Two Traverses for the Assessment of Satellite and Airborne Altimetry over the Interiors of Ice Sheets

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Key Points:

- We compare satellite-derived altimetry data with GNSS data from traverses on the Antarctic and Greenland ice sheets
- NASA's latest satellite laser altimeter is the most accurate with better than ±3 cm of bias and better than ±7 cm precision
- These best-case results are from the ice-sheet interiors but provide a characterization of the quality of satellite and airborne altimetry

Abstract

Two traverses have been conducted for validation of the NASA Ice, Cloud, and land Satellite 2 on the flat interiors of the Antarctic and Greenland ice sheets. GNSS data collected on three separate 88S Traverses intersect 20% of the ICESat-2 reference ground tracks and have height errors of 5.6 and 8.0 cm. GNSS data from the monthly Summit Traverse in Greenland have 0.9 cm of bias and 5.7 cm precision. 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 ±2.9 cm bias and better than ±6.7 cm precision. ATM heights have better than 9.3 cm bias and better than ±9.6 cm precision. CryoSat-2 heights have more than 20 cm of bias and more than ±40 cm precision. These best-case results are from the ice-sheet interiors but provide a characterization of the quality of satellite and airborne altimetry.

Plain Language Summary

The National Aeronautics and Space Administration and the European Space Agency each currently have satellites in orbit, with science goals of determining the mass change of our ice sheets, to determine their contributions to mean sea level rise. This requires dense measurements of the elevations of the ice sheets with centimeter-level accuracy and precision. We use very accurate ground-based elevations over Greenland and the Antarctic ice sheets to assess data from the NASA Ice, Cloud, and land Satellite 2 (ICESat-2) and the ESA CryoSat-2 satellite missions. Further, we assess data from the NASA Airborne Topographic Mapper. Our results show that the ground-based data are ideal for this type of validation and that the ICESat-2 and ATM data are meeting the centimeter-level of 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 (Smith et al., 2020; McMillan et al., 2014). 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 have strengths and limitations (Shepherd et al., 2012; Bamber et al., 2018). The NASA Ice, Cloud, and land Satellite 2 (ICESat-2) and the 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 et al., 2019a; 2019b) is an ongoing ICESat-2 effort to validate NASA satellite and airborne altimeters. Along this route, Global Navigation Satellite System (GNSS) data are collected for the validation of the Global Geolocated Photon Level 2A data product (ATL03; Neumann et al., 2019) and the Land Ice Along-Track Height (ATL06; Smith et al., 2019) Level 3A data product (Brunt et al., 2019b). These GNSS data have also validated Operation IceBridge airborne lidars: The Airborne Topographic Mapper (ATM) and the University of Alaska Fairbanks (UAF) Lidar (Brunt et al., 2019a). The ~300-km 88S Traverse is an ideal ICESat-2 validation surface because: 1) it is flat on long length scales; 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 cycle, which mitigates cloud-cover issues that have limited studies that uses only a few RGTs (e.g., Fricker et al., 2005).

The Summit Traverse in Greenland (Brunt et al., 2017) is another ongoing ICESat-2 validation project that has been conducted monthly since August 2006. These data were used to validate ICESat heights (Siegfried et al., 2011) and Operation IceBridge altimeters: ATM and the Land, Vegetation, and Ice Sensor (Brunt et al., 2017). The ~25-km survey intersects 7 km of ICESat and ICESat-2 RGTs. Unlike the 88S Traverse, this region has a measurable seasonal elevation signal (Hawley et al., *in review*). It is an ICESat-2 validation site because this GNSS time series is unmatched with respect to length and temporal density. Further, results from Summit augment results from the 88S Traverse, providing assessments in the opposite hemisphere.

