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Surface height and sea ice freeboard of the Arctic Ocean from ICESat-2:

Characteristics and early results

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Key Points

- We present the first winter season of surface height and sea ice freeboards of the Arctic Ocean from the new ICESat-2 mission.
- The six photon counting beams on ICESat-2 provide high resolution (to 27 m) and high precision surface (~ 2 cm) profiles of the ice cover.
- Retrieval approaches and key features of the sea ice products, and the evolution of freeboards over the past winter season are discussed.

Plain Language Summary

NASA's Ice, Cloud, and Land Elevation Satellite (ICESat-2) was launched in September of 2018. This mission is specifically designed to measure accurate surface heights for understanding changes in ice sheets, sea ice, ocean circulation, and vegetation biomass. For sea ice, the topic of focus here, the instrument onboard is tasked to measure freeboard— the vertical height of the floating ice above the sea surface – which will be used to estimate the thickness of the Arctic and Southern Ocean ice covers. Sea ice thickness is not only an important indicator of how the polar oceans are responding to a warming climate, but also useful for forecasting of future changes and for supporting logistics and operations in the polar regions. ICESat-2 employs a special kind of lidar for this mission: an altimeter that measures surface height based on accurate roundtrip timing of transmitted photons and individual photons reflected from the surface and provides fine details of the surface relief. The sea ice products from ICESat-2 takes on some unique and special characteristics compared to traditional approaches to measure surface height from space. This paper describes these key features and early results from the ICESat-2 mission.

Abstract

We present the first winter season of surface height and sea ice freeboards of the Arctic Ocean from the new ICESat-2 (IS-2) mission. The Advanced Topographic Laser Altimeter System (ATLAS) onboard has six photon-counting beams for surface profiling with a 10-kHz pulse-rate (inter-pulse distance ~ 0.7 m) and footprints of ~ 17 m. Geolocated heights assigned to individual photons scattered from the surface allow significant flexibility in the construction of height distributions used in surface finding. For IS-2 sea ice products, a fixed 150-photon aggregate is used to control height precision and obtain better along-track resolution over high reflectance surfaces. Quasi-specular returns in openings as narrow as ~ 27 m, crucial for freeboard calculations, are resolved. The fixed photon aggregate results in unique variable along-track resolutions and non-uniform sampling ($17\text{ m} \times 27\text{ m}$ to $17\text{ m} \times 200\text{ m}$

for the strong beams) of the surface. The six profiling beams – three pairs separated by 3.3 km with a strong and weak beam in each pair – provide correlated statistics at regional length scales for assessment of beam-to-beam retrieval consistency and accuracy. Analysis shows along-track height precisions of ~ 2 cm, and agreement in the monthly freeboard distributions across the strong beams to 1-2cm. In this paper, we describe briefly the approaches used in surface height and freeboard retrievals from ATLAS photon clouds, and detail the key features of these along-track sea ice products, focusing on the first release of data collected over the Arctic Ocean, which spans the period between October 14, 2018 – the start of data collection – and the end of March 2019.

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1 Introduction

NASA's Ice, Cloud, and Land Elevation Satellite (ICESat-2) was launched in September of 2018. The altimetry from this orbiting observatory serves to address science requirements that pertain to the monitoring of changes in ice sheets, sea ice, ocean circulation, and vegetation biomass (Markus et al., 2017). Combining data from the ICESat-2 (IS-2) mission with existing and forthcoming altimetry missions will add to a valuable multi-decadal record of elevation changes over different surfaces for understanding geophysical processes, climate change and for forecasts and projections of future climate. The routine collection of IS-2 science data began on October 14, 2018, approximately one month after launch. At this writing, there are more than seven months of data covering the Arctic and Southern Oceans. This paper aims to provide a description and an early assessment of the sea ice products of the Arctic Ocean from IS-2.

IS-2 is NASA's second-generation spaceborne lidar mission that uses a new technique for surface profiling. The Advanced Topographic Laser Altimeter System (ATLAS) (at 532 nm) onboard the IS-2 observatory employs a unique photon-counting approach (Degnan, 2002) that uses a low pulse-energy laser (at 532 nm) in a six-beam configuration for improved cross-track sampling and profiling sensitivity with reduced power demands on the satellite platform (Markus et al., 2017). On the ground, three beam-pairs trace tracks separated by about 3.3 km cross-track with intra-pair spacings of 90 m. Each pair consists of a strong and a weak beam, with the pulse energies of the strong beams that are ~4 times those of the weak. For range determination, sensitive photon detectors allow accurate roundtrip timing of transmitted photons and individual photons scattered from the surface. 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; this can be compared with the 167 m spacing between non-overlapping ICESat footprints of ~50-70 m in diameter (Zwally et al., 2002). The multiple IS-2 beams address the need for unambiguous separation of elevation changes from those induced by ice sheet local surface slopes, and are not a specific sea ice requirement. The ATLAS instrument on IS-2 provides multiple surface profiles with higher spatial resolution than preceding and current spaceborne altimeters.

For sea ice, the capability to obtain high-resolution samples (tens of meters) with vertical precision of less than a few centimeters is critical for obtaining local sea level in narrow openings within the ice cover for freeboard determination and for subsequent conversion to thickness estimates. This was demonstrated in previous studies using data from airborne campaigns equipped with photon counting lidars (e.g., Kwok et al., 2014; Farrell et al., 2015). The smaller footprint, higher precision, and pulse repetition rate selected for ATLAS stem from lessons learned from the use of ICESat data (lower resolution and sample spacing) for freeboard retrieval. In addition, photon-counting altimetry offers the opportunity for adaptive sampling of the surface at length scales that are more suitable for resolving the sea surface in narrow leads. Spatial resolution is key as the height accuracy of the local sea surface could easily be contaminated by adjacent ice surfaces with higher surface reflectance.

The focus of this paper is on the two along-track sea ice products (surface heights and total freeboards) from the IS-2 mission. We note at the outset that these are early results and the paper does not provide an exhaustive or comprehensive examination of the two sea ice products. There are many aspects of data quality, some of which will only be revealed by assessment with data acquired and processed by dedicated airborne campaigns (e.g., NASA's Operation IceBridge, AWI's IceBird), other satellite altimetry missions (e.g., CryoSat-2, Sentinel 3A/B), upcoming field programs (e.g., MOSAiC), and when a longer IS-2 time series becomes available. Also, the intent of the paper is not to describe the retrieval algorithms in detail (they have been published elsewhere: Kwok et al. (2014); Kwok et al. (2016)) but to provide an early assessment of the sea ice/surface heights and freeboard estimates derived from the photon-counting altimeter on IS-2. Even though the physical basis for surface altimetry is similar to analog waveform approaches, the emphasis here is on the additional considerations in the use of multi-beam surface heights and ancillary information from this data set, and the capability of this new instrument.

The paper is organized as follows. Section 2 describes the two IS-2 sea ice products (heights and freeboards) and other data sets used. A brief description of the height and freeboard retrieval algorithms can be found in Section 3. Sections 4 and 5 discuss the features and characteristics of the surface heights and freeboards of the along-track products from IS-2. Section 6 shows the time series of freeboard distributions for the period discussed here. The last section concludes the paper.

2 Data description

Here, we describe the convention used to identify the ATLAS beams and associated ground tracks, the two ICESat-2 along-track sea ice height and sea ice freeboard products (identified as ATL07 and ATL10) addressed in this paper, and other data sets used in our analysis. These ICESat-2 data products are provided in the Hierarchical Data Format – version 5 (HDF-5) format available through the NASA Snow and Ice Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC - <https://nsidc.org/data/icesat-2>). We note that all the parameters discussed, except for the summary statistics, here are available in the IS-2 data products.

2.1 ICESat-2, ATLAS beams and ground tracks

The ICESat-2 observatory was inserted into a 91-day exact repeat orbit with an inclination of 92° , allowing mapping to 88° latitude in both the northern and southern hemispheres. For every repeat cycle, there are 1387 orbits and corresponding spacecraft ground tracks referred to as Reference Ground Tracks (RGTs). The locations of the six beams are defined relative to these RGTs. Controlled pointing to the RGTs (with an expected uncertainty of ± 45 m) began in late March of 2019.

Figure 1a shows the six along-track surface profiles of the six ATLAS beams. Labeling of the ground tracks (GT) traced by the footprint pattern of the six beams follows the convention below (also see Figure 1). The six tracks formed by consecutive lidar footprints are defined from left to right relative to the direction of travel (ground track GT1L, GT1R, GT2L, GT2R, GT3L, and GT3R). The RGT is centered between GT2L and GT2R. Since the IS-2 observatory is re-oriented approximately twice per year to maximize sun illumination on the solar arrays, the ATLAS beams – with reference frame fixed to the observatory – are not always associated with a given ground track (e.g., GT1L is not always Beam 1). When ATLAS is in the forward orientation (Figure 1b), the ground tracks 1L, 2L, and 3L are sampled by the weak beams are on the left side of the beam pair. With the current setting (Energy level 4), the transmitted energy (per pulse) of the strong and weak beams are $\sim 139 \mu\text{J}$ and $\sim 34 \mu\text{J}$, respectively. Because of the arrangement of the rectangular beam array on ATLAS (Markus et al., 2017), the weak and strong beams are pitched relative to each other such that the weak beams lead the strong beams by ~ 2.5 km. When ATLAS is in the

backward orientation (Figure 1c), the relative positions of weak and strong beams are swapped and the strong beams lead the weak beams, which are then on the left side of the ground track pairs.

2.2 Surface heights (ATL07)

The ATL07 product contains profiles of sea surface/sea ice heights and surface type of individual height segments along each of the six ground tracks (Kwok et al., 2019b). Individual ATL07 height estimates are derived from height distributions constructed using 150 geolocated photons from the ATLAS Global Geolocated Photon Data product (ATL03) (Neumann et al., 2019); expected uncertainties of the individual photon times of flight are expected to be 1.5 ns (or ~ 0.23 m relative to the WGS84 ellipsoid) in the calibrated ATL03 product. In this first data release (R001) the ATL03 product is not fully calibrated and is expected to have slightly degraded height accuracy of ~ 0.4 m.

