IceBridge Narrow Swath ATM L1B Elevation and Return Strength with Waveforms, Version 1

USER GUIDE

How to Cite These Data

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

Studinger, M. (2018, updated 2020). *IceBridge Narrow Swath ATM L1B Elevation and Return Strength with Waveforms* (ILNSAW1B, Version 1). [Data set]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/V25X7LHDPMZY [Date Accessed].

National Snow and Ice Data Center

TABLE OF CONTENTS

1   DATA DESCRIPTION

1.1 Summary

This data set contains spot elevation measurements with corresponding waveforms of Greenland, Arctic, and Antarctic sea ice. The data complement the IceBridge ATM L1B Near-Infrared Waveforms data, which are measured at near-infrared wavelength. The data were acquired as part of aircraft survey campaigns funded by Operation IceBridge.

1.2 Parameters

The main parameters in this data set are filtered spot elevation measurements and the associated waveforms, collected at green wavelength.

1.3 File Information

1.3.1   Format

The data are in HDF5 (.h5) format. Each data file is paired with an associated XML file, which contains additional metadata.

1.3.2   File Contents

Following the HDF5 convention, the data are organized into groups and subgroups within each file. Figure 1 shows an overview of the file structure, using the file `ILNSAW1B_20171029_173512.atm6BT7.h5` as an example.
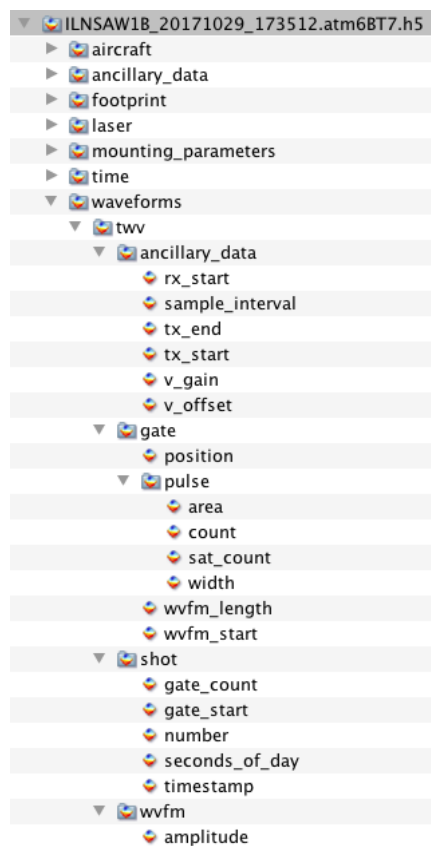
Figure 1. HDF5 ATM file structure

The individual groups contain the following information:

- `/aircraft` contains aircraft location and attitude, interpolated to the times of the laser shots.
- `/ancillary_data` contains spatial and temporal limits along with documentation and metadata for the files.
- `/footprint` contains the geolocated and filtered spot elevation measurements as well as the geographical coordinates of the laser spots on the ground.
- `/laser` contains pointing and range information for the laser.
- `/mounting_parameters` contains information used for computing the footprint location from the laser and aircraft information.
- `/time` contains the starting time of each laser pulse as UTC seconds of day.
- `/waveforms/twv` contains the waveform data and is described in more detail under the Methods section.

1.3.3   Naming Convention

The data files are organized in chronological order. Each file name contains the starting date and time for that file. Example file names:

```
ILNSAW1B_20171029_173512.atm6BT7.h5
ILNSAW1B_20171029_173512.atm6BT7.h5.xml
```

Files are named according to the following convention, which is described in more detail in Table 1:

```
ILNSAW1B_YYYYMMDD_HHMMSS.atm6BT7.xxx
```

Table 1. File Naming Convention

Variable	Description
ILNSAW1B	Data set ID
YYYYMMDD	Year, month, and day of survey
HHMMSS	Hours, minutes, and seconds of survey (beginning of file time)
atm6B	Airborne Topographic Mapper instrument identification
T7	ATM transceiver designation
.xxx	Indicates file type: • `.h5 = HDF5 data file` • `.h5.xml = XML metadata file`

1.4 Spatial Information

1.4.1 Coverage

Spatial coverage includes the Arctic, Greenland, and Antarctica, as noted by the spatial extents below.

Arctic/Greenland:
Southernmost Latitude 60° N
Northernmost Latitude: 90° N
Westernmost Longitude: 180° W
Easternmost Longitude: 180° E

Antarctica:
Southernmost Latitude: 90° S
Northernmost Latitude: 53° S
Westernmost Longitude: 180° W
Easternmost Longitude: 180° E

1.4.2   Resolution

The ATM surface elevation measurements were acquired by a conically scanning lidar system. The resulting array of laser spots is coupled with the motion of the aircraft and forms a tight spiral of elevation points. The laser footprints generally consist of overlapping, roughly elliptical patterns on the surveyed surface that form a swath of measurements along the aircraft flight path.

