Comparisons of Satellite and Airborne Altimetry With Ground-Based Data From the Interior of the Antarctic Ice Sheet

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Abstract  A series of traverses has been conducted for validation of the National Aeronautics and Space Administration Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) on the flat interior of the Antarctic ice sheet. Global Navigation Satellite System data collected on three separate 88S Traverses intersect 20% of the ICESat-2 reference ground tracks and have precisions of better than ±7 cm and biases of less than ∼4 cm. Data from these traverses were used to assess heights from ICESat-2, CryoSat-2, and Airborne Topographic Mapper (ATM). ICESat-2 heights have better than ±3.3 cm bias and better than ±7.2 cm precision. ATM heights have better than 9.3 cm bias and better than ±9.6 cm precision. CryoSat-2 heights have −38.9 cm of bias and ±47.3 cm precision. These best case results are from the flat ice-sheet interior but provide a characterization of the quality of satellite and airborne altimetry.

Plain Language Summary  The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) each currently has satellites in orbit, with science goals that include determining the mass change of the Antarctic ice sheet and its contributions to mean sea level rise. This requires dense measurements of the elevations of the ice sheet with centimeter-level accuracy and precision. We use very accurate ground-based elevation data over the ice sheet to assess data from the NASA Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) and the ESA CryoSat-2 satellite missions. Further, we assess data from a single flight of the NASA Airborne Topographic Mapper (ATM). Our results show that the ground-based data are ideal for this type of validation and that the ICESat-2 and ATM data have centimeter-level accuracy, while the CryoSat-2 data are closer to the decimeter level of accuracy.

1. Introduction

Determining the mass change of our ice sheets using satellite and airborne altimetry requires centimeter-level accuracy and precision (McMillan et al., 2014; Smith et al., 2020). Finer accuracy and precision yields better mass-change estimates. Laser and radar altimeters have been used for this purpose (Markus et al., 2017; Wingham et al., 2006), and each has strengths and limitations (Bamber et al., 2018; Shepherd et al., 2012). The National Aeronautics and Space Administration (NASA) Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) and the European Space Agency (ESA) CryoSat-2 missions orbit with a 92° inclination reaching latitudes of 88° north and south. This is farther poleward than their satellite predecessors, enabling complete coverage of all high-relief areas of Antarctica.

The 88S Traverse in Antarctica (Brunt, Neumann, & Larsen, 2019; Brunt, Neumann, & Smith, 2019) is an ongoing ICESat-2 effort to validate NASA satellite and airborne altimeters (Figure 1). Along this route, Global Navigation Satellite System (GNSS) data are collected and have been used for the validation of two ICESat-2 data products: (1) the Global Geolocated Photon Level 2A data product (ATL03; Neumann et al., 2019) and (2) the Land Ice Along-Track Height (ATL06; Smith et al., 2019) Level 3A data product (Brunt, Neumann, & Smith, 2019). These GNSS data have also validated Operation IceBridge airborne lidars: the Airborne Topographic Mapper (ATM) and the University of Alaska Fairbanks Lidar (Brunt, Neumann, & Larsen, 2019). The ~300-km 88S Traverse is an ideal ICESat-2 validation surface because (1) it is flat on long length scales (Figure 1b); (2) it intersects 20% of the 1387 ICESat-2 reference ground tracks (RGTs), providing a statistical representation of the full orbit cycle; and (3) these RGTs are spread throughout the ICESat-2 91-day orbital

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cycle, which mitigates cloud-cover issues that have limited studies that use only a few RGTs (e.g., Fricker et al., 2005).

Here, we present validation results for ice-sheet surface heights from two satellite altimeters and one airborne altimeter using 2 years of 88S Traverse data. In the following sections, we discuss GNSS data collection
for the most recent traverse, the data processing strategy for both GNSS and altimetry data, and the results of the comparisons between the different instruments.