The fixed 150 photons used in ATL07 height retrievals results in height segments (L_s) of variable length, which is determined by the number of along-track pulse footprints it takes to aggregate 150 photons used for height estimation (i.e., $L_s = \text{number of pulses} \times \text{interpulse distance}$); and, this length varies with surface reflectance (more on this in Section 3). The inter-pulse distance is ~ 0.7 m. The 150-photon aggregates were selected to provide a height precision of ~ 2 cm over relatively flat surfaces. The length of the strong beam height segments (L_s) varies between ~ 10 m and 200 m, while those from the weak beams are between ~ 40 m and 800 m. To compute the spatial resolution, the dimension of the beam footprint ($f \sim 17$ m) must be added to the segment length ($r_s = L_s + f$). Each height segment is assigned a surface type by a surface classification algorithm (see brief description in Section 3) that identifies the height segments suitable for use as local sea surface reference (sea surface height (SSH) segments) in calculations to derive freeboards in the ATL10 product described below. Sea ice heights are calculated only when the local sea ice concentration is $>15\%$ in the gridded MASIE product (Fetterer et al., 2010).

All heights in ATL07 are referenced to the WGS84 ellipsoid but with the following time-variable geophysical effects removed: ocean tides, solid earth tides, load tides, solid earth pole tides, inverted barometer effect, and the mean sea surface. The models used to provide these corrections can be found in Neumann et al. (2018). Of note is that the heights have been

corrected for an effect referred to as first-photon bias (Neumann et al., 2018) , which is due to the detector characteristic of this type of lidar. First-photon bias refers to a height bias, introduced by the photon-counting detectors, that depends on signal strength. In brief, for a short time (known as the deadtime) after an individual detector channel detects a photon it cannot detect another (i.e., it is dead). In consequence, with a limited number of detectors (16 and 4 for the strong and weak beams, respectively), photons that arrive early from the ground are more likely to be detected than those that arrive later, and hence the mean surface height estimate is biased upwards (i.e., towards the lidar). This effect is largest (up to several centimeters) for strong returns and for returns from flat surfaces (e.g., quasi-specular or mirror-like surfaces) where the return energy is concentrated in a short time duration. This is systematically corrected using the strength of the ground return and tabulated bias values derived using measured ATLAS detector deadtime. These corrections are available in the ATL07 product.

2.3 Sea ice freeboard (ATL10)

The ATL10 product (Kwok et al., 2019b) contains sea ice freeboards with the same along-track resolution as the height profiles in ATL07. That is, individual freeboard heights have the same variable length properties as those height segments (i.e., L_s) in ATL07. In ATL10, freeboards are calculated in 10-km segments only if that segment contains a local sea surface reference. The sea surface reference is the height of the local sea level (h_{ref}) obtained from a collection of sea ice leads (one or more) within that 10-km segment. The 10 km length is selected to minimize the contribution of residual sea surface slopes to uncertainties in freeboard calculations; the general expectation is that the local sea surface height is relatively constant over a length scale corresponding to the first mode baroclinic Rossby radius of deformation, which is on the order of 10 km for polar latitudes above 60° latitude (Chelton et al., 1998). Freeboard heights (h_f), in the 10-km segments, are calculated simply as the difference between the heights (h_s) in ATL07 and the local sea surface reference (i.e., $h_f = h_s - h_{ref}$). Since the residual sea surface slopes in the SSH anomalies (i.e., the mean sea surface has been removed) within a 10-km segment are expected to be small, we use the available lead population to estimate a single sea level estimate over a given segment rather than interpolate the lead heights over 10 kilometers.

At this time, sea level estimates across the beams have not been leveled relative to each other, thus freeboard segments are calculated only for individual beams and there is no dependence on additional sea surface references from the other beams. Also, freeboards are calculated only where the ice concentration >50% and where the height samples are at least 50 km away from the coast; this is to avoid uncertainties in coastal ice concentrations, tidal corrections, and contamination of ocean waves in the marginal ice zone. These are rather restrictive conditions, for controlling data quality, but in future releases we would look into providing freeboard retrievals in coastal zones and in regions of lower ice concentration within the ice margin.

2.4 Sentinel 1A/B data

The synthetic aperture radar (SAR) imagery used here for evaluation of ATL07 is from Sentinel 1A and 1B platforms. The Sentinel-1 system is a two-satellite constellation providing C-Band SAR imagery following the retirement of ESA's ERS-2 and the end of the Envisat mission. The Copernicus data used here was processed by ESA, and archived at the Alaska Satellite Facility.

3 IS-2 sea ice retrieval algorithms

In this section, we describe very briefly the sea ice algorithms used in ATL07 and ATL10. Illustrative examples of retrieved surface heights and freeboards are discussed in the following section. For a more detailed procedural description of these algorithms we refer the reader to Kwok et al. (2014), Kwok et al. (2016) and to the Sea Ice Algorithm Theoretical Basis Document (ATBD) (Kwok et al., 2019a). In particular, the Sea Ice ATBD contains descriptions of the implemented procedures and the parameters used in the derivation of the surface heights and freeboards in ATL07 and ATL10.

3.1 Surface finding

The expected surface return or photon height distribution (Figure 2), $s_e(h)$, is modeled as the convolution of the ATLAS system impulse response with a Gaussian surface height distribution of width w and height h_o (i.e., $G(h; h_o, w)$),

$$s_e(h; h_o, w) = s_i(h) * G(h; h_o, w).$$

Here, $s_i(h)$ is the system impulse response and $*$ is the convolution operator.

To determine the surface height, we find the best match between the received photon distribution, $s_{rec}(h)$, in a field of modeled returns, $s_e(h; h_o, w)$ (i.e., a template matching procedure). The squared difference between $s_{rec}(h)$ and $s_e(h)$ is used as our measure of similarity, viz.

$$e^2(h_o, w) = \frac{1}{N} \sum_N (\tilde{s}_{rec}(h_i) - \tilde{s}_e(h_i; h_o, w))^2$$

$$\sum_N \tilde{s}_{rec}(h_i) = 1 \quad \sum_N \tilde{s}_e(h_i; h_o, w) = 1.$$

The following equation,

$$\{\hat{h}_o, \hat{w}\} = \text{argmin}_{h_o \in [h_1, h_2], w \in [w_1, w_2]} e^2(h_o, w),$$

then provides an estimate of the height ($\hat{h}_o$) and the apparent width ($\hat{w}$) of the surface height distribution. The location $\{\hat{h}_o, \hat{w}\}$ on the surface with the best match is where the argument $e^2(h_o, w)$ attains its minimum value within the domain defined by $h_o \in [h_1, h_2]$ and $w \in [w_1, w_2]$. The two height distributions ($\tilde{s}_e(h)$ and $\tilde{s}_{rec}(h)$) are normalized because *a priori* knowledge of the expected strength (or reflectance) of the surface returns are not available.

Two key parameters that control the quality of the surface finding process are: 1) the number of signal photons used, and, 2) the bin size used to construct the height distribution, $\tilde{s}_{rec}(h)$. For processing ATLAS returns, height distributions ($\tilde{s}_{rec}(h)$) could be constructed using photon heights from a fixed or variable number of pulses. In our surface finding, we use a fixed number of photons accumulated over a variable number of pulses (or aggregates). Over surfaces with lower/higher reflectance, the aggregates will contain photons from a higher/lower number of pulses. This allows the surface finder to control the signal strength (or signal-to-noise ratio) of the constructed height distribution and thus the consistency in the quality of the height retrievals. We use 150-photon aggregates for surface finding to obtain a height retrieval precision of ~ 2 cm over relatively flat surfaces; based on the uncertainty of photon heights.

This is well suited for sea ice surfaces with a broad range of reflectance, where a factor of eight to nine difference – from dark leads to an ice surface that is covered with freshly-fallen snow – is expected. As a result, the length of the height segments and spatial resolution of the height profiles are proportional to signal strength and therefore non-uniform along the

altimeter track (discussed earlier). This variable resolution must be accounted for in the calculation of spatial statistics (discussed in a later section). We note again that the product of the inter-pulse distance (~ 0.7 m) and the number of lidar pulses used to construct a photon aggregate is referred as the length of a height segment (L_s). The bin size is based on the expected precision in individual photon heights and 2.5 cm is selected such that coherent height distributions can be constructed from the photon aggregate (see Figure 2). That is, overly fine binning produces noisy distributions with photon populations distributed over a broad range, while coarser binning blurs details in the distributions.

The surface finding approach described herein assumes an underlying Gaussian distribution of photon heights, where deviations from the modeled distribution are expected to introduce biases in the retrieved height estimates. For an actual sea ice surface, we expect non-Gaussian behavior given that the surface height distributions are sometimes skewed high (i.e., away from the surface) because of deformed ice features (i.e., ridges). But, the need to resolve narrow leads (tens of meters) limits the upper bound in the number of photons that could be used to resolve the higher moments (e.g., skew) in multi-parameter distributions, and this is additionally complicated by an asymmetric ATLAS system impulse response. To compensate for potential biases, ATL07 provides an adjustment of the height estimates from the surface finding procedure. This adjustment is based on the ATLAS impulse response and estimates of the deviation of the height distributions from that of a Gaussian height distribution. The details of this procedure are described in Kwok et al. (2019a).

3.2 Identification of sea surface types

Each height segment in ATL07 is assigned a surface type (dark_lead (smooth), dark_lead (rough), gray ice, snow-covered ice, rough, shadow, specular). These surface types were chosen as they are expected to broadly represent the surfaces encountered over the polar oceans during a typical winter. The primary use of surface types is for determining, together with local height statistics, whether a given height segment is suitable for use as a sea surface height sample in computing freeboards in ATL10. The surface type classifier uses three attributes derived from the photon distribution of a height segment, which are: photon rate (r_{surf}), width of photon distribution (w_s) and background rate (r_{bkg}).