Here, we present validation results for ice-sheet surface heights from two satellite altimeters and one airborne altimeter using three years of 88S Traverse data. We demonstrate that these results are not unique to Antarctica by assessing the same altimeters in Greenland, using data from the Summit Traverse. In the following sections, we discuss GNSS data collection, 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

Ground-based GNSS data have been collected on the Antarctic and Greenland ice sheets for altimetry validation. Three separate annual surveys have been conducted in Antarctica along the 88S Traverse in January 2018, 2019, and 2020 (Brunt et al., 2019b). 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 ~25 km long Summit Traverse (Brunt et al., 2017; Siegfried et al., 2011) is based out of Summit Station and intersects ~7 km of a descending (#879) and ascending (#749) ICESat-2 RGT. Since the launch of ICESat-2, Summit traverses have been coordinated in time with satellite overpasses. The 88S and Summit traverses have used different hardware (Table 1), but have used 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 and 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. Given the vehicle speeds and sampling rates, the effective footprints of the traverses range from 1 to 5 m (Table 1).

Traverse	GNSS Receiver	GNSS Antenna	Sample Rate	Survey Speed	Footprint Diameter	Bias ± Precision	Reference
88S Year 1	Trimble NetR9	Trimble Zephyr Geodetic 2	2 Hz	2 ms^{-1}	1 m	1.1 ± 4.1 cm (n = 26, 442)	Brunt et al. (2019a)
88S Year 2	Septentrio PolaRx5	PolaNt-x MF	2 Hz	2 ms^{-1}	1 m	0.2 ± 6.3 cm (n = 24,434)	Brunt et al. (2019b)
88S Year 3	Trimble NetRS	Trimble Zephyr Geodetic 2	1 Hz	2 ms^{-1}	2 m	1.7 ± 6.6 cm (n = 6,622)	*Sec. 4, this contribution*
Summit	Trimble R7	Trimble Zephyr	1 Hz	5 ms^{-1}	5 m	0.9 ± 5.7 cm (n = 710)	Brunt et al. (2017)

Table 1. GNSS hardware and survey parameters for the 88S and Summit traverses. The 'Bias ± Precision' terms represents a median measurement bias between two heights ± the 1-σ standard deviation. For the 88S Traverses, we compare heights from the two PistenBully vehicles; for the Summit Traverse, we compare heights from two passes made on the same day.

The 88S survey methods for the first two traverses have been described in detail. The 88S Year 1 methods evaluated the UAF lidar (Brunt et al. 2019a). The 88S Year 2 methods evaluated early data releases for the ATL03 (Neumann et al., 2019) and ATL06 (Smith et al., 2019) data products (Brunt et al. 2019b). The methods for data collection, processing, and evaluation for the 88S Year 3 traverse closely parallel those from Year 2. The 88S Year 3 traverse was conducted using two PistenBully tracked vehicles pulling ~20-m-long sleds with a GNSS antenna 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. The sample rate for the Trimble NetRS used during Year 3 was 1 Hz, which was the instrumentation limit. 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 with poorer precision associated with the slower sample rate, the speed of the vehicles, and a characteristic length scale of the sastrugi, which dominated the ice surface.

