name	Description	Units
ice_thickness_uncsys	Systematic sea ice thickness uncertainty	m
ice_thickness_W99mod5dist	Sea ice thickness from redistributed modified 50 percent first year ice (FYI) Warren snow loading	m
ice_type	Ocean and Sea Ice Satellite Application Facility (OSI SAF) sea ice type classification. Ice type in September is not available from OSI SAF, therefore all grid-cells are prescribed as multi-year ice.	type flag (0 = first-year ice, 1 = multi-year ice)
index	N/A	N/A
latitude	Latitude	degree N
longitude	Longitude	degree E
region_flag	NSIDC Northern Hemisphere region mask: updated v2 NSIDC mask not yet published but documented in Meier et al. (2022).	Region number (0: outside of defined regions, 1: Central Arctic, 2: Beaufort Sea, 3: Chukchi Sea, 4: East Siberian Sea, 5: Laptev Sea, 6: Kara Sea, 7: Barents Sea, 8: East Greenland Sea, 9: Baffin Bay and Davis Strait, 10: Gulf of St. Lawrence, 11: Hudson Bay, 12: Canadian Archipelago, 13: Bering Sea, 14: Sea of Okhotsk, 15: Sea of Japan, 16: Bohai Sea, 17: Gulf of Bothnia, Baltic Sea, 18: Gulf of Alaska, 30: land, 31: coast, 32: lakes)
seg_length	Segment length	m
snow_density	NESOSIM snow density	kg m^{-3}
snow_density_W99	Warren snow density	kg m^{-3}
snow_depth	NESOSIM snow depth redistributed (piecewise)	m
snow_depth_W99mod5dist	Modified 50 percent FYI Warren snow depth redistributed	m

Name	Description	Units
ssh_flag	Sea surface flag from ATL10, conservative lead segment classification based on radiometric surface classification and a local height filter, used for reference (10 km) sea surface estimation.	surface flag: 0 = ice, 1 = candidate lead segment, 2 = utilized lead segment

1.2.3 Naming Convention

Data files are named:

```
IS2SITDAT4-[HH]_[yyyymmdd][hhmmss]_[ttttccss]_[vvv_rr]_bnum[n]gt[mm]_[SITv]<_sm>.nc
```

The following table describes the file naming convention variables:

Table 2. File Naming Convention Variables and Descriptions

Variable	Description
IS2SITDAT4	ICESat-2 L4 Along-Track Sea Ice Thickness
[HH]	Hemisphere code. Northern Hemisphere = 01, Southern Hemisphere = 02 (not currently available)
[yyyymmdd]	4-digit year, 2-digit month, 2-digit day of month of data acquisition
[hhmmss]	2-digit hour, 2-digit minute, 2-digit second of data acquisition start time in UTC
[tttt]	4-digit Reference Ground Track (RGT) number. The ICESat-2 mission has 1,387 RGTs, numbered from 0001 to 1387.
[cc]	2-digit cycle number. Each of the 1,387 RGTs is targeted in the polar regions once every 91 days. The cycle number tracks the number of 91-day periods that have elapsed since ICESat-2 entered the science orbit.
[ss]	2-digit segment number. Not used. Always 01.
[vvv_rr]	3-digit version number of the corresponding ATL10 input files followed by 2-digit revision number.
bnum[n]	Beam number, e.g., bnum1 for beam 1. (See Appendix A – ATLAS/ICESAT-2 DESCRIPTION for more information on numbering of beams and ground tracks).
gt[mm]	Ground track number, e.g., gt1l. (See Appendix A – ATLAS/ICESAT-2 DESCRIPTION for more information on numbering of beams and ground tracks).
[SITv]	Version number of this sea ice thickness data product
<sm>	Optional file name extension for 10 km weighted mean along-track data
.nc	NetCDF-4 file name extension

Examples:

```
IS2SITDAT4_01_20190418175805_03130301_005_01_bnum1gt1l_01.nc
IS2SITDAT4_01_20190418175805_03130301_005_01_bnum1gt1l_01_sm.nc
```

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

1.2.4 Browse File

A `.png` browse file is provided for each granule showing the along track freeboard, snow depth, snow density, ice thickness, uncertainty, and segment length as well as a map with the granule location. Figure 1 shows an example browse file.

