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Key Points:
- We present a first assessment of the quality of the surface height and total freeboards from the ICESat-2 mission
- Correlations between the airborne and IS-2 height profiles and roughness are quite remarkable, >0.95 and >0.97, respectively
- Total freeboards in 10-km segment, calculated using three different approaches, show variability of 0.02 to 0.04 m

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ICESat-2 Surface Height and Sea Ice Freeboard Assessed With ATM Lidar Acquisitions From Operation IceBridge

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Abstract Surface height and total freeboard from the Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2, IS-2) sea ice data products (ATL07/ATL10) are assessed with near-coincident retrievals from the Airborne Topographic Mapper (ATM) lidar in four dedicated underflights during the 2019 Operation IceBridge Arctic deployment. Over a mix of seasonal and older ice, we find remarkable correlations between the ATM and IS-2 height profiles and roughness (in ninety-nine 10-km segments) that averages to >0.95 and > 0.97, respectively. Regression slopes near unity, between 0.93 and 0.99, indicate close agreement of the height estimates. Larger differences between the surface heights are seen in rougher areas where it is more difficult for the photon heights (used in IS-2 surface finding) to capture the surface distributions at short length scales. Total freeboard in 10-km segments, calculated using three different approaches, show variability of 0.02 to 0.04 m. Sources of residual variance, attributable to differences between the two instruments, are discussed.

Plain Language Summary NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) was launched in September of 2018. For sea ice, the topic of focus here, the lidar instrument onboard ICESat-2 is tasked to measure surface height and freeboard—the vertical height of the floating snow and ice above the sea surface—which will be used to estimate the thickness the Arctic and Southern Ocean ice covers. One of the first steps in the scientific use of data collected by any new satellite mission is an evaluation of data quality from the instrument. In this paper, we compare the ICESat-2 sea ice data with airborne measurements from Operation IceBridge taken in April of 2019. Operation IceBridge is a NASA airborne mission that has collected data over sea ice since 2009 and served as a bridge between the first ICESat and the new ICESat-2. For validation of the sea ice data, the airborne platform was tasked to fly the same satellite ground tracks. In our comparisons, we find the quality of the satellite surface height and freeboards to be high: the airborne and satellite data are in agreement with each other. These results will serve as a baseline for evaluation and improvements of future releases of the ICESat-2 data set.

1. Introduction

NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) was launched in September of 2018. This mission is specifically designed to provide accurate surface heights for understanding changes in the cryosphere, ocean, and vegetated surfaces (Markus et al., 2017). For sea ice, the Advanced Topographic Laser Altimeter System (*ATLAS*) onboard ICESat-2 (IS-2) is tasked to provide measurements of sea ice elevation for retrieval of freeboard—the vertical height of the floating snow and ice above the sea surface—and subsequently to estimate the thickness of the Arctic and Southern Ocean ice covers. The time-varying thickness distribution of sea ice is not only an important indicator of how the polar oceans are responding to a warming climate but also useful in the forecasting/projections of future changes, and for supporting logistics and operations in the polar regions.

IS-2 employs a multibeam photon counting lidar for profiling the surface, and this mode of altimetry imparts unique characteristics on the retrieved elevations compared to traditional waveform altimetry. In particular, for the IS-2 sea ice products, a fixed 150-photon aggregate is used in surface finding to control height precision and for improved along-track resolution over high reflectance surfaces (Kwok et al., 2019; Kwok et al., 2019). Using these fixed-count aggregates, quasi-specular returns in openings as narrow as ~27 m, crucial for freeboard calculations, can be resolved. As a consequence, the surface finding approach provides variable along-track resolutions and nonuniform sampling of the surface (27 to 200 m in the strong beams) that needs to be accounted for in the interpretation and assessment of the data, as in the analysis below.

At the time of this writing, the IS-2 project has released to the community a suite of IS-2 data products, which spans the period between 14 October 2018 and 2 May 2019. This suite includes two sea ice products of the ice-covered polar oceans: one containing surface heights (ATL07) and the other total freeboards (snow + ice, ATL10). As part of the IS-2 calibration/validation effort for assessment of data quality and verification of the retrieval algorithms, airborne underflights of the IS-2 ATLAS lidar tracks were conducted as part of Operation IceBridge (OIB; Koenig et al., 2010). In April 2019, four dedicated underflights were conducted during OIB to obtain near-coincident coverage of the IS-2 lidar tracks. In this note, we present the results from a comparison of the IS-2 surface height and freeboards with those obtained by the Airborne Topographic Mapper (ATM) lidar system. The aim is to provide a first assessment of the sea ice products and for the results to serve as a guide to the data quality of these early IS-2 products for science investigations. The next section describes the data sets used and the strategy used to obtain coincident time-space coverage for assessment. The comparisons of surface heights and freeboards are shown in sections 3 and 4. The last section concludes this paper.