The 88S and Summit 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, 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, 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 6 spots on the ground (Markus et al., 2017). We note that the RGT is an imaginary line intersecting the center of the 6-beam array. Recent results show that ICESat-2 has an average spot diameter of ~11 m (Magruder et al., in review; Magruder et al., submitted). We downloaded data optimized for ice-sheet surfaces from the National Snow and Ice Data Center (NSIDC). Specifically, we use ATL06 Release 3 for 14 Oct 2018 through 13 Mar 2020, covering ICESat-2 region 11 for 88S comparisons. For the Summit comparisons, we use data from the same time period for the #749 RGT (region 3) and the #879 RGT (region 5). ATL06 aggregates photon geolocation information on 40-m along-track length scales, with postings evenly-spaced every 20 m along track. We use 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 subset these datasets to either the 88S or Summit 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 low-slope interiors of the ice sheets, CryoSat-2 operates in a pulse-limited Low Resolution Mode (LRM; Wingham et al., 2006), where each transmitted pulse illuminates an area of ~2.2 km^2, with an across-track width of ~1,650 m. We downloaded Baseline-C data for 1 Oct 2018 through 27 Apr 2019 and Baseline-D data for 28 Apr 2019 through 13 Mar 2020, directly from ESA (Meloni et al., 2020), and then subset these datasets to either the 88S or Summit 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 (OCOG) retracker, as that is the common retracker used over the flat interiors of the ice sheets (Slater et al., 2018). The geographic coordinates for CryoSat-2 are referenced to the WGS84 ellipsoid. Heights for the Baseline C data product are given in the ITRF2008 reference frame, while heights for Baseline D are in ITRF2014. Along the 88S Traverse, ITRF2014 heights are above the ITRF2008 heights by 0.24 mm in East Antarctica sector and 0.48 mm in West Antarctica. Along the Summit Traverse the ITRF2014 are 0.30 mm below the ITRF2008 heights. These values were used to convert the Baseline C data into the same reference frame as the Baseline D and the GNSS data. 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. Along the 88S Traverse the permanent tide correction is -12.03 cm, while along the Summit Traverse, this correction is -10.40 cm. These values were 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 ~250-m swath width on the ground, and a narrow-scanning T7 unit with a 5° full-scanning angle and a ~40-m swath width on the ground; each unit has a ~1 m diameter ground footprint. We downloaded version 2 of the L1B Elevation and Return Strength data from the NSIDC, for 12 Nov 2018 over the 88S Traverse and 12 May 2019 over the Summit Traverse. These were the only Operation IceBridge flights over our traverses during the ICESat-2 mission. We then subset these datasets to either the 88S or Summit 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 three Antarctic altimetry datasets with the time-appropriate 88S GNSS dataset and the comparison of the three Arctic altimetry datasets with the time-appropriate Summit GNSS dataset. The effective footprint sizes of the altimeters vary: ATL06 has an effective footprint of ~20-m in the along-track direction and 5.5 m in the across-track direction; CryoSat-2 has a ~1,650-m effective footprint diameter; and ATM has a ~1-m effective footprint diameter. The effective footprint size of the GNSS data varied between 1 and 5 m, depending on the sample rate and vehicle speed (Table 1). The footprint sizes and the relative sizes of the datasets being assessed had an impact on the methods; specifically, the footprint sizes determined search radii and the relative sizes of the datasets being assessed determined how the search was conducted.

3.1 GNSS data assessment

Assessments the 88S Year 1 and Year 2 traverses (Brunt et al., 2019a; 2019b) and the Summit Traverse (Brunt et al., 2017) 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 datasets that were within 1 m of one another.

3.2 ICESat-2 Antarctic data comparison

Where one of the six ATL06 beams crossed the 88S Traverse data, we compared the heights of the two datasets. For ATL06 data before 1 Jul 2019, we used GNSS data from 88S Year 2; for ATL06 data after 1 Jul 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 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-σ 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 search criteria for a given crossover. ATL06 data still contain blunders and we therefore limit their effect on our overall statistics by removing data comparisons with height differences larger than 2 m.

3.3 CryoSat-2 Antarctic data comparison

Where a CryoSat-2 ground track crossed the 88S Traverse data, we compared heights from the two datasets. For CryoSat-2 data before 1 Jul 2019, we used GNSS data from 88S Year 2; for CryoSat-2 after 1 Jul 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 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 height differences larger than 2 m.

3.4 ATM Antarctic 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 and GNSS footprint sizes and the nonuniform spacing of both datasets) 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-σ standard deviation of those differences and recorded the number of GNSS postings that met the search criteria for a given crossover.

3.5 Greenland data comparisons

The Summit Traverse is considerably shorter than the 88S Traverse and only intersects two ICESat-2 RGTs. Thus, there are far fewer crossover opportunities for satellite-to-GNSS comparisons. However, the comparison methods for all three altimetric datasets in Greenland matched the methods for the Antarctic comparisons. For ATL06 and CryoSat-2 height postings with more than 30 GNSS heights ($n > 30$) within the search radius (20 and 90 m, respectively), we created a single GNSS pseudo-height from the median of the GNSS heights that met the search criteria. For ATM, the analysis was reversed, as discussed in Section 3.4.