The surface photon rate (photons/shot) is the average number of detected surface photons (photoelectrons) over the number of shots required to construct a 150-photon aggregate. In the absence of clouds, it provides a measure of the brightness or apparent surface reflectance. Low surface rates are typically from water/thin ice in open leads although very high rates at near nadir incidence angles are possible due to specular and quasi-specular returns from smooth open-water/thin ice surfaces. In fact, quasi-specular returns are quite common, and these surfaces are especially useful as large numbers of photons over very short length scales (few shots) are ideal for resolving very narrow leads within the ice cover. Between the two extremes, the surface types are less useful as sea surface references but may be of geophysical interest for the general understanding of surface and cloud conditions. The presence of clouds (atmospheric scattering) tend to reduce the strength of the surface returns because the transmitted or reflected energy are scattered away from the field-of-view of the lidar. The Gaussian width parameter (w_s) provides a measure of the surface roughness and used to partition the height segments within the four ranges of surface photon rates into the different surface types.

Prior to surface finding, background photons are separated from surface photons based on their distance from the primary height distribution (Kwok et al., 2019a); we use only that portion of the distribution between the dashed lines in Figure 2. Any photon event that is not designated as a surface photon is classified as a background photon; these could be associated with noise in the lidar instrument (e.g. stray light, detector dark counts, etc.) or scattered sunlight at the laser wavelength. Specifically, the solar background count rate (B_s) is the solar zenith radiance due to solar energy scattered by the surface or atmosphere, and thus contains reflectance information useful for surface identification. The solar zenith angle varies with latitude, seasonally, and with time of day. For Lambertian surfaces, under clear skies, the surface photon rate is approximately linearly related to the solar background rate. Deviations from a linear relationship are indicative of shadows (cloud shadows or ridge shadows), specular returns, or atmospheric scattering. For example, in the case of quasi-specular returns from a dark lead, the behavior of background vs photon rate is exactly the opposite: that is, while the surface photon rate is high for quasi-specular returns, the solar background rate is very low due to a low reflectance smooth surface. The presence of solar background provides another proxy of surface reflectance and adds to the confidence level of the surface type

classification. The reader is referred to the procedure described in (Kwok et al., 2019a) for further details.

3.3 Calculations of freeboard

Along-track freeboards are calculated in ATL10. As described earlier, freeboard heights (h_f), in consecutive 10-km segments, are calculated as the difference between the heights (h_s) in ATL07 and the local sea surface reference (i.e., $h_f = h_s - h_{ref}$). All available heights from leads, within a 10-km segment, are used to calculate the best estimate of h_{ref} , which is fixed (i.e., not variable) for the entire segment. Freeboards are calculated only when leads are present within a 10-km segment.

4 Surface heights in ATL07

In this section, we show example surface profiles from ATL07 and the potential utility of these data. Section 4.1 describes the key parameters included in two ATL07 height profiles, one with solar background and one without, while subsequent sections show aggregate statistics on the regional and seasonal evolution of these parameters across the Arctic Ocean.

4.1 Two surface profiles from ATL07

Figure 3 shows two surface profiles from ATL07 that are ~30 km in length. These surface profiles (in black) are overlaid on the geolocated photon clouds (extracted from the ATL03 product) from which the heights are retrieved. Individual photons are colored by the average photon rate of that height segment. In these examples, there are relatively flat stretches with low photon rates (blue dots) or low reflectance, likely of thin ice that is yet to be covered by snow. In these dark areas, the segment lengths (blue) are longer because of lower photon rates. Quasi-specular returns, seen at locations where the photon rate spikes (i.e., >10 photons/shot), are from mirror-like surfaces in narrow openings in the ice cover; e.g., at ~3.2 seconds in Figure 3a, and at several locations in Figure 3b (e.g., at 0.3 s, 0.5 s, and 2.8 s, etc.). Returns like these are used as sea surface height references for freeboard calculations. Photon rates (red line) over snow-covered segments are typically very stable at 6 - 10 photons/shot. In the following subsections, we provide more detailed discussions of photon rates, height segment lengths, and spatial resolution.

Also shown in Figure 3 is the corresponding background rate, largely due to reflected solar flux from the surface, measured in Megahertz (i.e., a 1 MHz rate is one million background photons per second; or about 1 background photon per 30 m of vertical height). Background is present in the first example (up to 5 MHz, Figure 3a) and absent in the second example (Figure 3b), since this profile was acquired when the sun is below the horizon. The solar background is, of course, highest during the polar summer and absent during polar night. The presence of background photons increases the spread of the surface photon clouds by 1 – 2 cm (for a 3 MHz rate) (Kwok et al., 2019a), as they occur at random locations, and adds to noise in the surface-finding process.

4.2 Photon rates, aggregates, and length of height segment

Table 1 shows the expected ATLAS photon rates (in number of surface photon returned per shot) from sea ice with different surface reflectance based on prelaunch calculations (Neumann et al., 2019). For the dark surfaces in sea ice leads, the transmitted strong/weak laser energies in ATLAS were designed to obtain returns of ~ 0.2 – 1.0 and ~ 0.05 – 0.2 signal photons per shot in the strong and weak beams respectively. Over snow-covered sea ice, the expectation is ~ 2.3 – 8.5 and ~ 0.6 – 2.1 signal photons per shot for the strong and weak beams (Table 1).

The observed distributions of photon rates at the current ATLAS energy setting (Level 4), seen in the six beams for two winter months (November and December), is shown in Figures 4a and 4b. In the winter, the mean rates in these distributions is dominated by the expected returns from a mixture of snow-covered sea ice with different roughness (i.e., photon rate ~ 6 – 8). The photon rate distribution for the weak beams (GT1L, GT2L, GT3L – dashed lines) are consistently at ~ 1.5 photons/shot. The strong beam photon rate distributions (in GT1R, GT2R, GT3R – solid lines), however, indicate that GT2R (Beam 3) has consistently weaker surface returns (~ 0.81 of GT1R and GT3R): the mean rates from GT1R and GT3R are ~ 6.8 while those from GT2R are ~ 5.5 . This is attributed to the expected variations in the custom construction of the optical component used to split the laser energy into the six beams. These values are consistent with pre-launch expectations.

The 150-photon aggregates used in surface finding, for both the strong and weak beams, is selected to provide a surface precision of better than a few centimeters (see next subsection) over typical surface distributions (i.e., not bimodal and without significant skews).

Figure 2 shows photon height distributions from surfaces with a range of surface roughness. Roughness is measured as the width of the Gaussian (w) used in the surface finding process described earlier. Figure 2a shows the photon height distribution from a relatively flat surface ($w = 0.06$ m), while the Figure 2d shows a distribution from an unusually rough surface ($w = 0.33$ m). The tail of the system impulse response is evident in both Figures 2a and 2b, but is masked by the surface roughness in the height distributions seen in Figures 2c and 2d.

Because a fixed number of photons is used in surface finding, photon rates determine the number of shots, or along-track distance traveled, it takes to construct these 150-photon aggregates. That is, the segment length adapts to changes in photon rates from surfaces of different reflectance: height segment lengths (L_s) are longer when the returns are lower and vice versa. The distributions of height segment lengths for the two winter months are shown in Figures 4c and 4d (strong beams – solid, weak beams – dashed). The mean segment lengths for the strong beams are between 15 and 19 m, and for the weak beams between 60 and 62 m. Segment lengths of the weak beams are approximately 4 times longer than those of the strong beams due to 4 times lower transmitted energy. The extreme segment lengths in both the strong and weak beams are determined by quasi-specular returns from the surface and by leads with very low reflectance. The segment lengths vary between ~10 m and 200 m, and between 40 and 800 m for the strong and weak beams, respectively. The upper bounds in segment length for both beams are controlled by a setting in the surface finding procedure. The upper bound limits the distance over which photon are collected to form the aggregates and serves to reduce the number of noise/background photons accumulated in long distance aggregates.

4.3 Variable segment lengths and spatial statistics

It is important to account for the non-uniform and variable length sampling of height estimates in the calculation of spatial statistics and construction of distributions. For example, the spatial mean ($\bar{h}$) and standard deviation (s) of heights should be calculated as follows:

$$\bar{h} = \frac{\sum_{i=1}^N L_s^i h_s^i}{\sum_{i=1}^N L_s^i} \quad s^2 = \frac{\sum_{i=1}^N L_s^i (h_s^i)^2}{\sum_{i=1}^N L_s^i} - \bar{h}^2 .$$

In these equations, the heights are weighted by the corresponding length of individual height segments (L_s) and N is the number of segments. In the results that follow, all first and second moments are weighted as above.

4.4 Along-track sampling

An additional feature of our procedure for along-track sampling in the ATL07 product is that the height segments overlap with each other. In the IS-2 sea ice surface finding algorithm, the start location of successive 150-photon aggregates is located at the center of the previous height segment such that there is an overlap of at least half the length of that segment in the sampling of the surface profile. Hence, along-track height estimates are not independent because they include photons from an earlier segment. This sampling approach, possible only with photon counting lidars like ATLAS, allows us to maximize the likelihood of acquiring pure lead samples (instead of mixture of lead and ice) in fixed 150-photon aggregates.

4.5 Surface height precision

A common measure of the quality of surface altimetry is precision, which is defined as the repeatability of height measurements over pre-determined length and space scales. For calculation of sea ice freeboard, it is important to maintain precision in altimetric height over the length scale from which freeboards are calculated relative to the local sea level, which in our case is 10 km. That is, a flat surface must remain flat to a few centimeters over that distance. For sea ice, precision in height can be assessed by calculating the standard deviation of height estimates over flat ice or open water surfaces when they are available. In Figure 5, we show the calculated precisions of 1.9 cm and 1.5 cm (height standard deviation) in two relatively flat stretches (3 to 5 km) of sea ice. These long spans of flat ice, though unlikely to be entirely flat, are quite unusual but more common near the ice margin away from the compact ice cover. These values are consistent with pre-launch expectations. Precision over sea ice will be monitored throughout the mission.

4.6 Height profiles and SAR image features

Here, we overlay IS-2 height profiles on near coincident Sentinel imagery to examine the sensitivity of the retrieved heights to surface features (leads and ice floes) in SAR imagery. The spatial resolution of the ScanSAR data used here is ~100 m and is somewhat lower than

the resolution of the IS-2 height profiles. However, the imagery provides a spatial context, along with the vertical dimension from the height profiles, for better albeit qualitative evaluation of the small-scale characteristics of the IS-2 heights.