The ATM narrow swath instrument has a scan angle of approximately 2.7° off-nadir, or a full swath width of 5.4°. The resolution of the swath is a function of aircraft altitude, aircraft ground speed, and scanner configuration for the lidar. For example, an altitude of 450 m above ground level corresponds to a swath of roughly 45 m width on the ground. Assuming an aircraft ground speed of 250 knots, a laser pulse rate of 3 kHz, and a scan angle of 2.7° off-nadir, the average point density within the swath is one laser shot per 2 m2. However, the sampling of laser shots within the swath is not evenly distributed.

1.4.3   Geolocation

Table 2 provides information for geolocating this data set. The reference frame is prescribed by the International Terrestrial Reference Frame (ITRF) convention.

Table 2. Geolocation Details

Geographic coordinate system	WGS 84
EPSG code	4326
PROJ4 string	+proj=longlat +datum=WGS84 +no_defs
Reference	https://epsg.io/4326

1.5 Temporal Information

1.5.1   Coverage

29 October 2017 to 20 November 2019

1.5.2   Resolution

IceBridge campaigns were conducted on an annually repeating basis. Arctic and Greenland campaigns were typically conducted during March, April, and May. Antarctic campaigns were typically conducted during October and November.

1.5.3   Instrumentation

The ATM T7 transceiver contains a Northrop-Grumman Fiber Laser that generates laser pulses of roughly 1.3 ns duration at a 10 kHz pulse repetition frequency. The pulses contain co-aligned NIR (1064 nm) and green (532 nm) wavelengths. The laser light is directed to a nutating scanner mirror and downward from the aircraft. Light that is backscattered upward is directed by the scanner mirror to a telescope and then separated into two paths toward separate photodetectors. Each photodetector is connected to separate but similar data systems, each containing a 4 gigasample/second multi-trigger waveform digitizer. The captured waveforms from the NIR and green systems are tagged with a precise time, which can be used to pair the waveforms received from a specific laser pulse, from the same ground location.

More information on the ATM transceivers used during IceBridge missions and the associated filename designations can be found in the List of ATM transceivers used during IceBridge missions.

2   DATA ACQUISITION AND PROCESSING

2.1 Background

A laser altimeter determines the distance to a target by measuring the elapsed time between the emission of a laser pulse and the detection of laser energy reflected back by the target. The distance to the target is calculated as half of the elapsed emission/return time multiplied by the speed of light through the atmosphere. The target distance is then integrated with platform location and attitude information and converted to geographic position.

2.2 Acquisition

The ATM instrument package includes suites of lidar, GPS, and attitude measurement subsystems. The instrument package is installed onboard the aircraft platform and calibrated during ground testing procedures. The distances between GPS, attitude sensors, and the ATM lidars are measured using surveying equipment.

One or more ground survey targets, usually aircraft parking ramps, are selected and surveyed on the ground using differential GPS techniques. Prior to missions, one or more GPS ground stations are established by acquiring low rate GPS data over long time spans. Approximately one hour prior to missions both the GPS ground station and aircraft systems begin data acquisition. During the aircraft flight, the ATM instrument suite acquires lidar, GPS and attitude sensor data over selected targets, including several passes at differing altitudes over the selected ground survey calibration sites. The aircraft and ground systems continue to acquire data one hour post-mission. Instrument

parameters estimated from the surveys of calibration sites are used for post-flight calculation of laser footprint locations. These parameters are later refined using inter-comparison and analysis of ATM data where flight lines cross or overlap.

2.3 Processing

2.3.1 Processing Steps

The following processing steps are performed by the data provider.

1. Process ATM lidar data to apply calibration factors to convert time of flight to range, compute scan pointing angles, and interpolate attitude to each lidar measurement.
2. Process GPS data into aircraft trajectory files using double-differenced dual-frequency carrier phase-tracking.
3. Determine all biases and offsets: heading, pitch, roll, ATM-GPS [x,y,z] offset, scanner angles, range bias.
4. Process the lidar and GPS data with all biases and offsets through the QFIT program. The output files in this data set contain waveforms, ancillary parameters, and surface elevations (ellipsoid height). The output files in the IceBridge ATM L1B Near-Infrared Waveforms data set contain waveform and ancillary parameters. Both data sets contain geographic location information in latitude/longitude coordinates.

Each ATM surface elevation measurement corresponds to one laser pulse. The measurements have not been re-sampled. The transmitted laser pulse and the received backscatter pulse from the ground surface are photodetected and captured by a waveform digitizer. Post-flight processing of the waveforms yields the time of flight between transmitted and received signals. This time of flight value is converted to a distance compensated for speed of light through atmosphere. GPS data is processed post-flight to yield the position of the aircraft at 0.5 second intervals. The scan azimuth of the lidar scanner mirror together with the aircraft attitude determine the pointing angle of the lidar. Aircraft position, pointing angle of the lidar, and range measured by the lidar are used to compute position of laser footprint on the ground.