4 Results

For the 88S Year 3, the bias and the 1σ standard deviation between the GNSS heights from the two PistenBully vehicles are 1.7 ± 6.6 cm (n = 6,622). These results are similar to those for Years 1 and 2 (Table 1). However, the data volume (n) that met the 1-m search criteria is significantly lower. We attribute this to the sampling rate (Table 1) and a ~24-hour 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 datasets is the result of uncorrelated errors in the datasets 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 datasets (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 (Bar-Sever et al., 1998); this is in part because of the separation in space (< 500 m) and time (<15 min) between the two survey vehicles. To assess the magnitude of such errors in the Year 3 dataset, we compared data collected along the same leg of the traverse for two different days (30 Dec 2019 and 15 Jan 2020). We compared the data from the two different days using the method described above. The difference between GNSS datasets 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 datasets is due to uncorrelated errors, then the error in a single measurement is 6.5 cm. We take the overall uncertainty in any single measurement in the Year 3 dataset to be the quadratic sum of the 4.7-cm error estimated from the spread between the GNSS datasets and this 6.5-cm uncertainty, or 8.0 cm.

The analysis of the Year 2 GNSS data (Brunt et al., 2019b) also included an assessment of correlated errors using data along the same leg of the traverse, separated by 13 days (28 December 2018 and 10 January 2019). The median difference between GNSS datasets from the two different days was 3.9 ± 4.6 cm (n = 12,444). The magnitude of this median difference divided by the square root of 2 gives an estimate of the correlated errors in the data from each day. For Year 2, that estimate was (3.9 cm / √2) 2.8 cm, for Year 3 it was (3.3 cm/ √2) 2.3 cm, and the RMS of the two is 2.5 cm, which we take to be a reasonable estimate of the correlated error in our GNSS data.

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 two 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 comparisons presented below use Years 2 and 3.

The comparisons between the 88S Traverse heights and the altimeters over the Antarctic Ice Sheet are fairly consistent (Table 2, Figure 1). ATL06 heights have better than ±3 cm biases and better than ±7 cm surface measurement precisions (1-σ standard deviations). ATM heights have better than 10 cm biases and better than ±10 cm surface measurement precisions. Differences are larger for CryoSat-2, with -21-cm biases for baseline C and 44-cm precisions. The results for Baseline D are further degraded, which have an additional 20 cm of bias, relative to Baseline C. Finally, the density of results on the right side of Figure 1, after 1 July 2019, is lower and related to the lower sampling rate of the Year 3 GNSS data.

Altimetry	GNSS	bias ± precision (cm)	N	radius (m)
88S				
ATL06, Spot 1	88S Year 2, 3	-1.59 ± 6.66	1062	20
ATL06, Spot 2	88S Year 2, 3	-0.58 ± 6.52	1106	20
ATL06, Spot 3	88S Year 2, 3	2.14 ± 5.88	1787	20
ATL06, Spot 4	88S Year 2, 3	1.62 ± 6.52	1741	20
ATL06, Spot 5	88S Year 2, 3	1.74 ± 5.84	1309	20
ATL06, Spot 6	88S Year 2, 3	2.86 ± 6.42	1230	20
CryoSat-2, C	88S Year 2, 3	-21.65 ± 43.54	5873	90
CryoSat-2, D	88S Year 3	-45.62 ± 49.57	7423	90
ATM, T6, 12 Nov 2018	88S Year 2	9.23 ± 6.14	202,085	4
ATM, T7, 12 Nov 2018	88S Year 2	8.49 ± 9.54	1540	4
Summit				
ATL06, Spot 3, 25 Nov 2018	Summit, 25 Nov 2018	-4.99 ± 0	1	20
ATL06, Spot 4, 25 Nov 2018	Summit, 25 Nov 2018	-6.19 ± 4.36	5	20
ATL06, Spot 3, 25 May 2019	Summit, 25 May 2019	-2.14 ± 5.88	1	20
ATL06, Spot 3, 22 Feb 2020	Summit, 22 Feb 2020	-3.28 ± 0	2	20
ATL06, Spot 4, 22 Feb 2020	Summit, 22 Feb 2020	-0.97 ± 2.15	2	20
CryoSat-2, D, 22 Dec 2018	Summit, 16 Jan 2019	-18.11 ± 12.59	2	90
ATM, T6, 12 May 2019	Summit, 17 May 2019	7.44 ± 3.48	1936	4
ATM, T7, 12 May 2019	Summit, 17 May 2019	2.60 ± 3.52	766	4