2. Data Description

In this section, we describe the OIB ATM and IS-2 ATLAS data sets used in our analysis, and the special considerations addressed in the airborne lidar acquisitions to capture near-coincident coverage of IS-2 beams that are crucial in the following analysis.

2.1. ICESat-2 Along-Track Products

IS-2 employs three beam pairs to profile the surface; the pairs are separated by about 3.3-km cross track with intrapair spacings of 90 m. Each pair consists of a strong and a weak beam, and the pulse energies of the strong beams are ~4 times that of the weak. Each beam profiles the surface at a pulse repetition rate of 10 kHz. At orbital velocities, individual laser footprints of ~17 m (in diameter) are separated by ~0.7 m. A more detailed description of the IS-2 mission and lidar system can be found in Markus et al. (2017) and Neumann et al. (2019). For sea ice, along-track heights and freeboards are derived for individual beams. Here, we use Release 001 of the sea ice retrievals provided in two along-track IS-2 products: ATL07 and ATL10 (Kwok, Cunningham, et al., 2019). ATL07 contains surface heights derived from ATLAS (photon counting lidar) and ATL10 contains total (snow + ice) freeboards derived from the surface heights. Retrieved heights in ATL07 and ATL10 are referenced to the WGS84 ellipsoid. In ATL07, the mean sea surface and the following time-variable geophysical contributions to the sea surface heights have been removed: ocean tides, solid earth tides, ocean loading, solid earth pole tides, inverted barometer effect. The total freeboards in ATL10 are calculated only in 10-km segments that contain a sea surface reference and the spatial resolution of individual estimates (~27 to 200 m) is similar to that of the height profiles in ATL07; that is, freeboards are not calculated everywhere.

2.2. ATM Lidar

The ATM is a conical-scanning lidar system that provides surface profiling swaths at off-nadir scan angles of 15° or 2.5°. Both a wide-scan and narrow-scan ATM were operated on the 2019 OIB Arctic flights. The lidar uses a laser wavelength of 532 nm (identical to ATLAS on ICESat-2), and profiles the surface (since 2017) with a 10-kHz pulse repetition frequency, 1.3-ns pulse width (comparable to 1.5 ns for ATLAS), and a scan rate of ~20 Hz. Per-sample height accuracy is ~7 to 10 cm. For a more detailed description of ATM data, the reader is referred to the following publications: Studinger (2018), Martin et al. (2012), Brunt et al. (2017), and Brunt et al. (2019). Nominally, the system is operated at a flight altitude of 500 m where the wide-scan system provides a cross-track swath of ~260 m full width. For the underflights, this nominal altitude is modified as described below.

2.3. Airborne Sampling Strategy

Successful acquisitions of coincident surface profiles for evaluation of IS-2 data quality are affected by two factors that are difficult to control: (1) uncertainties in the location of the ground tracks of the two instruments (i.e., ATM and IS-2) and (2) ice drift. In the collection of the OIB data sets, these factors were mitigated as follows. First, the altitude of the IceBridge airborne platform (P-3) was doubled (to ~1,000 m) to obtain a wider ATM swath (~520 m) to maximize the likelihood of capturing the IS-2 profiling tracks in the presence of ice drift and to reduce the impact of uncertainties in the predicted locations of the IS-2 and ATM tracks. At this altitude, the size of the lidar footprints is ~2 m in diameter. Second, to minimize the effect of ice drift, flights were designed such that there is near-zero time lag between the IS-2 overpass and arrival of the P-3 at the lidar ground track. Lastly, the four dedicated airborne underflights were conducted in an area north and west of Ellesmere Island where the sea ice is thicker and less mobile than in the thinner parts of the Arctic Ocean.