The two SAR images (Figure 6) are separated from the IS-2 data acquisition time by ~312 and ~72 minutes, respectively. So, it is expected the registration of the surface features are subject to ice drift on the order of several resolution cell (100s of meters) due to the time difference between the images. For both cases, the surface features seem to be registered quite well. This can be seen in the higher surface height associated with small ice floes interspersed within these refrozen leads (examples indicated by yellow arrows), and the edges of the refrozen leads in the images (examples indicated by arrows). The flat areas of low radar backscatter and low IS-2 surface heights in refrozen leads stand out, as discussed above, as good indicators of height precision. Of particular interest is the ability of IS-2 to detect along-track floe dimensions as indicated by horizontal bars (in red) in both figures. If floes size is defined as the distance spanned contiguous samples of raised freeboard heights (defined by a threshold) then the high precision of the IS-2 heights could be potentially useful for estimation of along-track floe dimensions.

5 Total freeboards in ATL10

In this section, we describe the lead statistics that are used to compute total freeboards, freeboard distributions from the strong beams, and expected differences between the strong and weak beams. We note that all of the results shown here are extracted directly from ATL10 products with no additional filtering or outlier removal.

5.1 Spans of open water in leads

Consecutive samples of the local sea surface segments are aggregated into leads in ATL10, and a lead may contain one or more height segments. We refer to the total length of these segments as lead length rather than lead width to distinguish it from our traditionally understood definition of lead width; which is a measure of the shortest distance between the edge of two ice floes. As IS-2 ground tracks cross leads at different angles, these lengths are typically higher than the actual lead widths. Figure 4c shows observed distributions of lead length in the strong and weak beams for all of November and December.

For the strong beams (solid colors), the distributions show modal along-track lead lengths of ~ 27 m with a mean of ~ 72 m and standard deviation of ~ 50 m for two of the strong beams (GT1R-Beam 5 and GT3R-Beam 1). Consistently, the statistics from GT2R (Beam 3) are slightly different; lead lengths are higher due to the lower transmitted laser energy (reminder that lengths are dependent on the distance it takes to construct a 150-photon aggregate). The results show, with ATLAS, we are able to consistently resolve lead lengths around 27 m (specular leads), or the approximate lower bound of leads widths detectable in IS-2 data. This represents a significant improvement over ICESat (spot size of 50-70 m and spot spacing of 167 m).

The distributions of lead length from the weak beams have modal lead lengths between ~ 55 and 57 m, mean lengths between ~ 146 and 160 m, and standard deviations between ~ 58 and 62 m. As expected, these statistics differ from the strong beams; the lengths are higher due to the lower transmit laser energy and hence longer distances over which 150-photon aggregates are collected.

5.2 Freeboard distributions and monthly composites – strong beams

On the surface, the three strong beams are separated from each other by ~ 3.3 km cross-track. We do not expect significant correlations between the profiles of the three strong beams at length scales of kilometers due to the short correlation length scale of deformed features on the ice cover (order of meters), and the high spatial resolution (10's of meters) of the IS-2 height segments. At the basin-scale, however, the freeboard distributions should be similar although the level of statistical variability expected due the sampling differences that result from the cross-track separation of the beams is not clear.

Visual inspection of three gridded monthly-composites (November, January, and March – Figure 7) of the strong beams (1, 3, and 5), show that they are almost indistinguishable from each other. The fields are on a 25-km grid constructed with the segment-length weighting described in Section 4.3 but there is no weighting in time; the displayed fields are smoothed with a 25-km Gaussian kernel. The bottom panels show the similarity in the freeboard distributions for the three months calculated from individual length segments (i.e., not from the gridded fields). The first and second moments of the monthly freeboard distributions of the three strong beams are within a centimeter of each other; a measure of the large scale consistency of the retrieved freeboards.

5.3 Differences between strong and weak beams

We expect differences in the freeboard distributions from the weak and strong beams. First, the height segment lengths of the weak beams are always longer. Second, there are fewer leads (or sea surface references) at the lower limit of the weak beam segment lengths in the Arctic. As discussed earlier, modal lead lengths of ~ 27 m for the strong beam can be compared to ~ 57 m for the weak beam. Hence, we expect a lower density of detected leads in regions with narrow leads, especially in the highly compact ice cover north of Greenland and the Canadian Arctic Archipelago resulting in fewer freeboard estimates over this part of the Arctic Ocean. Unlike the comparison between strong beams, we do not expect the freeboard distributions of the weak beams to be the same as those from strong beams due to this disparity in the sampling of the ice cover.

Figure 8 contrasts the composite freeboard maps and the freeboard distributions for the weak and strong beams for the month of December 2018. It can be seen that the freeboard is lower just north of Greenland and the Canadian Arctic Archipelago (i.e., lower density of thicker freeboard in red/yellow color), which is also evident in the lower population in the tail of the freeboard distribution of the weak beam. The differences in the strong and weak beams between October and March are summarized Table 2. Broadly, the mean freeboard of weak beams is generally lower in by 1-2 cm. Differences in the standard deviation of the freeboards are higher in March (up to 2 cm) likely due to the reduced sampling of the thicker and more deformed ice as discussed. The utility of the weak beams for sea ice studies will be explored in future work.

6 Arctic-wide freeboard (October through March)

In this section, we summarize the seasonal evolution of Arctic Ocean sea ice freeboards (ATL10) in the gridded fields between mid-October of 2018 and March 2019 (Figure 9). The gridded fields are described in Section 5.2. In the, the area of normalized freeboard distribution is scaled by the ratio of the area covered by ATL10 freeboards and the area enclosed by the Arctic Ocean (A_o). Here, we define the Arctic Ocean as the region bounded by the gateways into the Pacific (Bering Strait), the Canadian Arctic Archipelago (CAA), and the Greenland (Fram Strait) and Barents Seas. This scaling allows us to show the relative change as the sea ice expands to cover the Arctic basin during the fall and winter, i.e., area

under the distributions increase until sea ice covers the entire Arctic Ocean. Differences in Figure 9 (bottom panel) show changes in consecutive months.

In the latter half of October (Figure 9, middle panel) the freeboard distribution (solid red line) is distinctly bimodal. The population of the first mode, with peak at ~ 7 cm, consists of young seasonal ice with low freeboards (dark blue in the October composite) characteristic of the advancing ice cover. A secondary peak of higher freeboard (~ 30 cm) is that of older ice that survived the summer at high Arctic latitudes north of Greenland and the CAA.

As the Arctic basin fills in with sea ice, the area under the freeboard distributions increases. In November, this can be seen in the increase in population under the first mode of seasonal ice – the modal freeboard has grown by ~ 1 cm to ~ 8.5 cm from October. Between November and December, there is an observable broadening of the first mode, which suggests the addition of new ice areas to the ice cover as well as the increase in freeboard (associated with snow accumulation and basal ice growth) of that population of seasonal ice that exists in November. After the Arctic Ocean is fully ice-covered, the width of this mode becomes less variable as the coverage of new seasonal ice is expected to be less significant. The difference fields (bottom panel of Figure 9) show consistent month-to-month increases in freeboard.

During the growth season, freeboards are modified by the accumulation and redistribution of snow on the surface, and by the redistribution of ice due to thermodynamic (primarily growth in winter) and dynamic (openings and closings) forcing. These forcings tend to shift the two modes to the right (i.e., in the direction of higher freeboard): the population in the first mode is expected to move faster to the right due to higher basal growth of thinner ice, which is less insulated from the atmosphere than thicker, older ice. This monthly development is evident in the behavior of the observed distributions. The seasonal ice in the first mode, has a peak of 7.5 cm in October and a peak of 20.5 cm in March, while the second mode of older ice has growth less than 10 cm. Later in the growth season, as in February and March, the two modes merge into distributions with a less bimodal character because of the slower growth in freeboards of the second mode.

Also, of geophysical interest is the growth of the tails of the distributions over the six months. The tails are seen to become more pronounced as the winter wears on; at this extreme of the distributions, the changes in freeboard are expected to be dominated by ridging rather than thermodynamic growth. Regionally, this is largely linked to the

convergence of the ice cover north of Greenland and the CAA, which is of particular interest since this area is the source of the thickest ice in the Arctic Ocean.

7 Conclusions

In this paper, we present the first winter season of surface height and sea ice freeboards of the Arctic Ocean from the new ICESat-2 (IS-2) mission. Included is an overview of the sea ice retrieval algorithms and a description of the key features of the high-resolution surface heights (ATL07) and sea ice freeboard (ATL10) in this first release of sea ice products from the IS-2 project. The dataset used here spans a five-and-a-half-month period between October 14, 2018 – the start of data collection – and the end of March 2019. This first release of along-track sea ice data sets from IS-2 are available via the National Snow and Ice Data Center (NSIDC).

ATLAS is the first multi-beam spaceborne photon-counting lidar system and provides higher profiling resolution than preceding and current spaceborne altimeters. The ATLAS laser footprint of ~ 17 m, with an inter-pulse spacing of 0.7 m, represent a significant improvement in the sampling of the sea ice cover when compared to the 167 m spacing between non-overlapping spots of ~ 50 -70 provided by the Geoscience Laser Altimeter System (GLAS) instrument on ICESat. In terms of data quality, analysis shows along-track height precision of ~ 2 cm at length scales of kilometers, which expected based on pre-launch calculation. Below, we highlight the key features, discussed earlier – useful in the analysis of these products – that are associated with the use of fixed 150-photon aggregates in the retrieval of surface heights/freeboards and the available multi-beam profiling of the sea ice cover.

An important consequence of the fixed 150-photon aggregates used in surface finding is that the resolution of individual height samples is proportional to surface reflectance (i.e., photon rate) and therefore varies along the altimeter ground track. This adaptive sampling of the surface, at length scales that are more suitable for the expected narrow widths of sea ice leads, is crucial for freeboard calculations. However, with the large dynamic range in surface reflectance over sea ice (dark lead to snow-covered surface), the resolution can vary by a factor of eight. The variable resolution must be considered in the calculation of spatial

statistics of the sample population (e.g., regional or along-track means and standard deviations).