Table 2. Results for altimetry comparisons with the 88S (top) and Summit (bottom) GNSS data. Comparisons represent (altimetry – GNSS); thus, positive values represent altimetry heights that are above the GNSS surface. All Summit ATL06 data are from RGT #879.

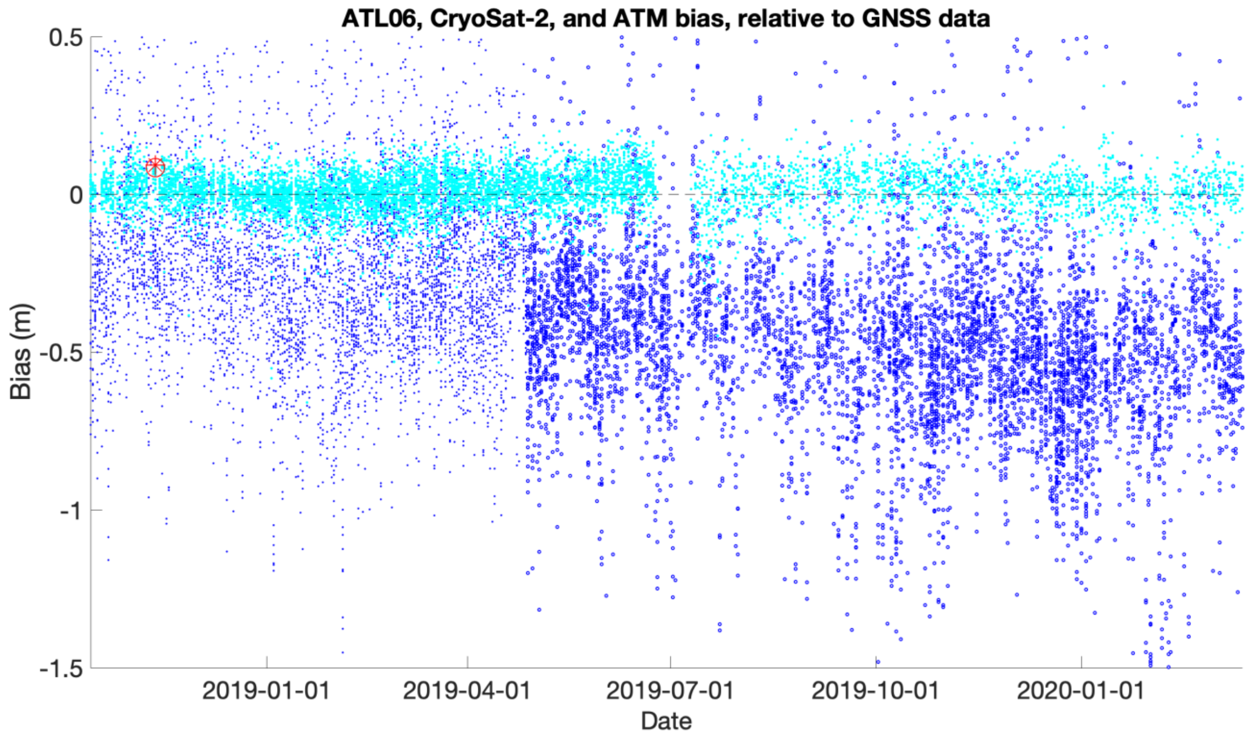

Figure 1. Bias results (in m) for ATL06 (cyan, all spots), CryoSat-2 (blue; '.' are Baseline C; 'o' are Baseline D), and ATM (red; '*' is T6; 'o' is T7) relative to the 88S Traverse data (Year 2, before 1 Jul 2020 and Year 3, after 1 Jul 2020).

