ATL07/10

Notes to users and known issues

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Input from the ICESat-2 PSO

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Notes to users and known issues

This document contains notes, which are of use in the analysis of the sea ice products, and issues that are known to the developers, which may be fixed in future releases of these products.

Feedback from the community will be added to future revisions of this document.

03/21/2021 update: We have changed the layout of this document to reflect issues that affect current data and those that only affected previous data releases (e.g. Issue X1…).

Contents

Issue 1. Multi-beam (swath) freeboards calculations currently disabled (ATL10)

Currently (starting from rel003) the multi-beam freeboard calculations are switched off as the beams have not been aligned relative to each other. Only single-beam freeboards are available in ATL10. That is, freeboards are only calculated using the local sea surface height (reference height) from the given beam.

To clarify further, there are currently (as of rel003) two different freeboard metrics available in ATL10:

i) Along-track freeboards at the ATL07 height segment scale (150 photon aggregate) for each beam, where the reference surface is calculated using leads within the given beam in 10 km along-track sections.

gtx/freeboard_beam_segment/beam_freeboard/beam_fb_height

ii) Along-track freeboards at the reference surface scale (10 km) for each beam, generated by averaging all freeboards within the given section.

gtx/freeboard_beam_segment/beam_fb_height

In rel001 & rel002 there were also two additional freeboard metrics provided in ATL10, calculated using a multi-beam ('swath') reference sea surface estimate generated from leads detected across all 6 beams in 10 km 'swath' sections. As the beams are yet to be fully aligned, these were erroneously made available and have since been removed. We expect these will be made available again in future releases.

Issue 2. Sea surface heights (SSH) inter-beam differences and absolute SSH analysis

Updated 03/20/21 and 08/12/21

As the ATL03 data across the six beams have not been fully aligned (Issue #1), differences are apparent in the ICESat-2 polar sea surface height anomalies (SSHA) (reference surface heights in ATL10). Care must be taken when using these data to carry out absolute SSH analyses or comparisons with other satellite data.

Our analysis of SSHA has indicated some significant (centimeter-scale) inter-beam differences, especially with strong beam 1 (Bagnardi et al., 2021). Despite this, the SSHA estimates from ICESat-2 show good agreement with SSHA estimates obtained from ESA's CryoSat-2 during the summer-fall 2020 CRYO2ICE orbit alignment and on basin/seasonal-scales across the Arctic (Bagnardi et al., 2021). Work is on-going to better understand and reduce the inter-beam biases.

Issue 3. Potential for erroneously high freeboard samples near the ice edge due to sea state

The reference sea surfaces used to calculate freeboards are based on sea surface heights identified in ATL07. Near the ice edge, the reference surfaces within the ice cover are affected by sea state, likely due to scattering from the troughs of waves propagating into the ice cover, resulting in surfaces that may be tens of centimeters below the local mean sea level. This can result in higher freeboards and can affect sporadic 10-km freeboard segments. Most of these anomalous retrievals are thought to have been filtered out (mainly through the 50% passive microwave ice concentration filter in ATL10) but they still likely occur on occasion.

A new reference surface height slope variable has been introduced in rel004 and its use in filtering out such returns is being explored for inclusion in future releases.

Issue 4. July 2019 data

Updated 11/09/21 for rel005

Data collected between 9-26 July 2019 have a small timing bias resulting from an erroneous Earth orientation parameter uploaded during the spacecraft's return to operations following a safehold event on 26 June 2020. This caused an error in spacecraft pointing, resulting in an extra approximately 1 degree of forward pitch, and shifted the onboard attitude control system interpretation of spacecraft time by roughly 19 seconds. The primary manifestation of this issue is telemetry band errors at steep coastal areas, at times resulting in loss of surface returns. We note that there may be some increased height errors from data collected during this time period, those errors are generally within the conservative estimates of geolocation and height uncertainty currently provided on the ATL03 product.

Preliminary analysis of the ATL07 July 2019 data indicate increased off-pointing (absolute levels and variability) compared to other months which can impact specular lead classifications (higher pointing angles generally reduce specular returns, see Issue #5).