On the surface, the three strong beams are separated from each other by ~ 3.3 km cross-track and hence we do not expect significant inter-beam correlations at the length scales near the resolution of the height segments. This is due to the short correlation length scale of deformation features (meters) on the ice cover. At larger length scales, however, we expect similarity in freeboard distributions, and the same applies to the weak beams. Thus, multiple beams are useful for providing correlated statistics at large scales for assessing beam-to-beam consistency and accuracy of the retrievals. At the basin-scale, we find the first and second moments of the freeboard distributions to be similar (within a centimeter) because of the near-identical behavior and sampling of the three beams.

Differences in the freeboard distributions from the weak and strong beams are expected due to disparity in the sampling of the ice cover. The weak beams have lower along-track resolution (due to the lower transmit energy) and hence fewer leads (or sea surface references) at the resolution limit of the weak beams. The lower density of leads detected in regions with narrow leads, especially in the highly compact ice cover north of Greenland and the Canadian Arctic Archipelago in mid-winter provides fewer sea surface references for freeboard estimates. Since the weak beams and the beam pairs are designed to address the requirements of ice sheet retrievals, the weak beams may also be of utility for certain sea ice applications..

The evolution of the mixture of Arctic seasonal and old sea ice from the fall into winter is clearly depicted in the monthly freeboard distributions derived from this first winter of IS-2 sea ice products. The month-to-month development of the distinct bimodal freeboard distributions from the fall, with a dominant mode of thin seasonal ice, is consistent with the expectations of the accumulation and redistribution of snow on the surface, and the redistribution of ice due to thermodynamic (primarily growth in winter) and dynamic (openings and closings) forcing.

These are early results and provide a guide to the use of the two IS-2 products and does not provide an exhaustive or comprehensive examination of the either products. There are many aspects of data quality, some of which will only be revealed when assessed with data acquired by dedicated airborne campaigns (e.g., NASA's Operation IceBridge, AWI's

IceBird), other satellite altimetry missions (e.g., CryoSat-2, Sentinel 3A/B), upcoming field programs (e.g., MOSAiC), and when a longer IS-2 time series become available. These assessments will be provided in future studies.

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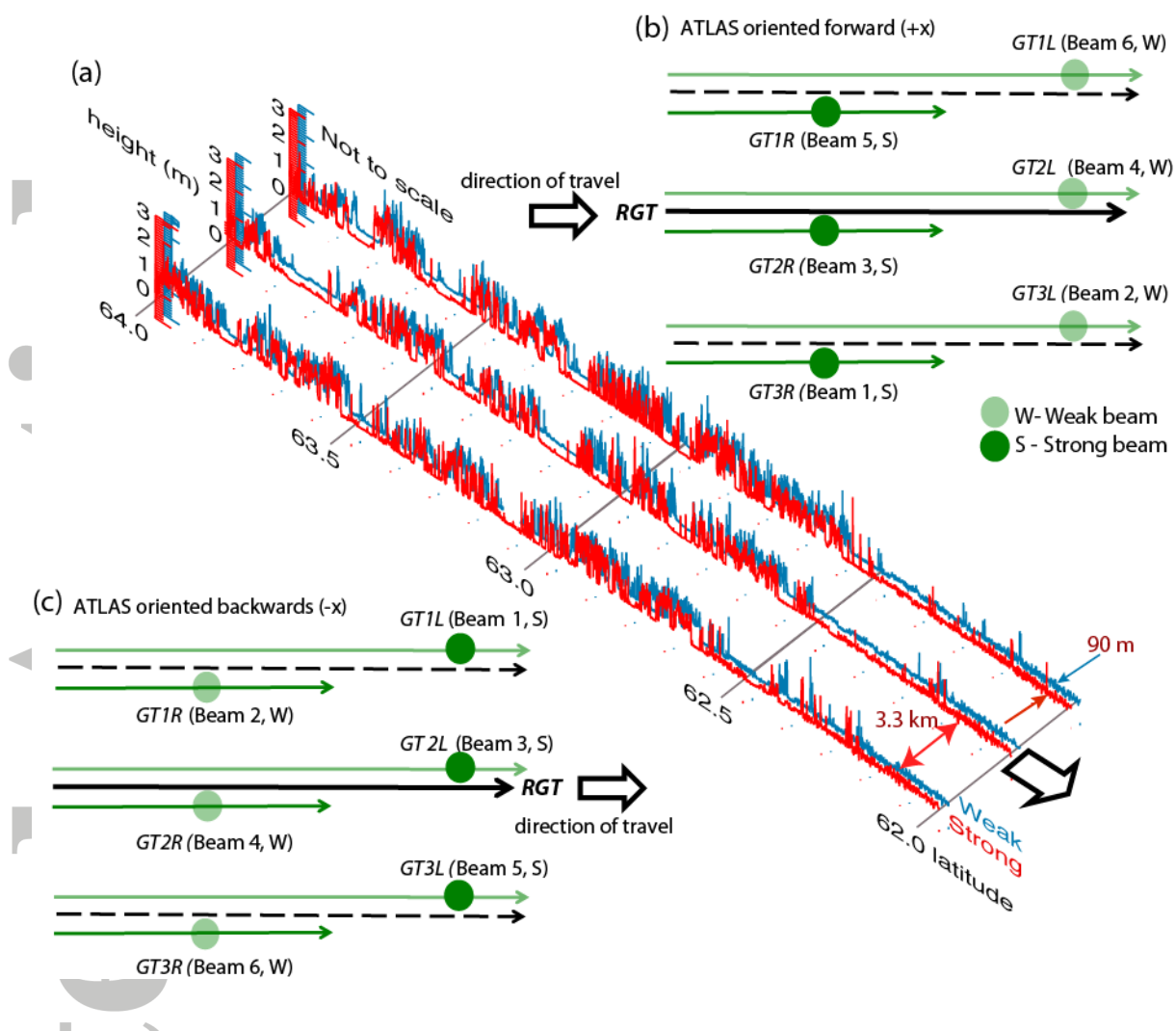


Figure 1. ATLAS beam pattern and ground tracks (GT). (a) Example of surface height profiles over sea ice from the six ATLAS beams. (b) Beam pattern on the ground when ATLAS is traveling in the forward (+x) orientation relative to the ICESat-2 observatory. (c) Beam pattern when ATLAS is traveling in the backwards (-x) orientation. On the surface, the reference ground track (RGT – solid black) is centered between the tracks of pair 2 (i.e., GT2L and GT2R). Left (L) and right (R) are relative to the center of each beam pair (dashed line). Track pairs (GT1, GT2, and GT3) are always numbered from left to right relative to direction of travel while the beam numbers and strength of the beams (W-weak, S- strong), fixed to the ATLAS instrument, do not change with orientation of the observatory. (b) and (c) are adapted from Figure 8 of Neumann et al. (2019).

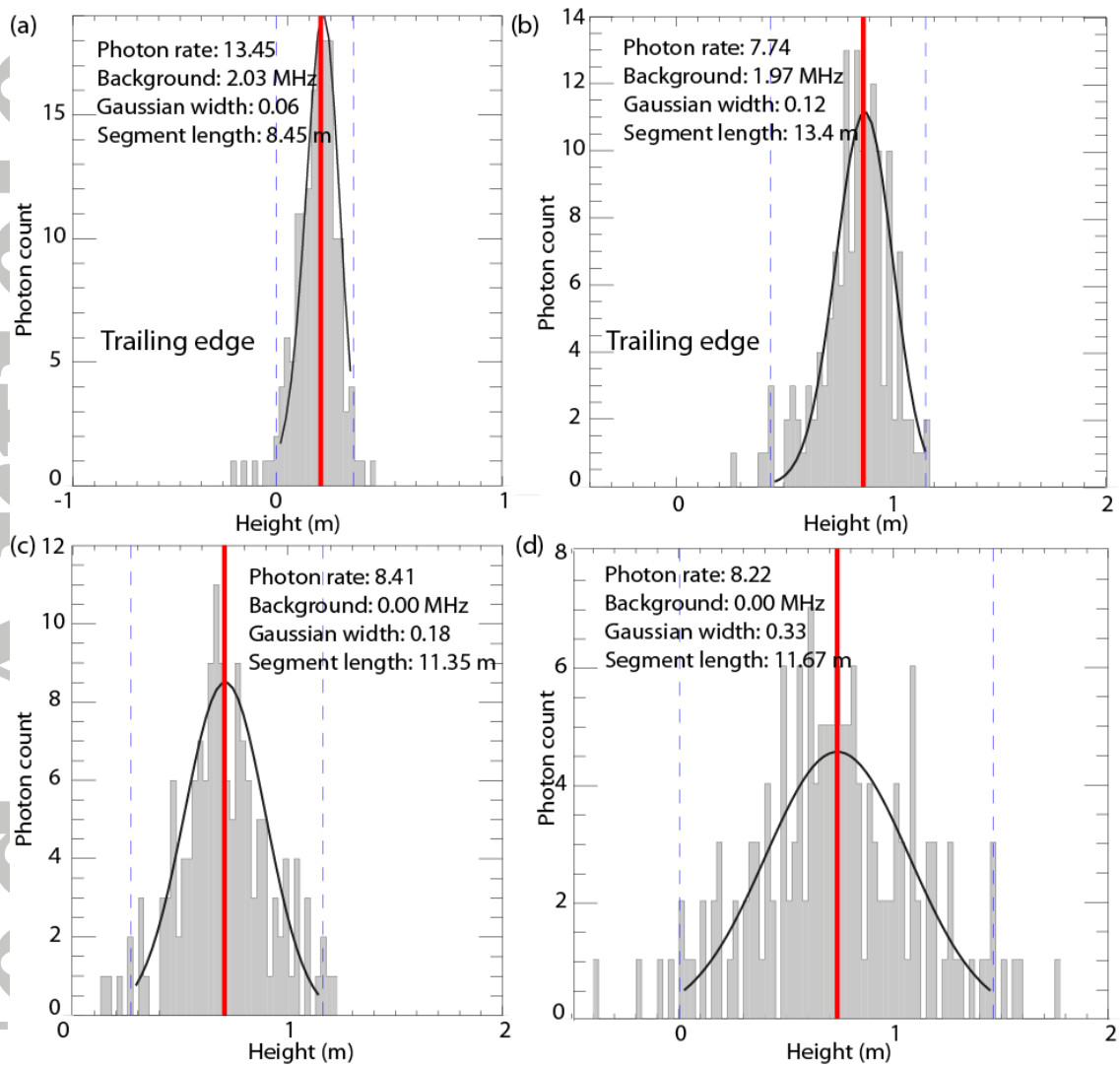


Figure 2. Height distribution of photon clouds (~ 150 photons) from a range of surfaces with different roughness. (a) and (b) show returns from relatively smooth surfaces where the trailing edge of the system response is evident. (c) and (d) show rougher surfaces that masks the shape of the system impulse response. The vertical line (red) is the retrieved surface height from fitting modeled returns (black) to the height distribution (see text for description of surface finding procedure). Dashed lines within each plot delineate that part of the distribution used in surface finding. Photons outside of the dashed lines are designated as background/noise photons. The photon rate (number/shot), the background (MHz), width of the fitted Gaussian (m), and segment length (m) are shown with each height distribution. The returns from (a) and (b) were acquired during the day (with background ~ 2 MHz) while the returns from (c) and (d) were acquired during the night (i.e., near-zero background). Bin size: 2.5 cm.