2.3.2 Trajectory and Attitude Data

Aircraft position is determined by Global Navigation Satellite System (GNSS) systems that incorporate NAVSTAR GPS and, for later campaigns, the Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS). Carrier phase measurements are logged by an antenna and receiver on the aircraft. In post-flight processing, these measurements are combined with similar measurements from static ground stations to produce a kinematic differential solution of the aircraft trajectory at 0.5 second intervals, and more recently at 0.1 second intervals.

Aircraft attitude is logged from a commercial Inertial Navigation System (INS), or IMU.

2.3.3   Overview of the TX and RX Range Gate Structure

The analog output from the optical detector is captured by an 8-bit waveform digitizer, sampling at a constant rate (2 or 4 gigasamples per second). A sequence of samples, or range bins, is recorded whenever the signal amplitude exceeds a programmable trigger threshold. Each sequence, or range gate, can contain a variable number of range bins depending on how long the signal exceeds the threshold. Each laser pulse generates a laser waveform record, or shot, which can contain multiple range gates, each of which contains multiple waveform amplitude samples. The laser record contains the starting position of each range gate, from which the time of each range bin can be determined. For example, Figure 2 shows a laser waveform reconstructed from a laser record containing six range gates: one for the transmitted pulse (TX; left panel), and four return gates (RX, right panel) from a complex target (tree). Range Gate 6 contains two distinct return pulses. The transmitted laser pulse travels through an optical window in the nadir view port on the aircraft to the target. The reflection of the transmitted laser pulse on the optical window can exceed the amplitude trigger threshold and is then recorded in a range gate. To separate the recorded transmit pulse from the window reflection, the transmit pulse is routed through an optical delay fiber that is several meters in length; thus, it appears several tens of nanoseconds after the window reflection. The fiber length can change with various system configurations and its delay is incorporated in the calibration for range determination. Since the window reflection does not occur on every laser shot, sometimes the recorded transmit pulse is in Range Gate 1 or Range Gate 2. The example in Figure 2 includes a window reflection. Therefore, the recorded transmit pulse that is used for the ATM range determination is in Range Gate 2. The capability of recording multiple range gates of varying lengths for each laser shot requires a pointer and indexing scheme to access the waveform data within an HDF5 file, as described below.
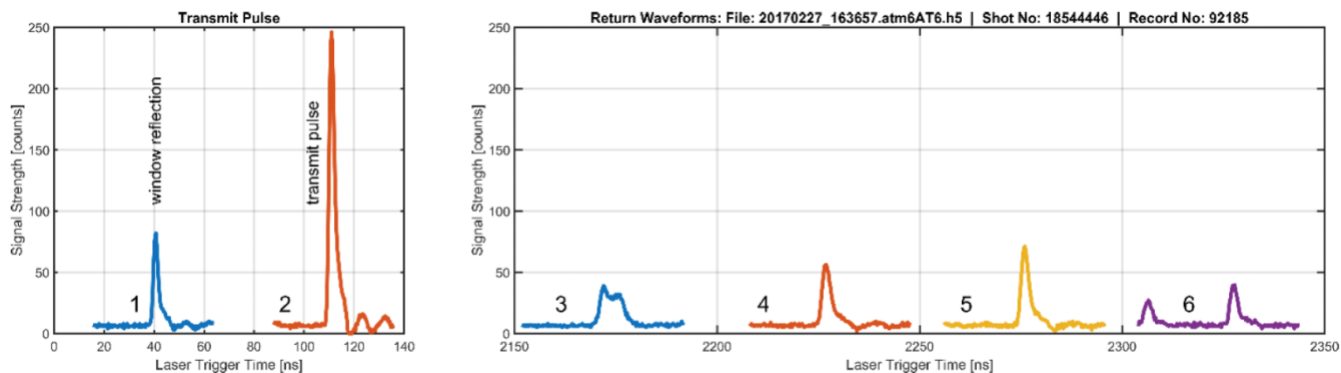

Figure 2. Example of how ATM waveform data are organized into range gates. The example shows a laser shot over a complex target (tree) that has triggered four return range gates, Range Gates 3 to 6, some of which contain multiple return pulses. The transmit pulse is recorded through a delay fiber (Range Gate 2) and is sometimes preceded by a window reflection (Range Gate 1).