Two of the four OIB flight days included three overlapping racetracks (with long/short dimension ~200/3.3 km) to increase the cross-track coverage, as well as to sample height profiles from ATLAS Beam 1 and Beam 3 along the two legs of the flight (Figure 1a: middle panel). Beams 1 and 3 are two of the strong beams (higher transmitted laser energy) of the three strong-weak beam pairs of ATLAS that are separated by ~3.3 km. Only two strong beams were surveyed because of the higher resolution of the strong beams and due to limitations in available flight hours . The racetracks were offset cross track from each other to produce a 10% overlap of the ATM swaths to accommodate cross-track ice drift (not shown in the figure). The remaining two flights were straight-line flight segments. The four OIB flights (~8 hr each) were flown on 8, 12, 19, and 22 April corresponding to four IS-2 passes (Reference Ground Tracks, RGT: 157, 218, 325, and 371) during the Arctic campaign in 2019. Near-zero time lag (less than 1 min) was achieved in three of the four flights and a lag of ~38 min was achieved during the last flight. These data sets were processed for rapid delivery (using rapid service GPS satellite ephemerides, and with incomplete refinement of instrument parameters) possibly resulting in slightly degraded absolute height accuracy from the nominal. In the following comparisons, the focus is on precision and freeboard and not absolute height accuracy.

3. Comparison of Surface Heights

First, we describe the procedure used to construct ATM height profiles that are registered to the along-track IS-2 profiles. Second, the regression results between the two surface profiles are discussed. Third, the freeboards are compared. The quality of IS-2 surface profiles and freeboards are assessed using samples in 10-km segments; this is the length used in freeboard calculations in ATL10 products.

3.1. Coregistration of ATM and ICESat-2 profiles

The ATM and IS-2 height samples are not expected to be exactly coregistered on the surface due to ice drift and uncertainties in the predicted locations of the two altimeters. Here, coregistration of the 10-km surface height profiles from the two instruments are refined by maximizing the correlation between the IS-2 height samples (in ATL07) and candidate ATM height profiles at the IS-2 sample locations. Candidate height profiles from the ATM data are constructed by shifting IS-2 sample locations (in 10-km segments) by small increments (by 0.5 m in along-track and cross-track directions). At each shift increment, weighted averages of the ATM heights within each IS-2 segment are computed. Since the spatial resolution of the surface heights in ATL07 vary along track, so do the number of ATM samples that go into constructing an equivalent IS-2 height estimate. Segment lengths (L_s) of the strong beams vary between ~27 and 200 m. With an IS-2 lidar footprint diameter of 17 m, the dimension of a resolution cell (or segment) is $17 \times L_s$ m. To produce the proper weighting of the ATM samples into the IS-2 segment, the IS-2 footprint is modeled as a Gaussian with a full width of 17 m. After the correlation process, we expect the registration of the data to be slightly better than the resolution of the ATM instrument (~2 m), assuming of course there is no ice deformation within that 10-km segment.

3.2. Comparison of Surface Heights From ATM and IS-2 in 10-km Segments

For the comparisons here, the IS-2 heights are regressed against the ATM heights and the regression parameters (slope, correlation, and standard error) are used as measures of quality; that is, ATM profiles are considered to be the reference data set. If the height correspondence were perfect then the regression slope and correlation would be unity, and standard error would be 0. At this time, we do not expect the regression intercepts to be 0 because residual biases are expected as the absolute altimetric IS-2 heights are not fully calibrated in the data release used here. For the current IS-2 release (Release 001), the absolute height accuracy of individual photons is ~40 cm, and this is expected to improve in future releases. Hence, the focus is on profiling precision rather than absolute height accuracy.