2. Data

2.1. GNSS Data

Three separate annual surveys have been conducted in Antarctica along the 88S Traverse in January 2018, 2019, and 2020 (Brunt, Neumann, & Smith, 2019) for altimetry validation (Figure 1). The ~750-km-long 88S Traverse is based out of South Pole; ~300 km of the traverse intersects ~275 ICESat-2 RGTs along 88°S. The 88S Traverses have used different hardware but have implemented similar data collection and processing methods, including (1) continuous GNSS data collection; (2) GNSS antenna height measurement, including any track indentation into the snow surface; (3) Precise Point Positioning GNSS processing (Bisnath & Gao, 2009) using Inertial Explorer; (4) data rejection based on a satellite elevation mask of 7.5° to reduce errors associated with GNSS multipath; (5) data rejection based on a vertical-accuracy sigma metric provided by the GNSS processing software; and (6) assessment of GNSS heights using crossover methods.

The 88S Year 1 methods are described in Brunt, Neumann, and Larsen (2019) and the Year 2 methods are described in Brunt, Neumann, and Smith (2019). The methods for data collection, processing, and evaluation for the 88S Year 3 traverse closely parallel to those from Year 2. The 88S Year 3 traverse was conducted using two PistenBully tracked vehicles pulling ~20-m-long sleds with a GNSS receiver (Trimble NetRS) and antenna (Trimble Zephyr Geodetic 2) mounted on the rear of each sled, which rode smoothly over the ice surface. The GNSS data were processed using Inertial Explorer, to the L1 phase center of the antennas; the measured antenna heights (2.04 and 2.05 m) were then used to correct the GNSS solutions to the snow surface. Similar to the previous surveys, the survey speed for Year 3 was ~2 m s⁻¹. However, the sample rate for the Trimble NetRS used during Year 3 was slower, at 1 Hz (as opposed to 2 Hz for Years 1 and 2), due to instrument limitations. These data were edited as described above to reduce errors associated with GNSS multipath and using a sigma metric for assessing vertical accuracy; while previous surveys used vertical sigma values of 13 cm, for Year 3 that value filtered too many data points and 20 cm was used instead. We attribute this difference to poorer precision in the Year 3 data set associated with the slower sample rate and a characteristic length scale of the sastrugi, which dominated the ice surface. The filtration associated with the 20 cm vertical sigma resulted in the removal of <5% of the Year 3 data from each vehicle.

The 88S Traverse GNSS heights are given in the ITRF2014 reference frame and the geographic coordinates (latitude, longitude) are referenced to the WGS84 ellipsoid. These GNSS heights are provided in a “tide-free” system (Schröder et al., 2017), where the solid-earth correction includes the correction for the permanent tide, meaning that the permanent crustal tidal deformation is removed. ICESat-2 data are in this reference frame (Neumann et al., 2019), and other altimetry data were transformed into this reference frame for direct comparison.

2.2. ICESat-2 Data

ICESat-2 is a photon-counting altimeter, with a single laser source splitting to create six spots on the ground (Markus et al., 2017). ICESat-2 data products are organized by ground tracks (GT1L, GT1R, GT2L, GT2R, GT3L, and GT3R); for our analyses, we assess the performance of the instrument spots (1–6) to account for the periodic 180° instrument rotations to maximize illumination of the solar panels and to keep the spacecraft radiators pointed away from the Sun. We note that the RGT is an imaginary line intersecting the center of the six-beam array. Recent results show that ICESat-2 has an average spot diameter of ~11 m (Magruder, Brunt, & Alonzo, 2020; Magruder, Brunt, Neumann, et al., 2020). We downloaded data optimized for ice-sheet surfaces from the National Snow and Ice Data Center (NSIDC). Specifically, we used ATL06 Release 3 for October 14, 2018 through April 30, 2020, covering ICESat-2 region 11 for 88S GNSS comparisons. ATL06 aggregates photon geolocation information on 40-m along-track length scales, with postings evenly spaced every 20 m along track. We used the built-in ATL06 surface-signal confidence metric (atl06_quality_summary), which is a combination of photon selection confidence, signal spread, estimated uncertainty, and
signal-to-noise ratio, for filtering the ICESat-2 data (Smith et al., 2019). We then subsetted these data sets to the 88S GNSS data. The ATL06 heights \(h_{li}\) are in the same reference frame as the GNSS data.