2.3.4   Range Determination

The transmit and receive waveforms are captured in separate range gates. The time delay between transmitted and received waveforms includes the delay between the TX and RX range gates and the tracked location of the pulse within each gate. When the laser fires, an electronic trigger starts the digitizer counting the number of elapsed sampling intervals. The gate start position is the value of this counter at the first bin of the gate. The trigger time, i.e., the time relative to the trigger, of any range bin can be computed as the gate start position plus the bin position within the gate, multiplied by the digitizer sampling interval. The time between any range bins in the two gates can be accurately computed as the difference between the two trigger times. A more complex task is the assignment of a sample time to a waveform. Figure 3 shows the two windows and the current ATM method for calculating the range measurement between the two windows.
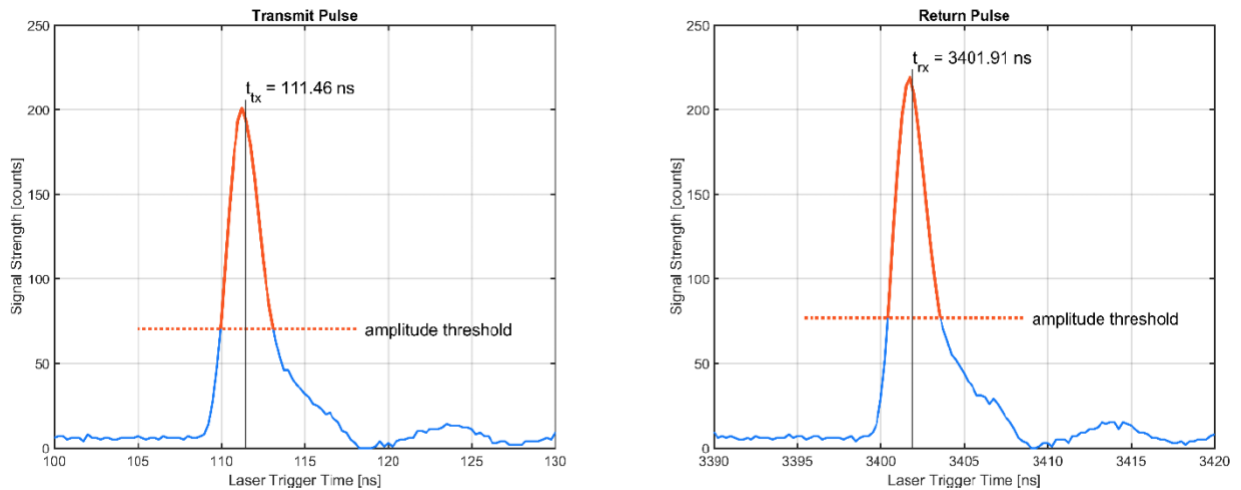

Figure 3. Example of range determination using a centroid estimate that cuts off data points below 35% of the maximum amplitude of the transmit and return pulse.

The ATM range determination uses a centroid estimate that cuts off all values below 35% of the maximum amplitude of the transmit or return pulse. The uncalibrated range between two positions in the TX and RX windows is:

$$range_{uncalibrated}[m] = \frac{1}{2} \cdot c \cdot (t_{rx} - t_{tx})$$

(Equation 1)

Uncalibrated range between two positions in the TX and RX windows, where c is the propagation speed of light through the atmosphere.

The example shown in Figure 4 yields an uncalibrated range of 493.22 m. As previously described, the optical delay fiber and other system components introduce a range bias that is determined in ground tests by shooting the laser at a target at a known distance.

Figure 4. Range bias determination (a.k.a. ground test) using a calibration target with a known distance. The distance to the calibration target is measured with an electronic distance meter (a.k.a. total station) with an accuracy of a few millimeters.

The range bias is a function of the return signal strength. For the ATM centroid tracker, the bias is almost constant for typical signal strengths encountered in flight, but deviates for weak signals that barely exceed the amplitude trigger threshold and for strong signals that saturate the digitizer. The range bias calibration determined from ground tests depends on the waveform tracking method. Users who wish to determine ranges using a different tracking method will need to develop a suitable calibration from the ground test data.

2.4 Quality, Errors, and Limitations

Fall 2018 Campaign (updated May 2021)