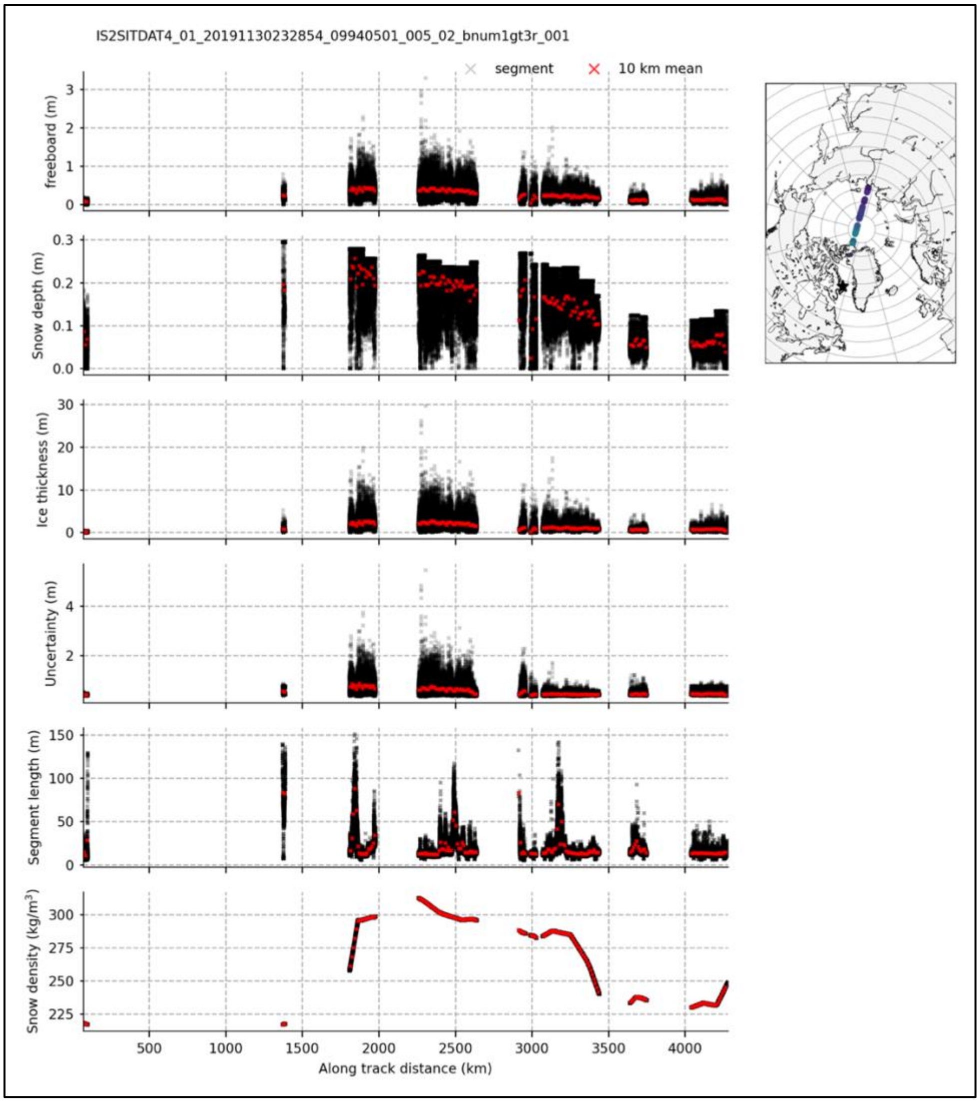

Figure 1. Example browse file for `IS2SITDAT4_01_20191130232854_09940501_005_01_bnum1gt3r_001.nc`

1.3 Spatial Information

1.3.1 Coverage

Data span the Arctic Ocean and its peripheral seas south of 88° N (northern limit of ICESat-2 data collection).

1.3.2 Resolution

Spatial resolution varies depending on the number of photon returns and segment length. Typical resolution is on the order of 25 m x 11 m for the strong beams (footprint of ~11 m plus the along-track segment length). Data are provided for the three strong beams independently, where each strong beam is separated by ~3 km across track. See Appendix A for more details.

1.3.3 Geolocation

The following table provides information for geolocating this data set:

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	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

1.4 Temporal Information

1.4.1 Coverage

14 October 2018 to 30 April 2019
1 September 2019 to 30 April 2020
1 September 2020 to 30 April 2021

1 September 2021 to 1 May 2022

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. ATL03 acts as the bridge between the lower level, instrumentation-specific data and the higher-level products. On the data set landing page under Documentation, users can download and consult a regularly updated list of ATL03 data gaps (.xlsx).