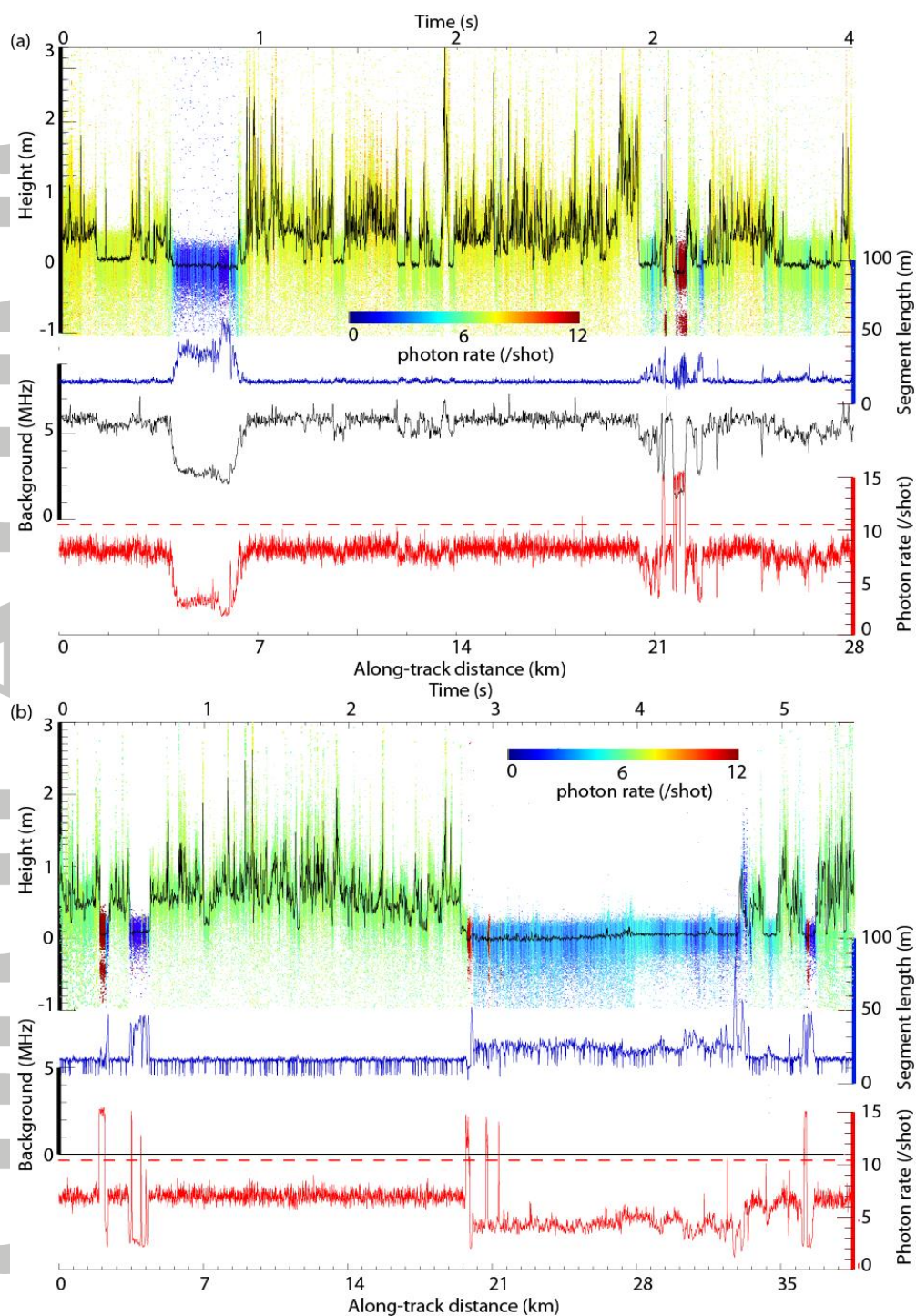


Figure 3. Along track surface height profiles and related parameters from a strong ATLAS beam when solar background is present (a) and absent (b). Each example shows the surface height profile (in black), the associated photon cloud, background rate (blue), photon rate (red). Color of photons in top panel is the average photon rate of a given 150-photon height segment. Surface photon rates above dashed line (red) are designated as specular returns.

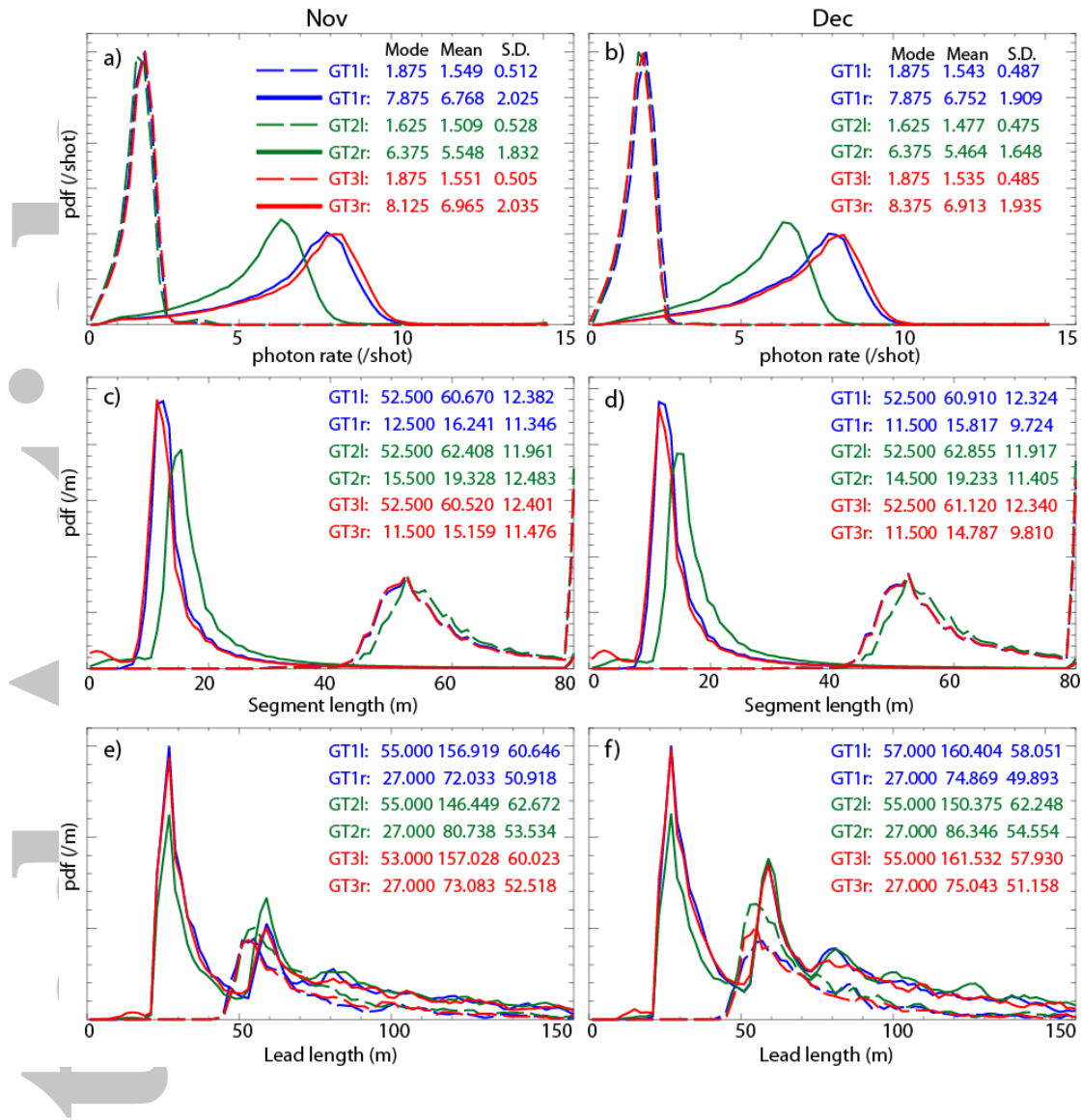


Figure 4. Distribution of photon rate (a, b), segment length (c, d), and lead length (e, f) in November and December 2018 for the six ATLAS beams showing differences between the weak (dashed lines) and strong (solid lines) beams over Arctic sea ice. The accumulated population in the tails of the distribution appears as a spike in the last bin. (See definition of lead length in Section 5.1)