The Summit Traverse comparisons for the altimeters are consistent (Table 2) with the Antarctic results. ATM has better than 8 cm height biases and better than ±4 cm surface measurement precisions. ATL06 has better than -7 cm height biases. CryoSat-2 differences are again larger, with nearly 20 cm of bias. However, we note the limited number *N* of the ATL06 and CryoSat-2 height postings for a given satellite – GNSS crossover. We maintained the stringent search criteria requirement ($n > 30$), which ultimately limited the total number of crossover comparisons that were made; in many cases this limited our results to cases where only 1 satellite altimetry posting per crossover met these stringent criteria.

Results for ATL06 heights straddle the GNSS surface in Antarctica, ranging from 2.86 to -1.59 cm; we calculated a single ATL06 bias relative to 88S of 0.83 cm, weighted based on the errors of each spot (or the square of the 1-σ standard deviation, divided by the square root of the number of crossovers (*N*) for each spot from Table 1). Results are slightly lower than the GNSS surface in Greenland, ranging from -0.97 to -6.19 cm. ATM results are consistent in both hemispheres, with results from both hemispheres being <10 cm above the GNSS surface. CryoSat-2 is the outlier, with the results from both hemispheres being significantly (>20 cm) below the GNSS surface.

5 Discussion

The traverse GNSS data used for the altimetry comparisons are internally consistent and have low errors. Based on results on the right side of Figure 1, future 88S surveys will sample at 2 Hz, similar to Years 1 and 2. The 88S Traverses have errors of 5.6 cm (Year 2; Brunt et al., 2019b) and 8.0 cm (Year 3); the Summit Traverse has 0.9 cm of bias and 5.7 cm precision.

The surfaces assessed here are the low-slope ice-sheet interiors, where geolocation errors are minimized. The ice sheets are also bright reflectors, 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 months of on-orbit data. The results are consistent with results from the early mission (Brunt et al., 2019b). For both assessments, spots 1 and 2 are slightly below the GNSS surface, while spots 3 through 6 are slightly above the GNSS surface. Future releases of ATL06 will focus on the reduction of these biases. However, ATL06 is more accurate and precise than any prior altimetric product even with the inclusion of spots 1 and 2 (Table 2).

The Summit Traverse is relatively small in scale, but these results are intended to augment the Antarctic results, by providing altimetry validation in the opposite hemisphere. For ATM and CryoSat-2, the bias results at Summit confirm the 88S results. For ATL06, the biases are of the same, relatively small magnitude as in the Antarctic, but of the opposite sign. We note that for both satellite altimeters, these results are based on very few crossovers that meet the stringent search and rejection criteria. However, it is critical to maintain continuity with respect to assessing the altimetric footprints in both hemispheres. For ATM, the number of crossovers that meet this stringent search and rejection criteria is high and the biases for ATM (both T6 and T7) are consistent for both hemispheres and consistent with Brunt et al. (2017).

Results for CryoSat-2 are the outliers. The biases range from -18 to -46 cm, below the GNSS reference surface. These differences are likely due to radar signal penetration into the firn layer (Rémy and Parouty, 2009); specifically they are likely due to the much higher sub-surface volume- 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 within Antarctica and a smaller region within Greenland. Determining the sensitivity of each method to individual sources of bias will help reconcile the differences between independent estimates of ice mass balance (McMillan et al., 2014; Shepherd et al., 2019).