2 DATA ACQUISITION AND PROCESSING

NOTE: The following description briefly outlines the input information and approach used to generate this sea ice thickness product. Users seeking a more detailed description of this data product should consult Petty et al. (2020).

2.1 Background

Sea ice thickness is calculated from ICESat-2 freeboards (ATL10)—the extension of sea ice above local sea level—assuming hydrostatic equilibrium. Additional input assumptions include the ice, water, and snow density, and snow depth. Figure 2 shows a basic schematic of a snow-covered sea ice floe in hydrostatic equilibrium.

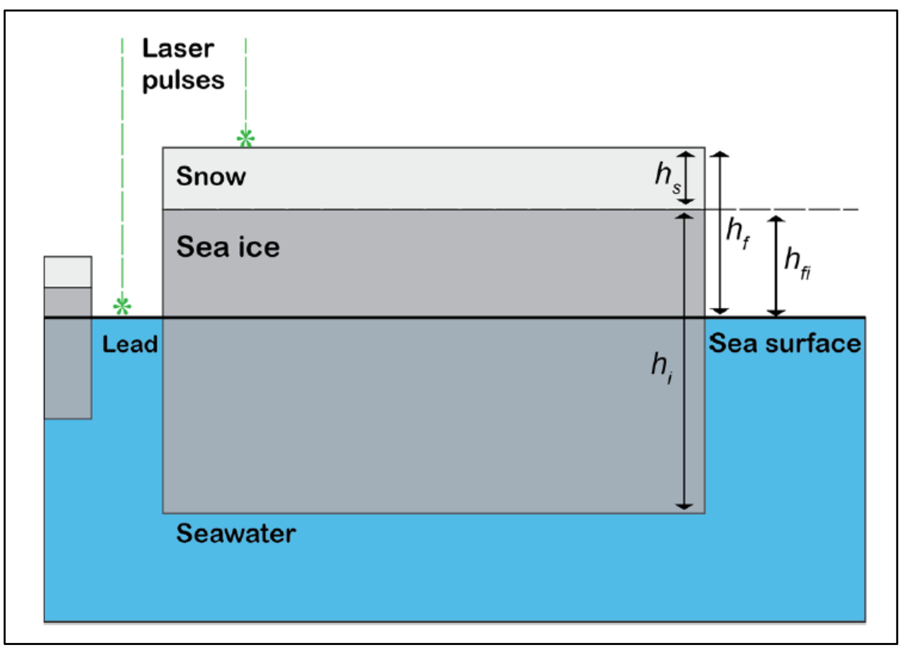

Figure 2. Schematic showing the main variables utilized to derive sea ice thickness (hi) from snow depth (hs), total freeboard (hf), and ice freeboard (hfi). This figure was taken from Petty et al. (2020).

2.2 Acquisition

Freeboard data for this product are taken from the ICESat-2 ATL10, Version 5 data set, which is only produced for regions greater than 25 km away from the nearest coastline and with an ice concentration above 50%. Generally, ATL10 data, as well as all the preceding ATLAS/ICESat-2 data products, provide freeboards from the six beams separately across both hemispheres. For this version of the sea ice thickness estimates, we provide data for the three strong beams in winter for the Northern Hemisphere only.

The snow depth and density estimates are taken from NESOSIM v1.1 forced by ERA5 (climate reanalysis provided by ECMWF) snowfall. This is an upgrade to the use of NESOSIM v1.0 forced by ERA-Interim snowfall in Petty et al. (2020), which was motivated by the end of ERA-Interim in August 2019. NESOSIM v1.1 includes additional code improvements (e.g., a new atmospheric snow-loss term) and bug fixes (see the NESOSIM GitHub page for details). To produce the NESOSIM output used in this data set, the ERA5 snowfall was calibrated against snowfall observations collected by CloudSat (Cabaj et al., 2020), then NESOSIM itself was calibrated against spring Arctic snow depth data collected by NASA's Operation IceBridge (adjusting the snow loss terms to achieve a 2010–2015 mean bias of 0 cm). More information about these upgrades can be found in Petty et al. (2022).

2.3 Processing

2.3.1 Sea Ice Thickness Processing

Assuming hydrostatic equilibrium, sea ice thickness (h_i) can be calculated from the ATL10 freeboard (h_f) as follows:

$$h_i = \frac{h_f \rho_w}{(\rho_w - \rho_i)} + \frac{h_s(\rho_s - \rho_w)}{(\rho_w - \rho_i)}$$

In the equation above, ρ_w is the density of water (1024 kg m^{-3}), h_s and ρ_s are the snow depth and density, respectively, and ρ_i is the bulk density of sea ice (916 kg m^{-3}).