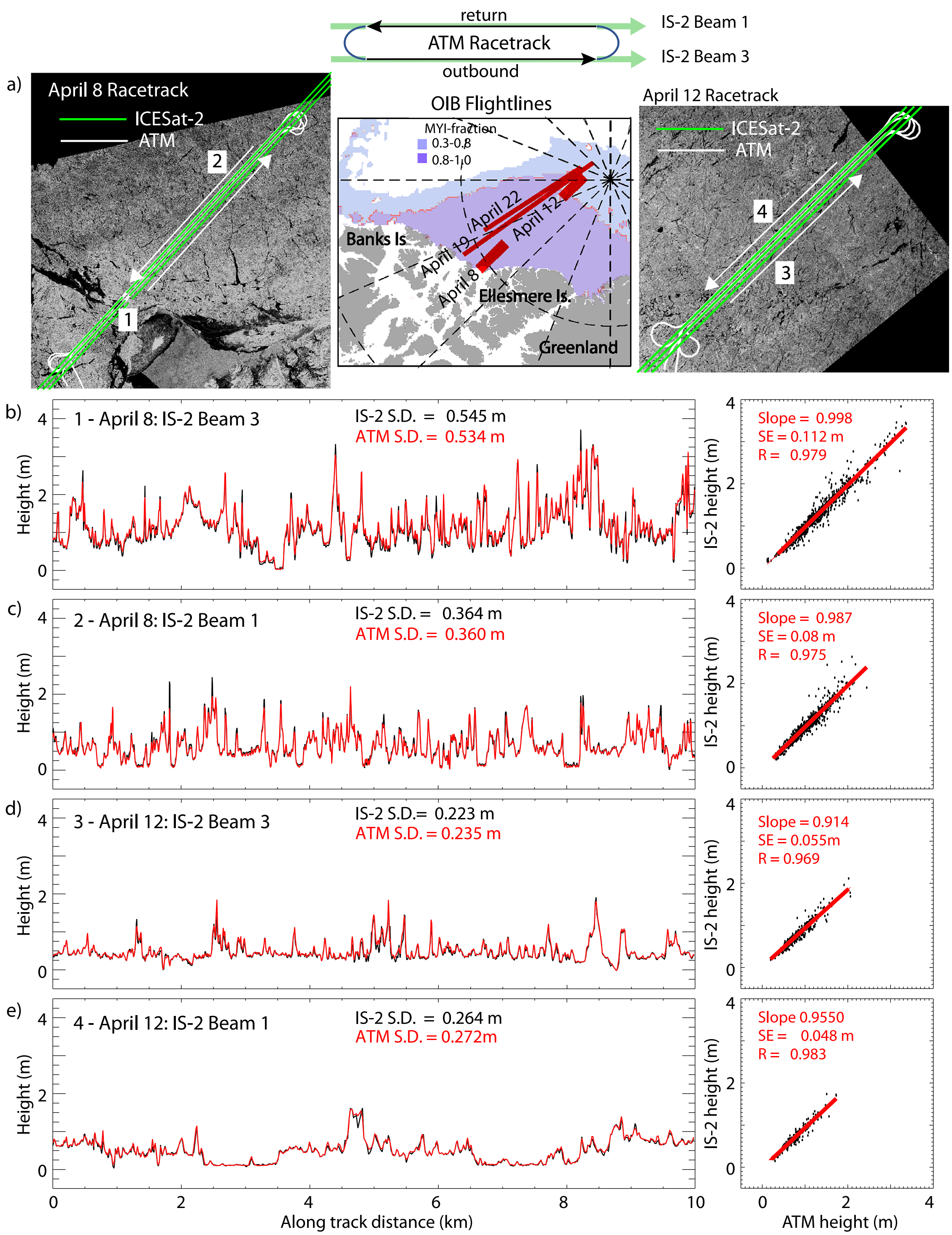

Figure 1. Comparison of IS-2 and ATM surface heights in 10-km segments. (a) Location of the four OIB flight tracks (middle panel) and with the two racetracks (8 April: left panel; 12 April: right panel) overlaid on synthetic aperture radar imagery. (b–e) Along-track surface profiles (10-km segments) and scatterplots with regression results (slope, correlation, and standard error) for four sample segments along the flight tracks on 8 and 12 April (Copernicus Sentinel Imagery 2019, processed by ESA, archived at the Alaska Satellite Facility). ATM = Airborne Topographic Mapper; OIB = Operation IceBridge; ICESat-2 = Ice, Cloud, and Land Elevation Satellite-2.

For all four OIB flight days, the winds were extremely light and with the near-zero time lag between the ATM and IS-2 at the beginning of airborne data acquisitions, wind-driven ice drift was not a significant issue. Only minor adjustments (tens of meters) were needed to coregister the two height profiles using the approach described earlier. On the racetrack days, the IS-2 tracks GT2L (Beam 3) and GT1L (Beam 1) were captured within the ATM swath in the first racetrack flown as ice drift was small. Similarly, GT2L (Beam 3) was captured in the straight-line flights on 19/22 April. However, we are not aware of observations that would allow us to assess the impact of any fine-scale ice motion and deformation along the near-coincident ATM and IS-2 height profiles. Below, we discuss the results from the racetracks and the straight-line days separately.

3.2.1. Racetracks—8 April (RGT 157) and 12 April (RGT 218)

The racetrack OIB flight on 8 April, centered ~100 km north of the Sverdrup Islands (80.5°N, Figure 1a: left panel) sampled some of the thicker and more deformed ice in the Arctic Ocean. Surface height profiles from IS-2 and ATM, for two locations (1 and 2) along the racetracks are compared in Figures 1b and 1c. In these profiles, the heights extend to >3.5 m above the lowest point (an indication of freeboard). Correlation between the height profiles are quite remarkable (>0.97 in both cases), and the regression slopes are near unity (~0.99). It can also be seen that scatter between the height samples are lower near the surface (below 1.5 m) compared to those containing deformed features (>1.5 m) within the IS-2 segments; this will be discussed further below.