### 2.3. CryoSat-2 Data

CryoSat-2 is a radar altimeter, operating in three different modes, depending on surface type. Over the flat interiors of the ice sheets, CryoSat-2 operates in a pulse-limited low resolution mode (LRM; Wingham et al., 2006), where the measurement refers to an area of \(\sim 2.2\, \text{km}^2\), with an across-track width of \(\sim 1.650\, \text{m}\) (Kurtz et al., 2014). We downloaded Baseline-D data for October 1, 2018 through April 30, 2020 directly from ESA (Meloni et al., 2020), and then subsetted this data sets to the 88S GNSS data. The CryoSat-2 time period was selected to match the ICESat-2 timeseries. The CryoSat-2 data product provides a surface-signal confidence metric; we filtered data with an overall "Quality_flag" value greater than 0. We used CryoSat-2 heights associated with the Offset Centre of Gravity retracker, as that is the common retracker used over the flat interiors of the ice sheets (Slater et al., 2018) and has been shown to be less sensitive to temporal changes in penetration depth (Slater et al., 2019). The geographic coordinates for CryoSat-2 are referenced to the WGS84 ellipsoid. Heights for the Baseline-D data product are given in the ITRF2014 reference frame (Schrama, 2018). CryoSat-2 heights are provided with a solid-earth correction in a mean-tide system which does not include a correction for the removal of the permanent tide ("mean-tide" system; Schröder et al., 2017). Along the 88S Traverse, the permanent tide correction is \(-12.03\, \text{cm}\). This value was used to put the CryoSat-2 data into the same reference frame as the GNSS data.

### 2.4. ATM Data

ATM consists of two conically scanning airborne lidars (Krabill et al., 2002; Martin et al., 2012), including a wide-scanning T6 unit with a 30° full-scanning angle and a \(\sim 250\, \text{m}\) swath width on the ground, and a narrow-scanning T7 unit with a 5° full-scanning angle and a \(\sim 40\, \text{m}\) swath width on the ground. Each unit has a \(\sim 1\, \text{m}\) diameter ground footprint. We downloaded version 2 of the L1B Elevation and Return Strength data from the NSIDC, for November 12, 2018. We then subsetted these data sets to the 88S GNSS traverse data. The heights for ATM are given in the ITRF2008 reference frame and the geographic coordinates are referenced to the WGS84 ellipsoid. Similar to the GNSS results, ATM heights are provided in a tide-free system, where the solid-earth correction includes the correction for the removal of the permanent tide.

### 3. Methods

Our methods include the comparison of the satellite and airborne altimetry data sets with the time-appropriate 88S GNSS data set. The effective footprint sizes of the altimeters vary. ICESat-2 has an average spot diameter of \(\sim 11\, \text{m}\), and therefore, ATL06 has an effective footprint diameter of 11 m in the across-track direction. However, ATL06 aggregates photon geolocation information on 40-m along-track length scales and therefore has an effective footprint diameter of \(\sim 40\, \text{m}\) in the along-track direction. CryoSat-2 has a \(\sim 1,650\, \text{m}\)-effective footprint diameter and ATM has a \(\sim 1\, \text{m}\)-effective footprint diameter. These effective footprint sizes determined horizontal search radii used in the various comparisons.

#### 3.1. GNSS Data Assessment

Assessments of the 88S Year 1 and Year 2 traverses (Brunt, Neumann, & Larsen, 2019; Brunt, Neumann, & Smith, 2019) have previously been made. An assessment of the 88S Year 3 GNSS heights is made here; methods closely follow the GNSS assessments of the previous traverse studies. We compared the 88S Year 3 heights from the two PistenBully vehicles at areas of track crossover, using a nearest-neighbor method, filtered to only include heights from the two data sets that were within 1 m of one another.
3.2. ICESat-2 Data Comparison
Where one of the six ICESat-2 beams crossed the 88S Traverse data, we compared the ATL06 heights of the satellite and ground-based data sets. For ATL06 data before July 1, 2019, we used GNSS data from 88S Year 2; for ATL06 data after July 1, 2019, we used GNSS data from Year 3. The number of ATL06 data points in the 88S Traverse latitude band was smaller than the number of GNSS data points. For each ATL06 height posted at 20-m along track, we found the \( n \) number of GNSS heights that were within a 20-m horizontal search radius. For each ATL06 height posting with more than 30 GNSS heights within the 20-m search radius \( (n > 30) \), we created a single GNSS pseudo-height from the median of the GNSS heights that met the search criteria. For the total number \( N \) of the ATL06 height postings per spot for a given GNSS crossover, we calculated the median of the differences between each ATL06 posting and the associated single GNSS pseudo-height; we take this value to be the measurement bias for a given ATL06–GNSS crossover. We also calculated the \( 1-\sigma \) standard deviation of those differences, which we take to be the surface measurement precision for a given ATL06-GNSS crossover and recorded the number \( N \) of ATL06 postings that met the horizontal search criteria for a given crossover.