2.3.2 Snow Depth Redistribution

Snow data from NESOSIM are provided at a relatively coarse 100 km horizontal resolution (while the Warren snow climatology represents large-scale snow conditions from a quadratic fit to in situ observations). Both are significantly larger than the freeboard segment resolution from ATL10 (mean of ~20–30 m for the strong beams). A linear piecewise function is used to redistribute snow depth from the coarse NESOSIM resolution to the high resolution ATL10 data:

$$h_s = \begin{cases} \frac{h_f}{h_{f-cutoff}} h_{s-thick}, & h_f < h_{f-cutoff} \\ h_{s-thick}, & h_f > h_{f-cutoff} \end{cases}$$

Here, $h_{f-cutoff}$ represents the freeboard cut-off value and $h_{s-thick}$ the snow depth cut-off for high freeboards. Both are calculated using linear regressions derived from high-resolution snow depth data collected by NASA's Operation IceBridge. The large-scale mean snow depth is conserved through an iterative process. More details can be found in Petty et al. (2020).

2.4 Quality, Errors, and Limitations

Uncertainty estimates are provided for each individual sea ice thickness estimate in this data set. This is challenging due to the general lack of validation of data and the poor constraints on the uncertainty of the individual terms contributing to the sea ice thickness estimation. Random and systematic uncertainties are provided based on the partial derivatives of the unconstrained variables in the hydrostatic equilibrium equation (see Section 2.3.1), which are also combined into a total thickness uncertainty.

Random uncertainties are based on precision estimates and small-scale variability unaccounted for in the input data. Systematic uncertainties are based on the spread of available input assumptions. Systematic uncertainties are expected to be largely correlated, while random uncertainties are considered uncorrelated. For more detailed information on the uncertainty calculations including equations, see Petty et al. (2020).

2.5 Data Set Production

Additional information is provided in the product to assist with post-analysis of these data, including the OSI SAF ice type (first-year or multi-year ice) mask (Breivik et al., 2012) and an NSIDC Arctic Ocean region mask.

A 10 km smoothed data set is also included to enable rapid access and evaluation of the along-track data granules. The data are binned into 10 km along-track sections, with segment length weighted means calculated for all variables. This smoothed data product is provided in files with the file name ending `*_sm.nc`. Find more details on the file naming convention in Section 1.2.3 Naming Convention.

A separate data product with monthly 25 km gridded sea ice thickness can be found on the ICESat-2 L4 Monthly Gridded Sea Ice Thickness data set landing page.

2.6 Instrumentation

See Appendix A – ATLAS/ICESAT-2 DESCRIPTION for a short description of the ATLAS instrument on the ICESat-2 satellite.

3 VERSION HISTORY

Table 4. Version History Summary

Version	Release Date	Description of Changes
V1	26 April 2022	Initial release based on ATL10 V5

4 RELATED DATA SETS

- ICESat-2 L4 Monthly Gridded Sea Ice Thickness
- ATLAS/ICESat-2 L3A Sea Ice Height (ATL07)
- ATLAS/ICESat-2 L3A Sea Ice Freeboard (ATL10)

5 CONTACTS AND ACKNOWLEDGMENTS

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6 REFERENCES

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Petty A. A., Keeney, N., Cabaj, C., Kushner, P., & Bagnari, M. (2022). Winter Arctic sea ice thickness from ICESat-2: upgrades to freeboard and snow loading estimates and an assessment of the first three winters of data collection. *The Cryosphere Discussions,* preprint. https://doi.org/10.5194/tc-2022-39

7 DOCUMENT INFORMATION

7.1 Publication Date

26 April 2022

7.2 Date Last Updated

31 October 2022

APPENDIX A – ATLAS/ICESAT-2 DESCRIPTION

The ATLAS instrument on the ICESat-2 satellite utilizes a photon-counting lidar and ancillary systems (GPS and star cameras) to measure the round-trip time of photon pulses from ATLAS to Earth and back again and to determine the geodetic latitude and longitude of these signal photon pulses on the Earth's surface. Laser pulses from ATLAS illuminate three left/right pairs of spots on the surface that as ICESat-2 orbits Earth trace out six ground tracks that are typically about 14 m wide. 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. The ATL10 data product is organized by ground track, with ground tracks 1L and 1R forming pair one, ground tracks 2L and 2R forming pair two, and ground tracks 3L and 3R forming pair three. Each pair also has a Pair Track—an imaginary line halfway between the actual location of the left and right beams (see Figure A - 1 and Figure A - 2). 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 A - 1). 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 A - 2). The first yaw flip was performed on December 28, 2018, placing the spacecraft into the backward orientation. The current spacecraft orientation, as well as a history of previous yaw flips, is available in the "ICESat-2 Major Activities" document on the ATL10 landing page under the technical references tab.