The first release of the Operation IceBridge 2018 Antarctic ATM lidar data was delivered to NSIDC in Aug 2019. Subsequently a problem was identified related to the application of the solid Earth tide correction in the data-processing stage. The resulting errors in elevations varied in both space and time over wavelengths of hundreds of kilometers. The error was corrected, the data reprocessed, and the resulting change in position was computed. Over the entire campaign, the vertical change (reprocessing minus initial processing) varied between -10.3 cm and +14.4 cm. The mean change for each survey flight varied between -6.0 cm and +5.1 cm, with a root sum of squares (RSS) deviation from the mean of between 0.6 cm and 4.4 cm. The vertical change summary is presented in Figure 5. The mean is the large dot, the thick bar shows mean +/- the standard deviation, and the thin bar shows the full range from minimum to maximum. The horizontal change was less than 15 cm throughout the campaign.
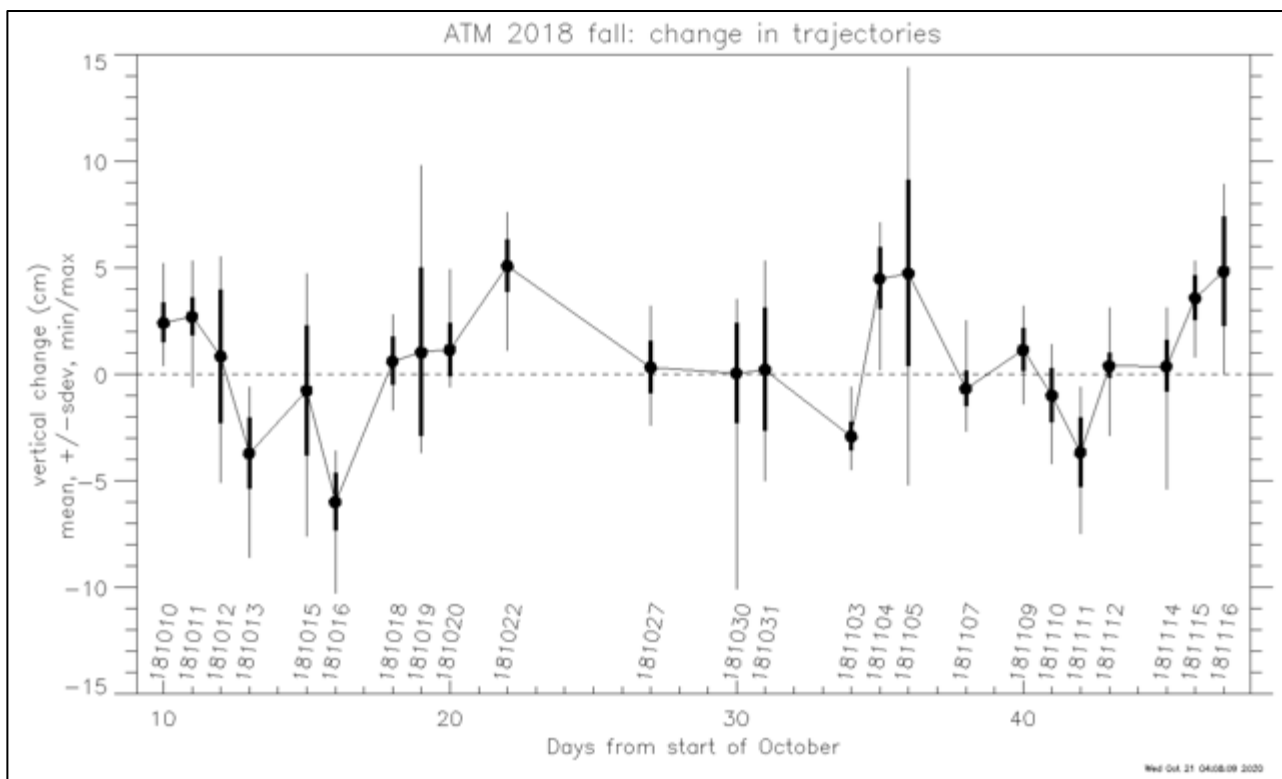
Figure 5. ATM 2018 Fall: Change in Trajectories After Solid Earth Tide Correction

Spring 2019 Campaign (updated May 2021)