6 Conclusions

The GNSS data collected on the flat interiors of the Antarctic and Greenland ice sheets 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 all three altimeters provide a large statistical population and show that ATL06 heights are the most accurate and precise assessed here, with better than ±3 cm biases and better than ±7 cm surface measurement precisions. ATM is also very precise, and has biases less than 10 cm. CryoSat-2 is the outlier with biases greater than 20 cm. The Summit Traverse is shorter in distance but is an unmatched GNSS time series on an ice sheet. Results at Summit are based on a smaller population size; however, they support the results from 88S and provide results in the opposite hemisphere. The sample population at Summit will get larger with time, with more satellite overpasses, making this a more valuable dataset in the mission years to come.

Acknowledgments and Data

Funding was provided by the NASA ICESat-2 Project Science Office. We thank the National Science Foundation Office of Polar Programs for logistical support for both the Arctic and Antarctic traverses. We thank the 88S Traverse teams, the Summit Station Science Technicians, and the numerous personnel with the U.S. Antarctic Program for survey support. We thank NSIDC for ICESat-2 data distribution.

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

References

Arthern, R., Wingham, D., & Ridout, A. (2001). Controls on ERS altimeter measurements over ice sheets: Footprint-scale topography, backscatter fluctuations, and the dependence of microwave penetration depth on satellite orientation. Journal of Geophysical Research: Atmospheres 106(D24), 33471–33484. https://doi.org/10.1029/2001JD000498

Bamber, J., Westaway, R., Marzeion, B., & Wouters, B. (2018). The land ice contribution to sea level during the satellite era. Environmental Research Letters, 13(6), 63008. https://doi.org/10.1088/1748-9326/aac2f0

Bisnath, S. & Gao, Y. (2009). Current state of precise point positioning and future prospects and limitations, in: Observing our changing Earth, Springer Berlin Heidelberg, 615–623.

Brunt, K., Hawley, R., Lutz, E., Studinger, M., Sonntag, J., Hofton, M., et al. (2017). Assessment of NASA airborne laser altimetry data using ground-based GPS data near Summit Station, Greenland. The Cryosphere, 11(2), 681–692. https://doi.org/10.5194/tc-11-681-2017

Brunt, K., Neumann, T., & Larsen, C. (2019a). Assessment of altimetry using ground-based GPS data from the 88S Traverse, Antarctica, in support of ICESat-2. The Cryosphere, 13(2), 570–590. https://doi.org/10.5194/tc-13-579-2019

Brunt, K., Neumann, T., & Smith, B. (2019b). Assessment of ICESat-2 ice-sheet surface heights, based on comparisons over the interior of the Antarctic ice sheet. Geophysical Research Letters, 46(22), 13,072–13,078. doi:10.1029/2019GL084886

Fricker, H., Borsa, A., Minster, B., Carabajal, C., Quinn, K., & Bills, B. (2005). Assessment of ICESat performance at the salar de Uyuni, Bolivia. Geophysical Research Letters, 32(21). https://doi.org/10.1029/2005GL023423

Hawley, R., Neumann, T., Stevens, C., Brunt, K., & Sutterley, T. (in review). Greenland Ice Sheet Elevation Change: Direct Observation of Process and Attribution at Summit. Geophysical Research Letters.

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., et al. (2002). Aircraft laser altimetry measurement of elevation changes of the Greenland ice sheet: Technique and accuracy assessment, Journal of Geodynamics., 34, 357–376. https://doi.org/10.1016/S0264-3707(02)00040-6

Magruder, L., Brunt, K., & Alonzo, M. (in review). ICESat-2 geolocation accuracy validation using ground-based corner cube retro-reflectors. IEEE Transactions on Geoscience and Remote Sensing.

Magruder, L., Brunt, K., Neumann, T., Klotz, B., & Alonzo, M. (submitted). Passive ground-based optical techniques for monitoring the on-orbit ICESat-2 geolocation and footprint diameter. Earth and Space Science.