3.3. CryoSat-2 Data Comparison
Where a CryoSat-2 ground track crossed the 88S Traverse data, we compared heights from the two data sets. For CryoSat-2 data before July 1, 2019, we used GNSS data from 88S Year 2; for CryoSat-2 after July 1, 2019, we used GNSS data from Year 3. Similar to ATL06, the number of CryoSat-2 data points in the 88S Traverse latitude band was also smaller than the number of GNSS data points, and we followed nearly the same methodology as that of ATL06. However, we used a somewhat arbitrary horizontal search radius of 90 m to partially accommodate the large effective footprint diameter of CryoSat-2, while attempting to limit the effects of local slope in the GNSS data. Similar to ICESat-2, we removed CryoSat-2 data comparisons with less than 30 GNSS heights within the search radius.

3.4. ATM Data Comparison
The number of ATM data points in the 88S Traverse latitude band was larger than the number of GNSS data points, and we therefore reversed the analysis relative to that of ATL06: for each GNSS height posting, we found the ATM heights that were within a 4-m (chosen based on the ATM footprint sizes and the non-uniform spacing of both data sets) horizontal search radius. For each GNSS height with more than 30 ATM heights within the 4-m search radius, we created a single ATM pseudo-height from the median of the ATM heights that met the search criteria. For all of the GNSS height postings for a crossover, we calculated the median of the differences between each GNSS posting and the associated single ATM pseudo-height. We also calculated the \( 1-\sigma \) standard deviation of those differences and recorded the number of GNSS postings that met the horizontal search criteria for a given crossover.

4. Results
For the 88S Year 3, the bias and the \( 1-\sigma \) standard deviation between the GNSS heights from the two PistenBully vehicles is \( 1.7 \pm 6.6 \text{ cm} \) \((n = 6,622)\). These results are similar to those for Year 1 \((1.1 \pm 4.1 \text{ cm}, n = 26,442, \text{ Brunt, Neumann, & Larsen, 2019})\) and Year 2 \((0.2 \pm 6.3 \text{ cm} n = 24,434; \text{ Brunt, Neumann, & Smith, 2019})\). However, the data volume \((n)\) that met the 1-m horizontal search criteria is significantly lower. We attribute this to the sampling rate (2 Hz for Years 1 and 2; 1 Hz for Year 3) and a \( \sim\)24-h data loss in one of the GNSS instruments (due to a loose wire) on the Year 3 traverse. If we assume that the 6.6-cm spread in the differences between the two Year 3 GNSS data sets is the result of uncorrelated errors in the data sets associated with each vehicle, then the error in a single measurement would be that spread divided by the square root of the number \((n)\) of data sets \((2)\), or 4.7 cm. We acknowledge that the GNSS error estimates presented here are small and may not account for correlated errors, such as those associated with the atmosphere \((\text{Bar-Sever et al., 1998})\); this is in part because of the separation in space \((<500 \text{ m})\) and time \((<15 \text{ min})\) between the two survey vehicles. To assess the magnitude of such errors in the Year 3 data set,
we merged the GNSS data sets associated with both vehicles and then compared data collected along the same leg of the traverse separated by ∼16 days (December 30, 2019 and January 15, 2020). We compared the data from the two different days using the same method as for comparing the different GNSS profiles. The difference between GNSS data sets from the two different days is 3.3 ± 9.2 cm (n = 2,236). If we again assume that spread in the differences between the two GNSS data sets is due to uncorrelated errors, then the error in a single measurement is 6.5 cm.

The analysis of the Year 2 GNSS data (Brunt, Neumann, & Smith, 2019) also included an assessment of correlated errors using data along the same leg of the traverse, separated by 13 days (December 28, 2018 and January 10, 2019). Results for Year 2 (3.9 ± 4.6 cm, n = 12,444) and Year 3 (3.3 ± 9.2 cm, n = 2,236) were similar and thus, we proceed under the assumption that correlated errors, including those associated with the ionosphere, troposphere, and satellite GNSS orbit, are less than ∼4 cm.