The first release of the Operation IceBridge ATM lidar data was delivered to NSIDC in April 2020. At that time, a problem had been identified related to the application of the solid Earth tide correction in the data-processing stage. The resulting errors in elevations varied in both space and time over wavelengths of hundreds of kilometers. The error was subsequently corrected, the data reprocessed, and the resulting change in position was computed. Over the entire campaign, the vertical change (reprocessing minus initial processing) varied between -6.5 cm and +8.8 cm. The mean change for each survey flight varied between -1.8 cm and +2.8 cm, with a root sum of squares (RSS) deviation from the mean between 0.5 cm and 2.6 cm. The greatest magnitudes of vertical change tended to be at distances farthest from the staging airport (at Thule, April 3-23, 2019 or Kangerlussuaq, May 5-16, 2019). The results are presented in Figure 6. The horizontal change was less than 10 cm throughout the campaign.
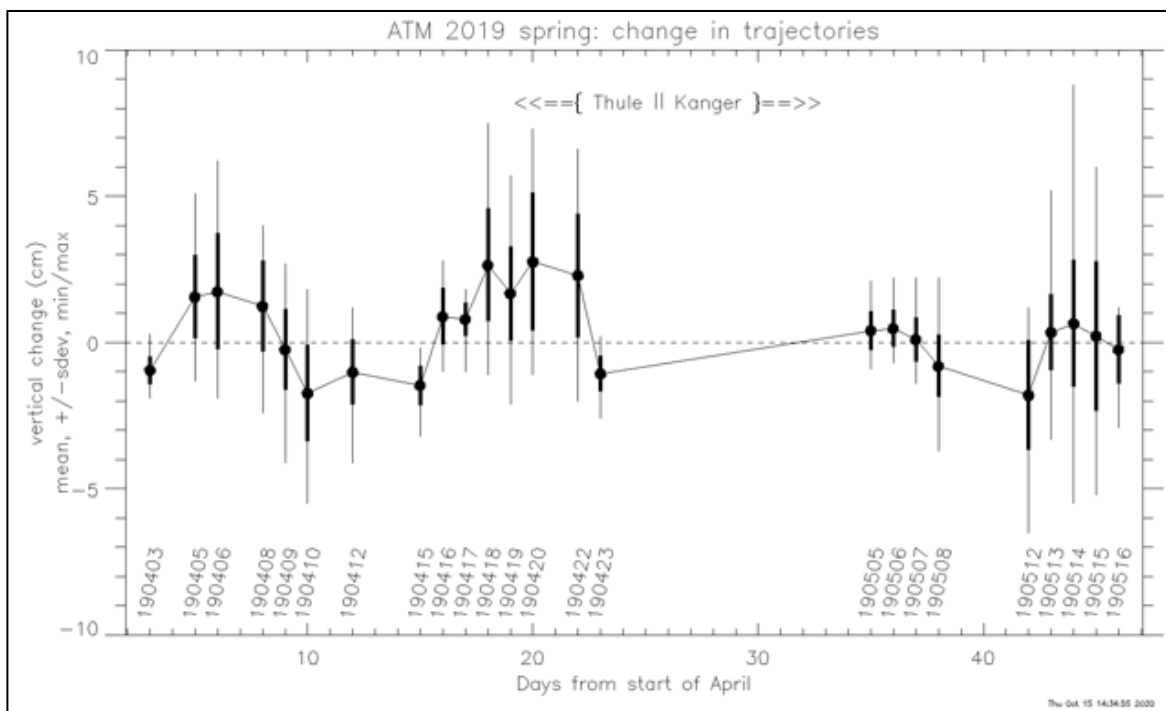
Figure 6. ATM 2019 Spring: Change in Trajectories After Solid Earth Tide Correction

> **Note:** The information below has been retained for provenance. The issues have been addressed as described in the preceding sections.

Fall 2018 and Spring 2019 Campaigns (10/10/2018 to 05/16/2019):

As compared to most other Operation IceBridge ATM laser altimetry data sets, this particular data set has certain limitations in accuracy that result from a recently identified problem related to the application of the solid Earth tide correction in the data processing stage. This error can cause long-wavelength errors in elevations that are less than decimeter in magnitude and which vary in both space and time. The error wavelength is typically hundreds of kilometers, so it should not significantly affect most analyses of this data set, but it can be smaller because it depends on the number and position of base stations used for the trajectory solution and on other factors including moon phase. The error only affects the 2018 DC-8 Antarctic and 2019 P-3 Arctic Spring ATM data sets published at NSIDC DAAC. Resolution of this error is in progress, and a future version of this data set will eliminate it. The user should consider the elevation issue in any scientific interpretation or other use of the data set. Users are requested to report their findings about data quality to NSIDC User Services, to be forwarded to the ATM team, for information and comment before publication or reporting elsewhere.

2.5 Methods

2.5.1   Level 1B QFIT Geolocated Spot Elevation Measurements

The geolocated and filtered spot elevation measurements are located in the group /footprint. Data are organized in chronological order. For example: if number of laser shots in the file is N, the timestamps of the laser shots are stored in an array of length N contained in /time/seconds_of_day, and the corresponding measured elevations are stored in an array of length N contained in /footprint/elevation.

2.5.2   Waveform Data

The waveform data are stored in the subgroup /waveforms/twv. Each laser shot can be associated with a varying number of range gates that can also vary in length (number of digitizer samples). Elements in the subgroup /ancillary_data are single values. The subgroup ./shot contains arrays of N values (e.g., ./shot/number), corresponding to each laser shot. Arrays in the subgroup ./gate correspond to each range gate. The largest subgroup (./wvfm) contains the 8-bit digitizer samples in the field ./wvfm/amplitude as a concatenation of all the waveform gates recorded in the file. The link between laser shots, range gates, and digitizer samples/range bins is implemented by a pointer/index scheme. The waveform data for a particular laser shot is found by locating the gates recorded for the laser shot, then locating the waveform samples associated with those gates. Consider a laser shot j, where $1 \leq j \leq N$. Using the conventions that a(j) is the j-th element of array a and a(i:j) is the sub-array taken from elements i through j, the time of the shot is given by ./shot/seconds_of_day(j). The number of gates associated with this laser shot is ./shot/gate_count(j). Data for the first gate associated with this shot is located in the gate arrays at index ./shot/gate_start. The first waveform sample for the first gate of this laser shot is located at ./shot(gate_start(j)).