The Reference Ground Track (RGT) refers to the imaginary track on Earth at which a specified unit vector within the observatory is pointed. Onboard software aims the laser beams so that the RGT is always 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 (i.e. the satellite has a 91-day repeat cycle) 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 by appending the two-digit cycle number to the RGT number, e.g. 000103 (RGT 0001, cycle 03) or 138705 (RGT 1387, cycle 05).

Users should note that between 14 October 2018 and 30 March 2019, the spacecraft pointing control was not yet optimized. As such, ICESat-2 data acquired during that time do not lie along the nominal RGTs, but are offset at some distance from the RGTs. Although not along the RGT, the geolocation information for these data is not degraded.

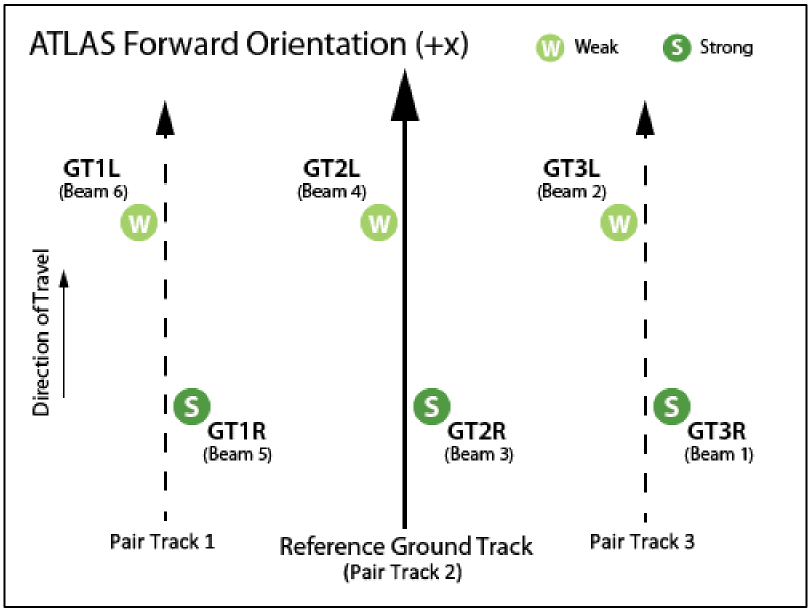

Figure A - 1. Spot and ground track (GT) naming convention with ATLAS oriented in the forward (instrument coordinate +x) direction.

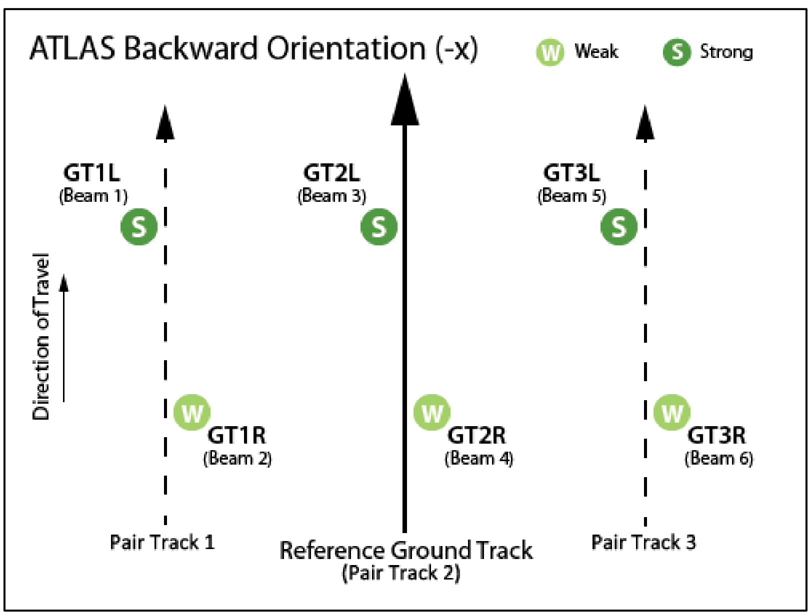

Figure A - 2. Spot and ground track (GT) naming convention with ATLAS oriented in the backward (instrument coordinate -x) direction.