Overall, we take the uncertainty in any single GNSS measurement in the Year 3 data set to be the RSS of (a) the RMS of the uncorrelated errors (4.7 and 6.5 cm), which is 5.7 cm and (b) the correlated error (∼4 cm).

The result of the RSS of 5.7 and 4 cm is 6.9 cm.

We also directly compared the GNSS heights from the three different 88S Traverses. Years 2 and 3 are relatively similar, with a bias of 1.7 ± 11.9 cm (n = 1,270), with Year 3 heights are above Year 2 heights. However, heights from the Year 1 are well above the other 2 years: Year 1 was 5.3 ± 12.5 cm (n = 1,122) above Year 3 and 8.4 ± 12.3 cm (n = 27,230) above Year 2. We note that the 88S GNSS comparisons presented below use Years 2 and 3. There is a spatial structure to the differences between the three 88S Traverse data sets. We binned the heights along 88S from each year into bins of half of a degree of longitude (∼2 km at this latitude). We made comparisons between the different years within those bins, using a nearest-neighbor method, filtered to only include heights from the two comparison data sets that were within 5 m of one another. Figure 1c provides the median residuals for the various comparisons (Year 2 minus Year 1 in black; Year 3 minus Year 1 in blue; and Year 3 minus Year 2 in red) for every half of a degree of longitude. The left side of the plot (from −155°W to 170°E), delineated by the dashed line in Figure 1c, shows more variability, which we interpret to be associated with the topographic high along the traverse (Figure 1b) and redistribution of snow by the wind on annual time scales.

The comparisons between the 88S Traverse heights and the altimeters are fairly consistent (Table 1 and Figure 2). ATL06 heights have better than ±3.3 cm biases and better than ±7.2 cm surface measurement precisions (1−σ standard deviations). ATM heights have better than 9.3 cm biases and better than ±9.6 cm surface measurement precisions. Differences are larger for CryoSat-2, with −38.9-cm bias and ±47.3-cm precision. The results for CryoSat-2 have more spread; to mitigate the effect of outliers in the CryoSat-2 comparison, we removed comparison results with overall height differences larger than 2 m (4.1%). Finally, the

| Altimetry          | GNSS                  | Bias ± precision (cm) | N   | Radius (m) |
|--------------------|-----------------------|-----------------------|-----|------------|
| ATL06, spot 1      | 88S Years 2, 3        | −1.7 ± 7.1            | 1,113 | 20         |
| ATL06, spot 2      | 88S Years 2, 3        | −0.6 ± 6.6            | 1,163 | 20         |
| ATL06, spot 3      | 88S Years 2, 3        | 2.2 ± 6.0             | 1,889 | 20         |
| ATL06, spot 4      | 88S Years 2, 3        | 1.6 ± 6.6             | 1,835 | 20         |
| ATL06, spot 5      | 88S Years 2, 3        | 1.9 ± 5.8             | 1,393 | 20         |
| ATL06, spot 6      | 88S Years 2, 3        | 3.2 ± 6.6             | 1,311 | 20         |
| CryoSat-2          | 88S Years 2, 3        | −38.9 ± 47.3          | 12,737| 90         |
| ATM, T6, November 12, 2018 | 88S Year 2   | 9.2 ± 6.1             | 202,085| 4          |
| ATM, T7, November 12, 2018 | 88S Year 2 | 8.5 ± 9.5             | 1,540 | 4          |

Comparisons represent (altimetry – GNSS); thus, positive values represent altimetry heights that are above the GNSS surface.
density of results on the right side of Figure 2, after July 1, 2019, is lower and related to the lower sampling rate, and ultimately fewer data points meeting the rejection criteria, of the Year 3 GNSS data.

Results for ATL06 heights straddle the 88S Traverse GNSS surface, ranging from −1.7 to 3.2 cm; we calculated a single ATL06 bias of 0.8 cm, weighted based on the errors of each spot (or the square of the $1-\sigma$ standard deviation, divided by the square root of the number of crossovers $N$ for each spot from Table 1).