The value of this first waveform sample is ./wvfm/amplitude(./gate/wvfm_start(./shot/gate_start(j))). The number of samples in each gate is stored in the array ./gate/wvfm_length. Therefore, the waveform recorded in the first gate of shot j can be read as:

./wvfm/amplitude(k2:k3),

where:

k = ./shot/gate_start(j)

k2 = ./gate/wvfm_start(k)

```
k3 = ./gate/wvfm_start(k) + ./gate/wvfm_length(k) - 1
```

More generally, the digitized waveform for range gate i of the laser shot j would be:

```
./wvfm/amplitude(k2:k3),
```

where:

```
k = ./shot/gate_start(j)
```

```
k2 = ./gate/wvfm_start(k+i-1)
```

```
k3 = ./gate/wvfm_start(k+i-1) + ./gate/wvfm_length(k+i-1) - 1
```

In order to reassemble all range gates into a time tagged series, the offset for the first range bin/sample needs to be known. This information is stored in the field ./gate/position as the number of digitizer samples since the laser was triggered. Together with the length of each range bin/sample in nanoseconds (./ancillary_data/sample_interval = 0.25 ns for 4 Giga samples per second digitization rate), the time in nanoseconds can be calculated using ./gate/position*sample_interval. In this way, the range gates for a laser shot can be reassembled in order to determine the time of flight between the transmit and receive pulses. Figure 5 illustrates the indexing scheme using values from an example data file. If the first range gate within a file starts at index 1 (./gate/wvfm_start(1) = 1) and is 192 range bins/samples long (./gate/wvfm_length(1) = 192), then the second range gate will begin at index 193 (./gate/wvfm_start(2) = 193).
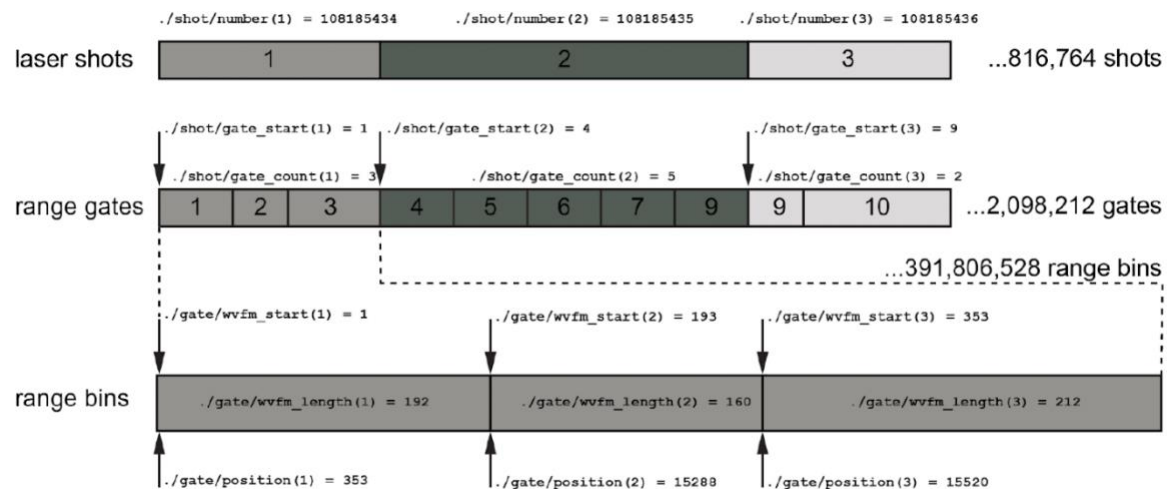

Figure 7. Pointer and indexing schema for access of the waveform data (range gates) for a particular laser shot. Range gate numbers are also referred to as record numbers.

The example file contains 816,764 individual laser shots whose unique shot identifiers are stored in the field ./shot/number. The start index for the first range gate for each shot (./shot/gate_start) and the number of range gates for each shot (./shot/gate_count) are of the same size as ./shot/numbers. Together, the 816,764 individual laser shots contain a total of 2,098,212 range gates that are comprised of 391,806,528 digitizer samples.

2.6 Waveform Signal Quality and Complex Return Pulses

Several parameters, provided in the subgroup `/waveforms/twv/gate/pulse`, allow users to assess the quality and complexity of waveforms (Table 3).