Figure 2a summarizes the results from the regression analysis of seventeen 10-km segments (spanning 170 km) for each of the outbound and return legs of the racetrack, sampling Beams 3 and 1, respectively. The correlations with ATM heights were high and near identical for both IS-2 Beams (0.97 ± 0.01), with regression slopes that are near unity (0.98 ± 0.02 and 0.99 ± 0.02). And since the heights are correlated so are the height standard deviations $\left(\sigma_h^{10km}\right)$, which are between 0.98 and 0.99. In this region of relatively rougher ice, σ_h^{10km} are up to 0.6 m compared to the relatively smoother areas $\left(\sigma_h^{10km} \sim 0.22\ m\right)$ sampled on 12 April (Figure 2b). As seen in the plots, the standard error is also correlated to σ_h^{10km}.

Racetrack on 12 April (centered at 86.5°N; Figure 1a: right panel) was flown in the central Arctic in a region with thinner seasonal and second-year ice. Figure 2b summarizes the regression results. Except for smoother ice here, the results are relatively similar to those from 8 April with consistently high correlations (0.95 ± 0.03 and 0.95 ± 0.04), although slightly reduced compared to 8 April, and regression slopes close to unity (0.95 ± 0.03 and 0.94 ± 0.04) for both the outbound and return legs. This set of racetrack comparisons also suggest consistency in the behavior of the two IS-2 beams sampled.

3.2.2. Straight-Line Segments—19 April (RGT 325) and 22 April (RGT 371)

These two flight lines (locations shown in Figure 1a: middle panel) were flown to the west of the second racetrack (on 12 April); these are located in areas of thinner seasonal and second-year ice $\left(\sigma_h^{10km} = 0.28\ m\right)$. The regression results are summarized in Figures 2c and 2d. Again, the results are consistent with those from 8 and 12 April with correlations (0.97 ± 0.01 and 0.96 ± 0.01) and regression slopes close to unity (0.95 ± 0.03 and 0.93 ± 0.04). For both flights, the height standard deviations $\left(\sigma_h^{10km}\right)$ are also highly correlated (0.97 and 0.98).

3.2.3. Residual Variance and Regression Slope

While the correlations are high between the IS-2 height samples and those simulated by aggregating higher-resolution ATM heights, it is worth noting some of the potential sources of variability that could contribute to the residuals in our assessments. These sources of variability include the following: (1) Scan gaps in the ATM samples: The ATM spots may not cover the entire height segment footprint in the IS-2 sea ice products; (2) Registration error: It is expected that the two height profiles are not exactly aligned (spatially) with our registration approach—even though wind-driven ice drift is small, there could be ice deformation forced by far-field internal stress; (3) Surface finding: The IS-2 sea ice surface finding algorithm uses a fixed number of photons (150) and that number may not be sufficient for sampling a broad height distribution (i.e., ridge population within a resolution segment) and thus may explain the regression slopes that are somewhat lower than unity; and (4) ATLAS footprint: the 17-m footprint used here is based on prelaunch measurements and our knowledge will improve with ongoing calibration effort. This list is by no means exhaustive but includes only those uncertainties that could be introduced during the processing and analysis of these data. Also, of note is that differences in observational geometry (i.e., nadir [IS-2] vs. off-nadir [ATM] scattering), especially over deformed features, may