Markus, T., Neumann, T., Martino, A., Abdalati, W., Brunt, K., Csatho, B., et al. (2017). The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): Science requirements, concept, and implementation. Remote Sensing of Environment, 190, 260–273. https://doi.org/10.1016/j.rse.2016.12.029

Martin, C., Krabill, W., Manizade, S., & Russell, R. (2012). Airborne Topographic Mapper Calibration Procedures and Accuracy Assessment, NASA Technical Memorandum 2012-215891.

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., et al. (2014). Increased ice losses from Antarctica detected by CryoSat-2. Geophysical Research Letters, 41(11), 3899–3905. https://doi.org/10.1002/2014GL060111

Meloni, M., Bouffard, J., Parrinello, T., Dawson, G., Garnier, F., Helm, V., et al. (2020). CryoSat Ice Baseline-D validation and evolutions. The Cryosphere, 14, 1889–1907. https://doi.org/10.5194/tc-14-1889-2020

Neumann, T. A., Martino, A. J., Markus, T., Bae, S., Bock, M. R., Brenner, A. C., et al. (2019). The Ice, Cloud, and Land Elevation Satellite-2 Mission: A global geolocated photon product. Remote Sensing of Environment, 233, 111325. https://doi.org/10.1016/j.rse.2019.111325

Rémy, F., & Parouty, S. (2009). Antarctic ice sheet and radar altimetry: A review. Remote Sensing, 1(4), 1212–1239. https://doi.org/10.3390/rs1041212

Shepherd, A., Ivins, E., A, G., Barletta, V., Bentley, M., Bettadpur, S., et al. (2012). A reconciled estimate of ice-sheet mass balance. Science, 338(6111), 1183–1189. https://doi.org/10.1126/science.1228102

Shepherd, A., Gilbert, L., Muir, A., Konrad, H., McMillan, M., Slater, T., et al. (2019). Trends in Antarctic Ice Sheet elevation and mass. Geophysical Research Letters, 46(14), 8174–8183. https://doi.org/10.1029/2019GL082182

Siegfried, M., Hawley, R., & Burkhart, J. (2011). High-resolution ground-based GPS measurements show intercampaign bias in ICESat elevation data near Summit, Greenland. IEEE Transactions on Geoscience and Remote Sensing, 49(9), 3393–3400. https://doi.org/10.1109/TGRS.2011.2127483

Slater, T., Shepherd, A., McMillan, M., Muir, A., Gilbert, L., Hogg, A. et al. (2018). A new digital elevation model of Antarctica derived from CryoSat-2 altimetry. The Cryosphere, 12(4), 1551–1562. https://doi.org/10.5194/tc-12-1551-2018

Smith, B., Fricker, H. A., Gardner, A. S., Medley, B., Nilsson, J., Paolo, F., et al. (2020). Pervasive ice sheet mass loss driven by competing ocean and atmosphere processes. Science, 368(6496), 1239–1242. doi:10.1126/science.aaz5845

Smith, B., Fricker, H. A., Holschuh, N., Gardner, A. S., Adusumilli, S., Brunt, K. M., et al. (2019). Land ice height-retrieval algorithms for NASA's ICESat-2 photon-counting laser altimeter. Remote Sensing of Environment, 233, 111352. https://doi.org/10.1016/j.rse.2019.111352

Smith, B., Gardner, A., Schneider, A., & Flanner, M. (2018). Modeling biases in laser altimetry measurements caused by scattering of green light in snow. Remote Sensing of the Environment, 215, 398–410. https://doi.org/10.1016/j.rse.2018.06.012

Wingham, D., Francis, C., Baker, S., Bouzinac, C., Cullen, R., de Chateau-Thierry, P., Laxon, S., et al. (2006). CryoSat: a mission to determine the fluctuations in Earth’s land and marine ice fields. Advances in Space Research, 37, 841–871. https://doi.org/10.1016/j.asr.2005.07.027

Figure1.

ATL06, CryoSat-2, and ATM bias, relative to GNSS data
0.5
0
-0.5
-1
-1.5
Bias (m)
2019-01-01
2019-04-01
2019-07-01
2019-10-01
2020-01-01
Date