ATM results are relatively consistent with ICESat-2 results, with biases <10 cm above the GNSS surface. CryoSat-2 results show significant negative offset (>30 cm) from the GNSS surface.

### 5. Discussion

The 88S Traverse GNSS data used for the altimetry comparisons are internally consistent and have low errors. These data sets have errors of 5.6 cm (Year 2; Brunt, Neumann, & Smith, 2019) and 6.9 cm (Year 3). Based on results on the right side of Figure 2, future 88S Traverses will sample at 2 Hz, similar to Years 1 and 2. Further, based on Figure 1c, comparisons between ICESat-2 data and 88S GNSS data with more than a year of separation in time will exclude the ground-based data between 170°E and 155°W.

The surface assessed here is a flat ice-sheet interior, where the height changes just 100 m along the 300 km traverse (Figure 1b). In flat regions such as this, geolocation errors are minimized. The ice sheet is also a bright reflector, providing a strong signal return for the laser altimeters. We acknowledge that the altimetry comparisons presented here are limited with respect to applicability to the margins of the ice sheet and other geophysical surfaces, which will most certainly have larger spreads (poorer precision) with respect to the signal returns. However, the methods presented here provide a means to characterize the quality of the satellite and airborne altimetry.

Validation for ICESat-2 at 88S represents a relatively long time period within the mission including ~17.5 months of on-orbit data. These results are consistent with ATL06 results from the early mission (Brunt, Neumann, & Smith, 2019), which assessed ~6.5 months of on-orbit data. For both assessments, spots 1 and 2 are slightly below the GNSS surface, while spots 3–6 are slightly above the GNSS surface. Future releases of ATL06 will focus on the reduction of these spot-specific biases. However, ATL06 is more accurate and precise than any prior altimetric product even with the inclusion of spots 1 and 2 (Table 1).

The result for CryoSat-2 shows a significant negative bias of 38.9 cm below the GNSS reference surface. This difference is likely due to radar signal penetration into the firn layer (Rémy & Parouty, 2009); specifically, it
is likely due to the much higher subsurface volume-scattering and layer-scattering present in the Ku-band radar signal, which has an extinction length on the order of ~10 m (Arthern et al., 2001), compared to the much lower value of <2 cm (expected for a 532 nm laser pulse in fine-grained snow; Smith et al., 2018). This study helps provide metrics for determining the sensitivity of radar estimates to surface penetration over a wide area in the flat interior of the Antarctic ice sheet. Reconciling the differences between the height assessments from ICESat-2 and CryoSat-2 will provide a better understanding of the differences between independent estimates of ice-sheet mass balance based on either laser or radar altimeters (McMillan et al., 2014; Shepherd et al., 2019). The high accuracy and precision of ATL06 over flat ice-sheet interiors could also provide improvements to CryoSat-2 retrieval algorithms that attempt to account for the impacts of surface and volume scattering within the radar returns (e.g., McMillan et al., 2016). This could be done by using the ATL06 surface heights as a constraint on the location of the snow–air interface in the radar return.

6. Conclusions

The GNSS data collected on the flat interior of the Antarctic ice sheet are sufficiently accurate for assessing the airborne and satellite altimetry presented here. The 88S Traverse intersects 20% of the RGTs of both ICESat-2 and CryoSat-2. The large number of crossovers at 88S for these satellite altimeters and the airborne altimeter (ATM) provides a large statistical population and shows that ATL06 heights are the most accurate and precise assessed here, with better than ±3 cm biases and better than ±7.2 cm surface measurement precisions. ATM is also very precise with biases less than 10 cm. Results for CryoSat-2 in LRM mode show a significant negative offset, with biases greater than 30 cm, due to radar signal penetration into the firm layer.

Conflicts of Interest

The authors have declared that no conflict of interest exists.

Data Availability Statement

ICESat-2 (https://nsidc.org/data/icesat-2) and Operation IceBridge ATM (https://nsidc.org/data/icebridge) data are available via NSIDC. CryoSat-2 data are available via the ESA CryoSat-2 Science Server (https://science-pds.cryosat.esa.int/). GNSS data for the Antarctic traverses are available on the ICESat-2 website (https://icesat-2.gsfc.nasa.gov).
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