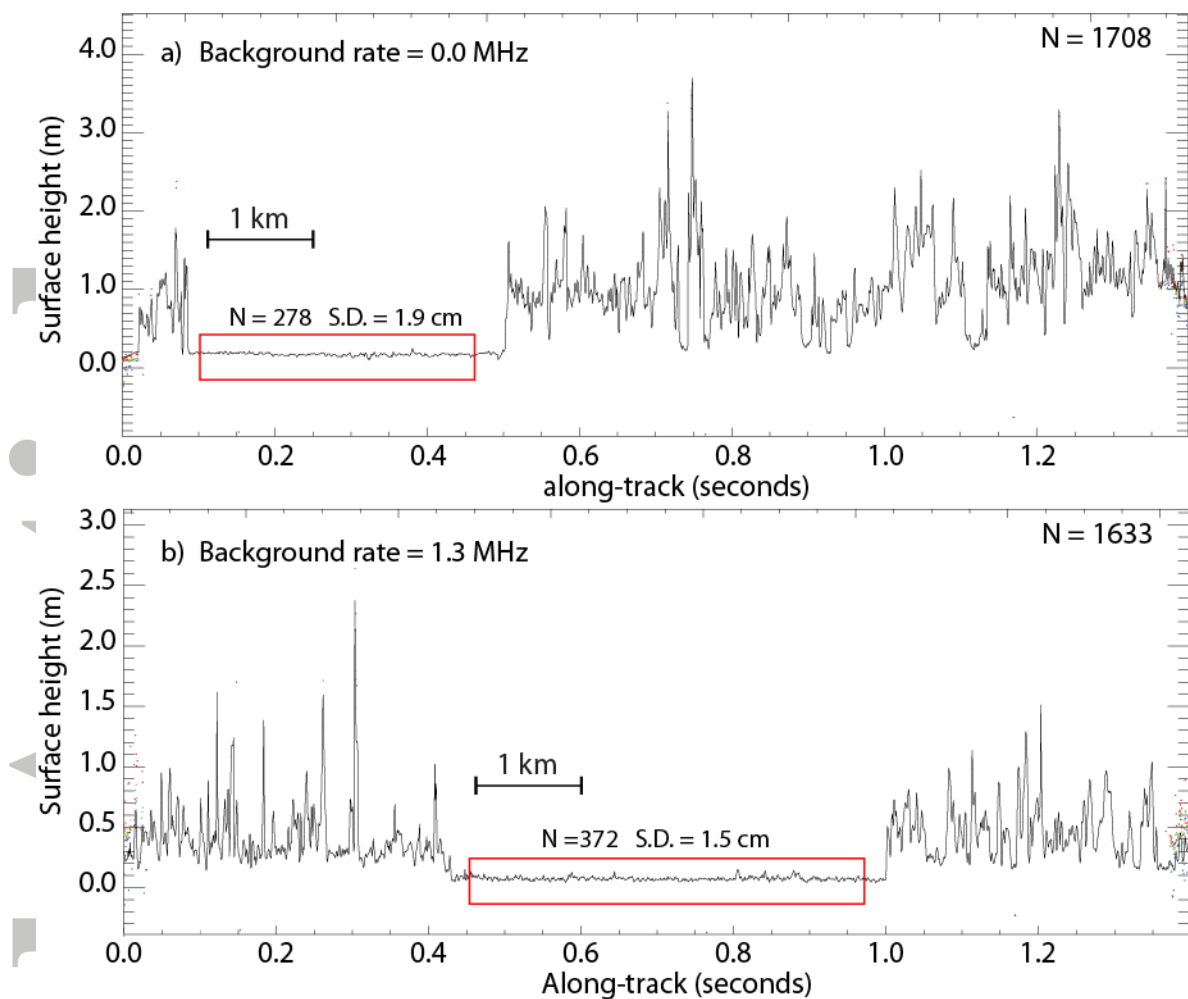


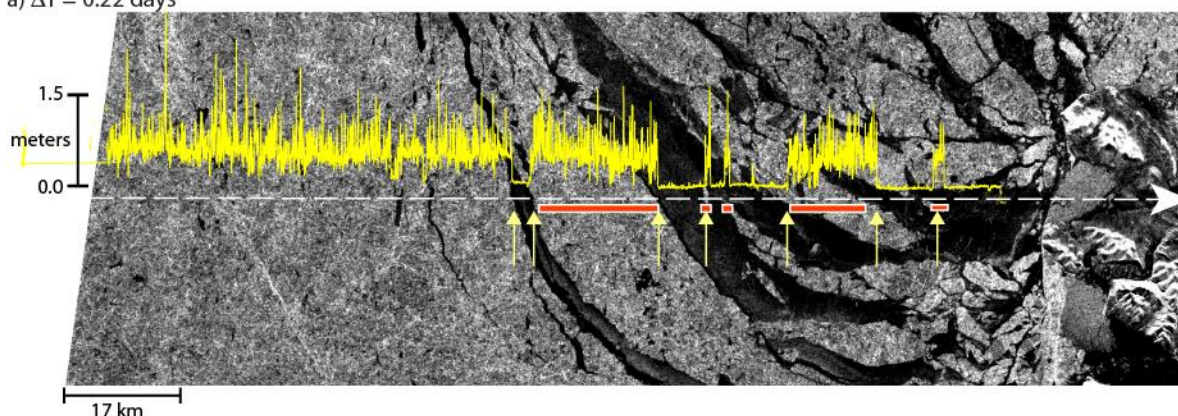
Figure 5. Profiles of surface heights over sea ice without (a) and with (b) solar background. S.D. is the standard deviation of the heights over relatively flat surfaces (in the red boxes) calculated using N height segments within each profile. Along-track time (in seconds) can be converted to approximate ground distance using a velocity of 7 km/s.

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a) $\Delta T = 0.22$ days



b) $\Delta T = 0.05$ days

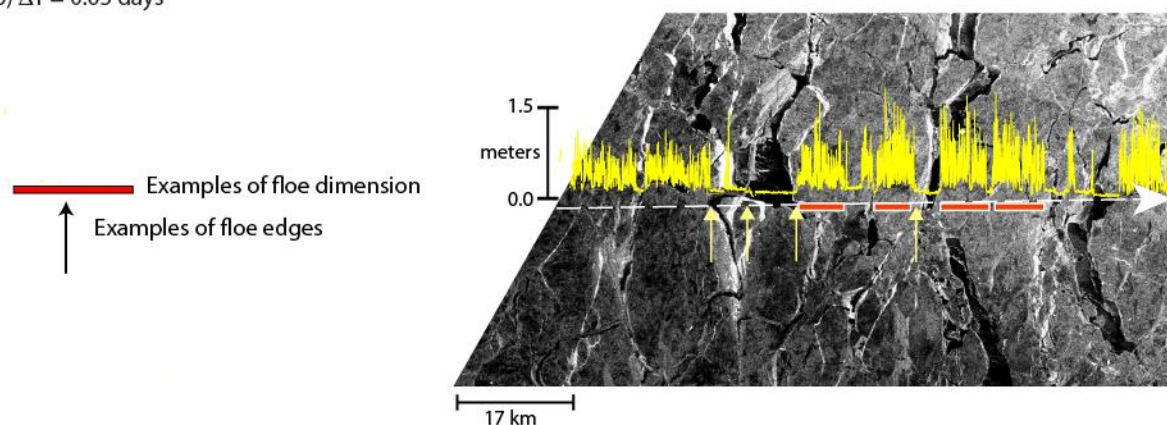


Figure 6. Overlays on Sentinel SAR Imagery. (a) December-1 near Ellesmere Island (RGT972). (b) October-29 in the Weddell Sea (RGT451). ΔT is the time difference between the Sentinel image and the ICESat-2 overpass. Yellow arrows point to examples of floe edges and red bars are examples of floe size. (Copernicus Sentinel Imagery 2019, processed by ESA)

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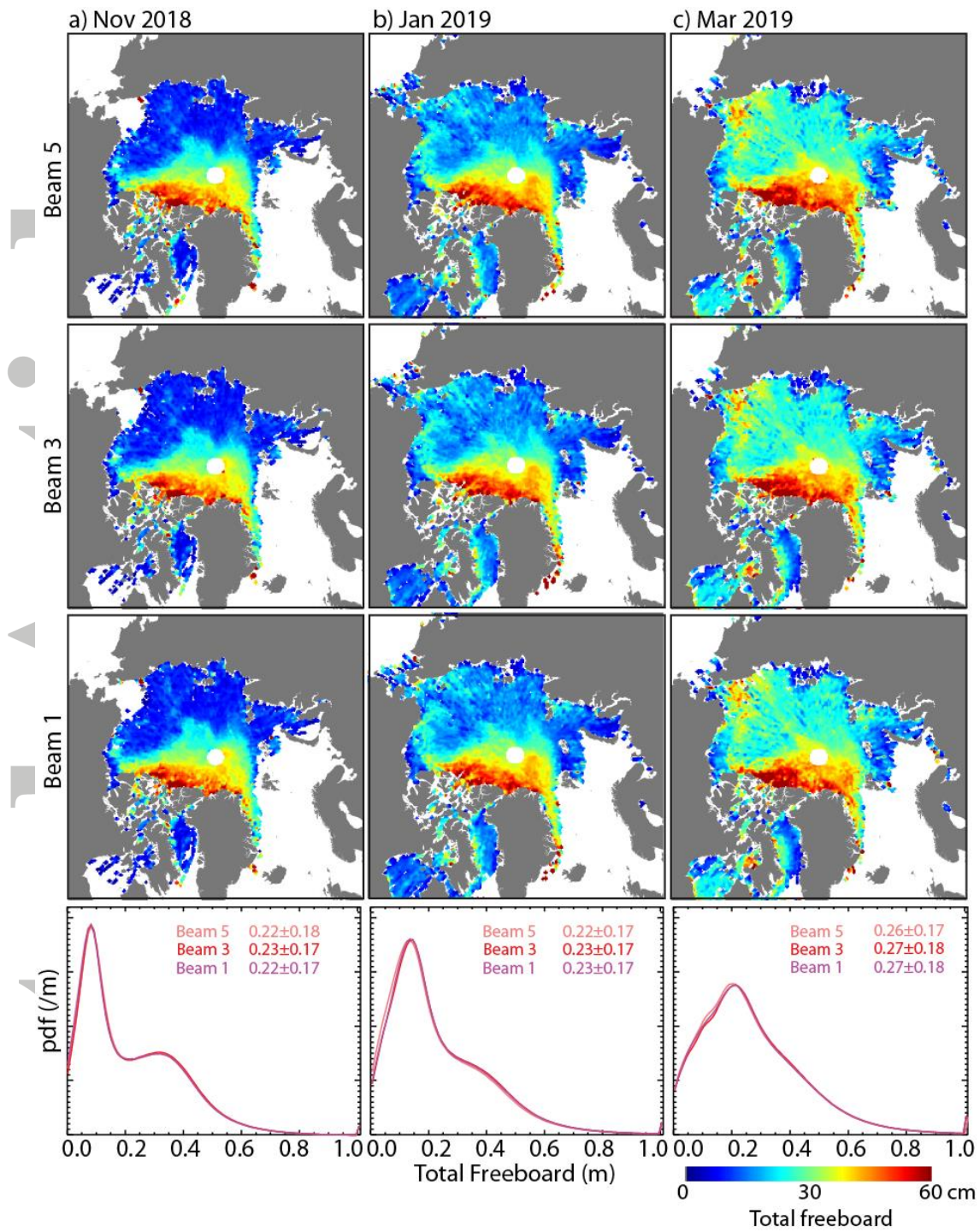


Figure 7. Gridded monthly composites of total freeboard and their distribution from the three strong beams (1, 3, and 5) from ATL10. (a) Nov 2018. (b) Jan 2019. (c) March 2019.