Table 3. Parameters Used to Assess Waveform Quality and Complexity

Field	Description
./area	Area of waveform pulse above noise floor
./count	Number of pulses in gate (number of threshold crossings divided by 2)
./sat_count	Number of waveform amplitudes at saturation value
./width	Width of pulse (number of samples) based on a threshold of 35% of the maximum amplitude

Some return signals contain complex waveforms. Complex returns showing multiple peaks or a broadened pulse indicate interaction of the laser pulse with complex surfaces such as sea-ice pressure ridges, crevasses, or melt ponds (Figure 6).
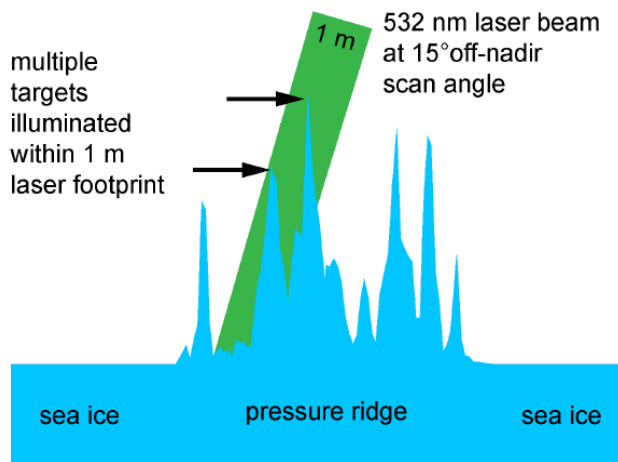

Figure 8. Example of surface characteristics that can cause complex return waveforms, when the laser pulse hits multiple targets within the size of the footprint.

To identify these scientifically interesting waveforms, several parameters can be used that indicate a deviation from a single return on a relatively smooth ice surface. The `./width` field indicates

pulse broadening from interacting with a complex target or a steep surface within the laser footprint (Figure 7b). Only data points above the threshold (35% of the maximum amplitude) are used. The `./area` parameter also indicates pulse broadening but takes into account all data points above the noise floor. This allows for the identification of changes in the waveform in the tail of a laser pulse. The `./count` parameter indicates multiple targets for a single transmit pulse (such as returns from the water surface and bottom of shallow melt ponds) or multiple targets over extremely rough surfaces (such as pressure ridges) (Figure 7a).
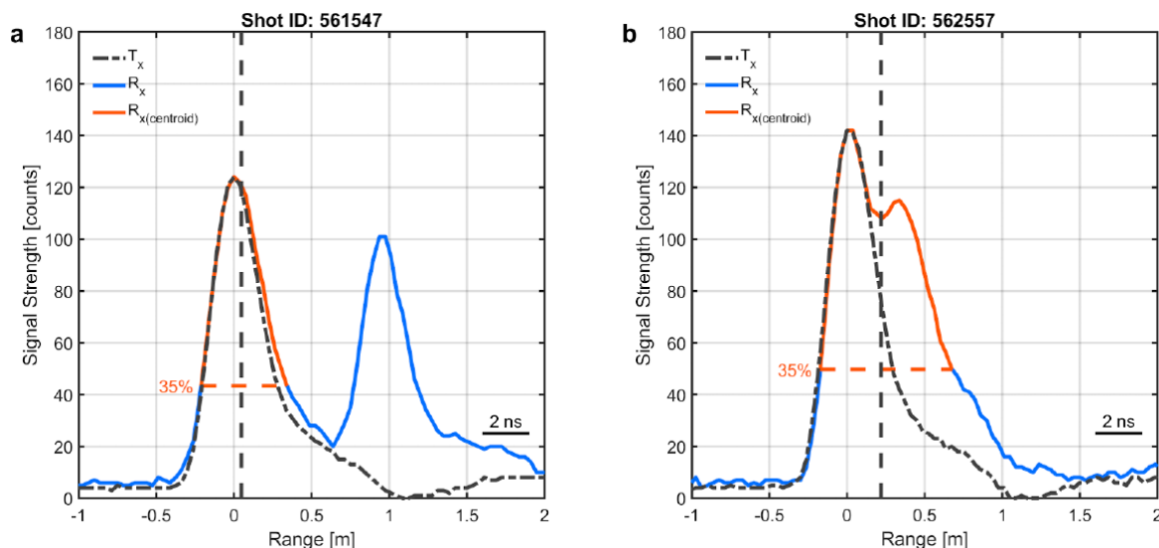

Figure 9. Example of complex return waveforms (blue) over a sea-ice pressure ridge. The transmit waveform is shown in dashed gray and scaled to the maximum amplitude of the return pulse to show the deviation of the return pulse. Multiple separate return pulses can be identified by the ./count parameter (a), while return pulses much broader than the transmit pulse (b) will be revealed by larger values in the ./width field. The vertical dashed line in both panels marks the location of the centroid, indicating that the centroid estimates from complex return pulses need to be interpreted properly.

3   RELATED DATA SETS

- IceBridge ATM L1B Near-Infrared Waveforms
- IceBridge Narrow Swath ATM L1B Elevation and Return Strength
- IceBridge ATM L1B Elevation and Return Strength
- IceBridge ATM L1B Elevation and Return Strength with Waveforms

4   ACKNOWLEDGMENTS

The ATM project team would like to acknowledge the dedicated flight crews, whose efforts allowed the safe and efficient collection of this data over some of the most isolated and extreme regions on this planet.

5   DOCUMENT INFORMATION

5.1 Publication Date

July 2018

5.2 Date Last Updated

April 2025