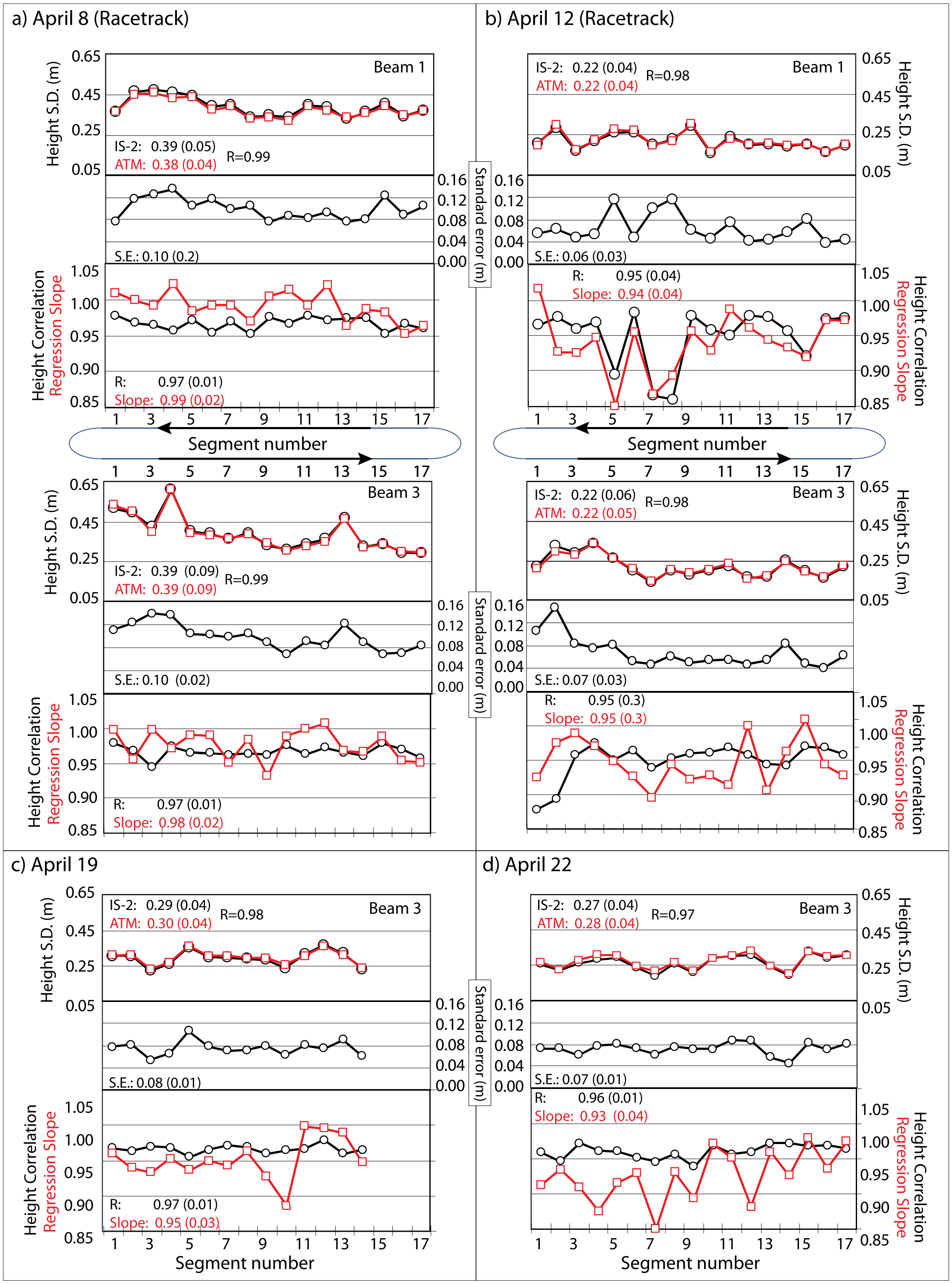

Figure 2. Summary of regression results and standard deviation of IS-2 and ATM heights within 10-km segments from the four OIB underflights. (a) Racetrack on 8 April. (b) Racetrack on 12, (c) 19, and (d) 22 April. On the racetrack days, the outbound legs (right pointing arrow; bottom panels) sampled IS-2 Beam-3 and the return legs (left pointing arrows; top panels) sampled Beam 1. Numerical values in each panel summarizes the mean, standard deviation (in brackets), and correlations of the 17 along-track segments, which spans 170 km. ATM = Airborne Topographic Mapper; IS-2 = Ice, Cloud, and Land Elevation Satellite-2.