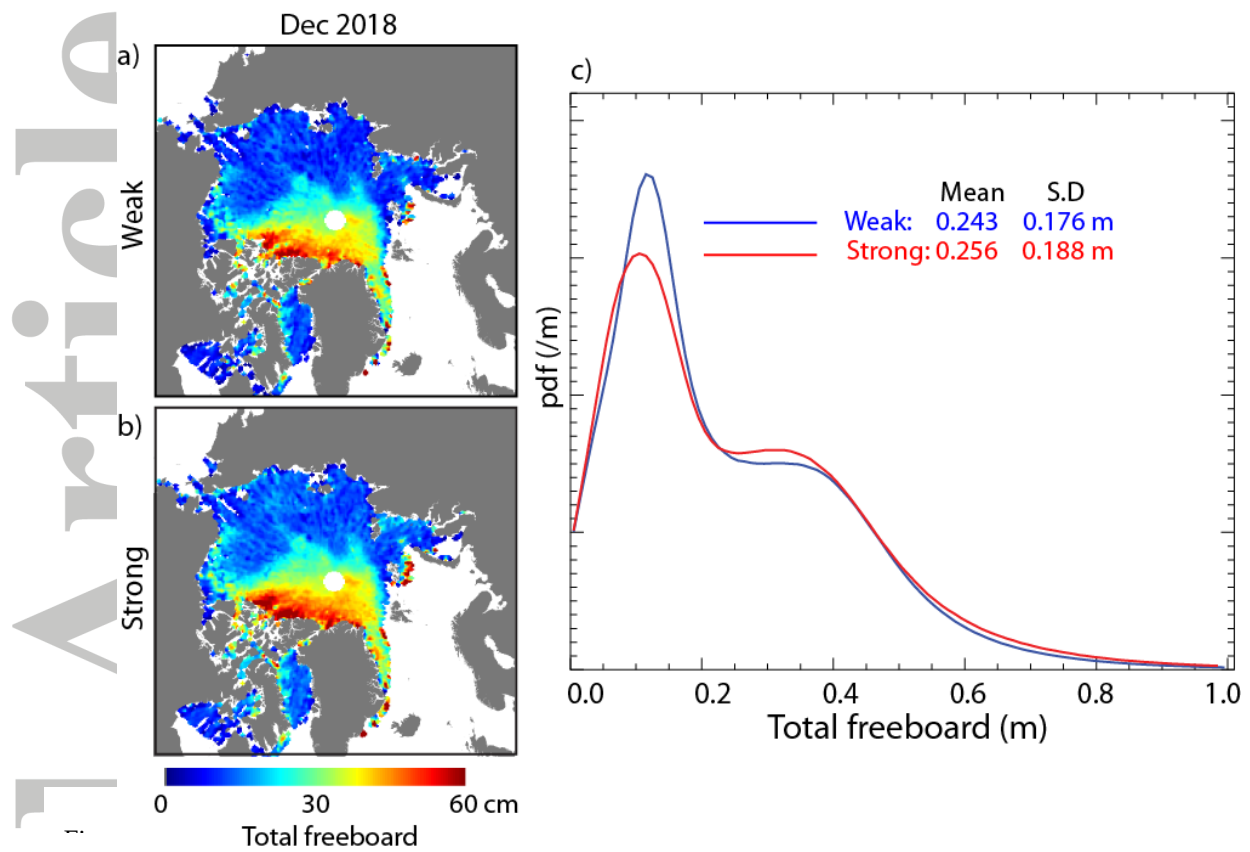


Figure 8. Differences between strong and weak beams for December 2018. (a) Average of three weak beams. (b) Average of three strong beams. (c) Freeboard distribution. Table 2 show differences for all months.

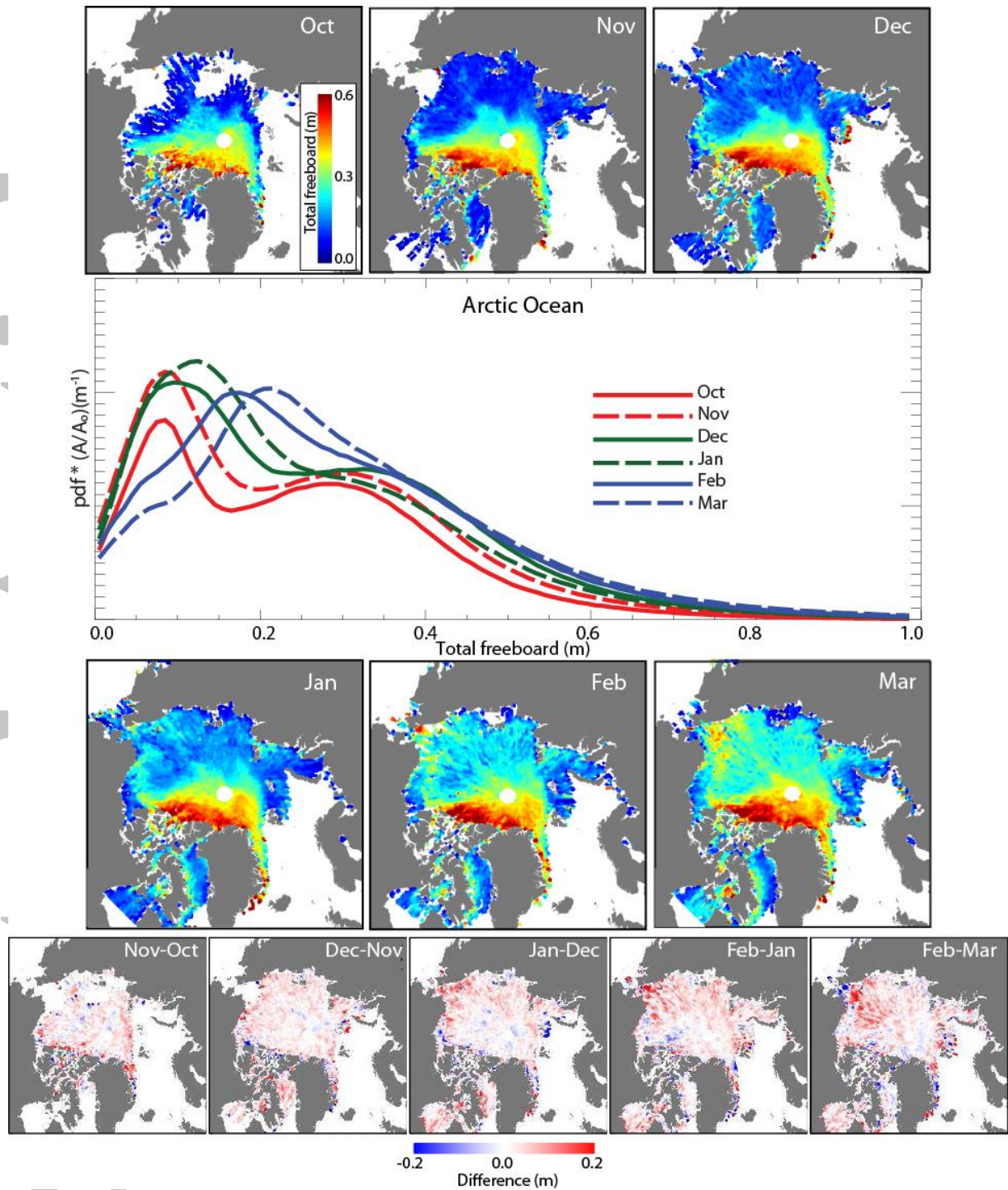


Figure 9. Evolution of total freeboard in the Arctic Ocean (domain described in text) between mid-October 2018 and March 2019 based on the gridded freeboard composites derived from averages of the three strong beams. A_0 is the fixed area of the Arctic basin (described in text), and A is the area of the ice cover. Monthly differences are shown in the bottom panel. These distributions are of the area of the Arctic Ocean defined in the text whereas the distributions in Figure 7 includes the peripheral seas.

Table 1

Expected returns from sea ice for Lambertian surfaces at 532 nm

Surface type	Surface reflectance	Weak beam (photons/shot)	Strong beam (photons/shot)
Sea ice - snow covered	0.8 - 0.9	0.6 – 2.1	2.3 – 8.5
Leads	0.05 – 0.2	0.05 - 0.2	0.2 – 1.0

Table 2

Statistics of the 3-beam-averaged strong vs weak freeboard distributions.

months		Mean	S.D.
Oct	Strong	0.240	0.169
	Weak	0.236	0.168
Nov	Strong	0.235	0.178
	Weak	0.225	0.171
Dec	Strong	0.256	0.188
	Weak	0.243	0.176
Jan	Strong	0.236	0.181
	Weak	0.230	0.169
Feb	Strong	0.276	0.191
	Weak	0.257	0.176
Mar	Strong	0.289	0.194
	Weak	0.268	0.175

Note: the mean freeboard does not show expected increases between October and January because it is weighted by the growth in area of the thinner (lower freeboard) seasonal ice cover.