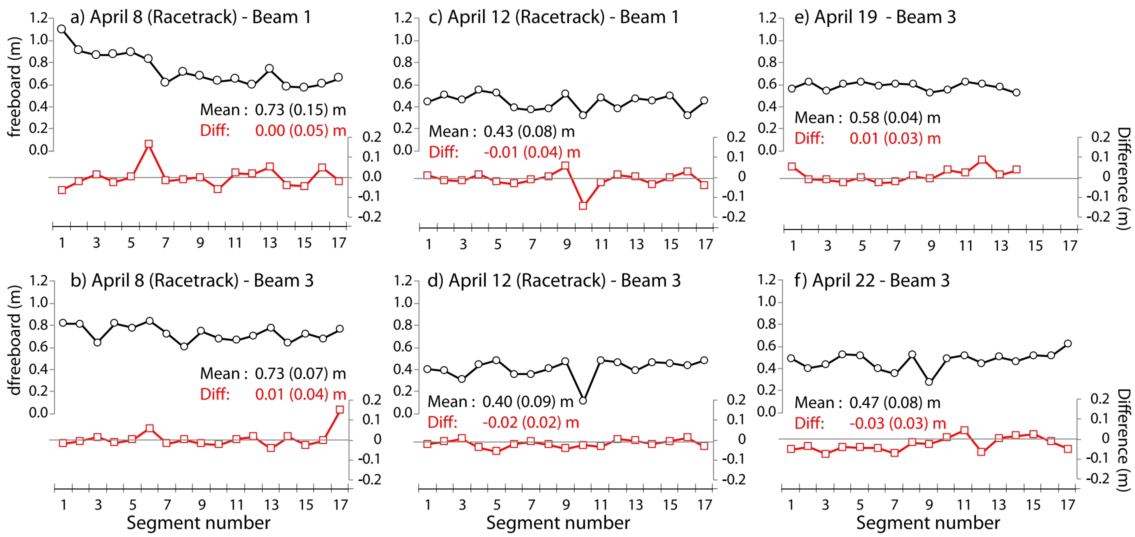

Figure 3. Differences in total "freeboard" in 10-km segments. (a) Racetrack: 8 April. (b) Racetrack: 12 April. (c) Outbound transect: 19 April. (d) Outbound transect: 22 April. For these calculations, the lowest height in the Ice, Cloud, and Land Elevation Satellite-2 profile within each 10-km segment is selected as the reference height for freeboard calculations. And, similarly, the lowest height in the Airborne Topographic Mapper segment. The results from two other approaches are discussed in the text and presented in Table 1.

introduce variability in altimetric heights. Any of these factors would lead to decorrelation of the two surface profiles.

At the centimeter level height differences (at the 10-km length scale) seen here, a true measure of the IS-2 data quality is more difficult to estimate as the uncertainties of the height estimates of the two data sets become comparable.

3.2.3.1. Comparison of Freeboards

Even though the extremely light winds during these flights and the more compact ice cover along these flight lines were ideal for acquiring coincident sea ice data sets, these conditions were not conducive to ice deformation or open water production (i.e., leads) required for computing freeboard. In fact, very few leads were available in both data sets for freeboard calculations. Here, we determine the local sea surface heights used to calculate freeboard using three approaches: (1) Using the lowest surface height within each 10-km IS-2 segment; and the lowest ATM height in the corresponding segment; (2) using the average height of the sea surface samples identified in the IS-2 ATL07 product, and the corresponding height samples in the ATM profile; and (3) IS-2 and ATM freeboards are calculated independently: The IS-2 freeboards are based on the average height of sea surface samples in the ATL07 product, while the ATM freeboards are based on the average heights in openings identified in optical imagery (CAMBOT) (Studinger, 2018) registered to the ATM height samples.

3.2.3.2. Freeboard Differences Using the First Approach

Freeboard is calculated using the location of the lowest height in the IS-2 profile (assuming that IS-2 sea surface is correctly located) as the sea surface reference, and for ATM, the lowest height in the registered 10-km segment. This tells us how close the lowest ATM height is to the lowest height in the IS-2 profile—a test of the coregistration process. The results are shown in Figure 3 and summarized in Table 1. If the selected heights of the reference surfaces were different, it could be seen in the mean differences between the calculated freeboards. Over the ninety-nine 10-km segments the difference is 0.00 ± 0.04 m. This is an indication that the profiles are relatively well aligned and that freeboards relative to the location of the lowest sample in the IS-2 profile is small. Thus, if we selected the lowest height to be the reference level, the differences in freeboard would be 0.00 ± 0.04 m. This method, however, does not give us an indication of how well open leads are identified in the two profiles.

3.2.3.3. Freeboard Differences Using the Second Approach

In this approach, we use the IS-2 sea surface samples and the ATM heights at corresponding IS-2 sea surface locations to calculate the height reference for the two profiles, respectively. As discussed earlier, the more compact ice cover during these flight days restricted the number of 10-km segments from 99 to 17. Using

Table 1
Freeboard and Freeboard Differences in 10-km Segments Calculated Using Three Different Reference Surfaces

Flight date/Beam	Number of 10-km segments	Freeboard (m)	Freeboard Differences (IS-2 − ATM) (m)
Lowest levels in IS-2 and ATM[a]			
April-08/Beam 3	17	0.73 ± 0.07	0.01 ± 0.04
April-08/Beam 1	17	0.73 ± 0.15	0.00 ± 0.05
April-12/Beam 3	17	0.40 ± 0.09	−0.02 ± 0.02
April-12/Beam 1	17	0.43 ± 0.08	−0.01 ± 0.04
April-19/Beam 3	14	0.58 ± 0.04	0.01 ± 0.03
April-22/Beam 3	17	0.47 ± 0.08	−0.03 ± 0.04
IS-2 sea surface locations[b]			
April-12/Beam 3	3	0.49 ± 0.02	0.01 ± 0.04
April-12/Beam 1	6	0.36 ± 0.13	−0.03 ± 0.01
April-19/Beam 3	3	0.58 ± 0.03	0.05 ± 0.03
April-22/Beam 3	5	0.47 ± 0.08	−0.03 ± 0.03
Independent IS-2 and ATM levels[c]			
April-12/Beam 1	2	0.39 ± 0.06	−0.04 ± 0.02
April-22/Beam 3	2	0.45 ± 0.08	−0.03 ± 0.03

Note. ATM = Airborne Topographic Mapper; IS-2 = Ice, Cloud, and Land Elevation Satellite-2.
[a]Total IS-2 freeboards in the IS-2 10-km segments are calculated using the lowest surface height within that IS-2 segment. And, similarly, total ATM freeboards are calculated using the lowest surface height in that ATM segment. [b]The average height of the sea surface samples identified in the IS-2 ATL07 product is used as the reference height for freeboard calculations. Similar to (a), the average ATM heights at corresponding locations in the ATM profile is used as the reference height. [c]The IS-2 and ATM freeboards are calculated independently, the IS-2 freeboards based on the average height of sea surface samples in the ATL07 product. The ATM freeboards are based on the average heights in openings identified in optical imagery (CAMBOT) registered to the ATM swath.

this approach, we find the differences to be 0.00 ± 0.03 m (for the 17 10-km segments with IS-2 sea surface samples). Assuming that the IS-2 sea surface samples are correctly identified, then the two IS-2 and ATM freeboards can be said to be relatively unbiased with a standard deviation of 0.03 m.

3.2.3.4. Freeboard Differences Using the Third Approach

Of the seventeen 10-km segments with IS-2 sea surface reference, there were only five segments where we were able to clearly identify openings (leads) in the ATM-CAMBOT imagery (i.e., camera data registered to the ATM swath) that are of sufficient size for calculation of sea surface height in the ATM data. Whereas the IS-2 sea surface samples are located along the IS-2 track, the ATM reference heights are based on samples designated as open water based on image intensity; the resulting classifications are also checked visually. For both the 12 (Beam 3) and 22 (Beam 3) April, the Sun elevation angles (8° and 12° for the 2 days) were low resulting in poor image contrast that led to fairly low-quality classifications of the image pixels; these were confirmed by visual inspections. For the 2 days, the differences between the freeboards were (also see Table 1): −0.04 ± 0.02 and − 0.03 ± 0.03 m, respectively.

3.2.3.5. Remarks on Freeboard Calculations

Even with the limited number of segments and the lower than desired image quality, the differences suggest that all three approaches seem to provide consistent results. As mentioned earlier, at the centimeter level freeboard differences (at the 10-km length scale) seen here, a true measure of the IS-2 freeboard quality becomes more difficult as the uncertainties of the two data sets can be comparable.

4. Conclusions

In this note, we provide a first assessment of the surface height and freeboard estimates in the two sea ice products (ATL07/ATL10) from the IS-2 mission. The sea ice data were compared to near-coincident ATM data acquired by four dedicated airborne underflights during the 2019 OIB Arctic deployment. The results of this work serve as an early guide to data quality for sea ice investigations. Here, we highlight some of these early results:

- Favorable conditions—light winds and near-zero time lag, consequently low wind-driven ice drift, between airborne underflight and satellite overpass—provided for an excellent coincident airborne ATM data set for assessment of the IS-2 surface height and freeboards.
- We find remarkable correlations between the two height profiles (in ninety-nine 10-km segments). For the four OIB flights, the average correlation over six 170-km flight segments ranges between 0.95 and 0.97.

Average regression slopes were near unity, between 0.93 and 0.99. Standard deviation in heights along 10-km segments are correlated to better than 0.97.

- Larger differences between the surface heights are seen in rougher sea ice areas, where it is more difficult for the photon counting system to capture the variability in surface height distribution at short length scales.
- Total freeboards in 10-km segments, calculated using three different approaches, show variability of 0.02 to 0.05 m.
- There are no observable differences in the quality of ATLAS Beam-1 and Beam 3.
- With centimeter level differences in height and freeboard (at the 10-km length scale) between the airborne and spaceborne data sets, a true measure of the IS-2 data quality is more difficult to obtain as the uncertainties of the height and freeboard estimates of the two data sets are comparable.
- This is an evaluation of the first release of the IS-2 data, and it is expected that the data quality will improve with each subsequent release as we incorporate our understanding and a more detailed characterization of the photon counting system into the processing of the sea ice data.

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