These data were initially held for assessment but have since (rel003 onwards) been publicly released (see Note X3). The data should still be treated with caution.

In rel005 QA we noticed the 9-26 July 2019 data are missing in ATL10 which was traced to the introduction of the new pointing angle filter in rel005 (see following Issue #5). All these files were automatically failed as they now contain no valid freeboard segments.

Issue 5. Off-pointing and calibration maneuvers

Updated 10/26/21 for rel005

The outer-beam pairs of ICESat-2 are angled roughly +/– 0.35 degrees away from the middle beam, which translates to an across track separation on the ground of +/– 3 to 4 km (at the nominal ICESat-2 altitude of ~ 500 km when the satellite is pointing at nadir). The middle beam points generally at nadir (with a slight offset to avoid highly specular returns/saturation issues) but can vary during the mission by a similar amount to the inter-beam pointing angle.

During a calibration scan or off-pointing maneuver the entire beam swath can point up to an additional 5 degrees off-nadir, which translates to an across track distance on the ground of +/– 40 to 50 km (depends also on the pitch/yaw/roll of the satellite). Data assessments from the ICESat-2 PSO suggest this doesn't significantly degrade the ATL03 geolocation quality (e.g. accuracy), however analysis from the ICESat-2 sea ice PSO has demonstrated reductions in photon rates and, crucially for freeboard determination, reduced specular returns during off-pointing. More specifically, we find that above incidence angles (angle of the beam at the Earth's surface relative to nadir) of ~1.5 to 2 degrees, specular lead returns are no longer found (specular as defined by the sea ice classification algorithm in the ATBD) and thus SSH and freeboards cannot be determined given the current algorithm design. Work is on-going to better understand the impact of incidence angle on the sea ice data products towards possible algorithm improvements.

In rel004 all ATL07 and ATL10 granules affected by off-pointing calibration maneuvers were held (i.e. not sent to the NSIDC for public dissemination) using information contained in a TechRef document produced by the ICESat-2 PSO that lists the times of all known satellite calibration maneuvers. Target of Opportunity (TOO) off-pointing requests involve similar amounts of off-pointing and were not held in rel004. A limited number of TOO requests over sea ice have been submitted by the ICESat-2 PSO (e.g. to 'fill-in-the pole' between mid-June and September 2020). We did not hold these granules as they were specifically requested, and we believed the limited data were useful for assessment purposes. Our limited preliminary analysis confirmed the almost complete lack of freeboards from these granules during the off-pointing maneuvers, due to the absence of specular lead classified segments needed for sea surface height retrievals. As noted earlier, we do not necessarily expect significant degradation in the quality (e.g. geolocation accuracy) of the segment heights during off-pointing. The list of TOO-affected sea ice granules is available from the PSO on request.

In rel005, the ATL03 data now include specific information related to expected geolocation quality and known satellite maneuvers in the PODPPD flag. This information is now sampled and carried through to ATL07 and ATL10:

gtx/sea_ice_segments/geolocation/height_segment_podppd_flag in ATL07
gtx/freeboard_beam_segment/height_segments/podppd_flag in ATL10

more information about the PODPPD flag can be found in the updated ATBD (Section 4.2 & 4.3).

Due to the issues surrounding surface classification and thus freeboard determination related to off-pointing discussed earlier we now filter the specific heights and freeboards within the granules using the PODPPD flag and beam angle information (as of rel005). More detailed description of this new filtering is included in the ATBD (Section 4.3). Briefly, if the PODPPD flag indicates that the geolocation quality is degraded we invalidate the relevant ATL07 height segments. Additionally, if the PODPPD flag indicates a calibration scan is occurring OR the *beam_coelev* variable indicates significant beam off-pointing (a *beam_incidence_angle* > *max_incidence_angle*, default of 1 degree) the surface segment type is set to invalid (-1), which also invalidates the freeboard. See Figures 1 and 2 for examples of this new filtering.

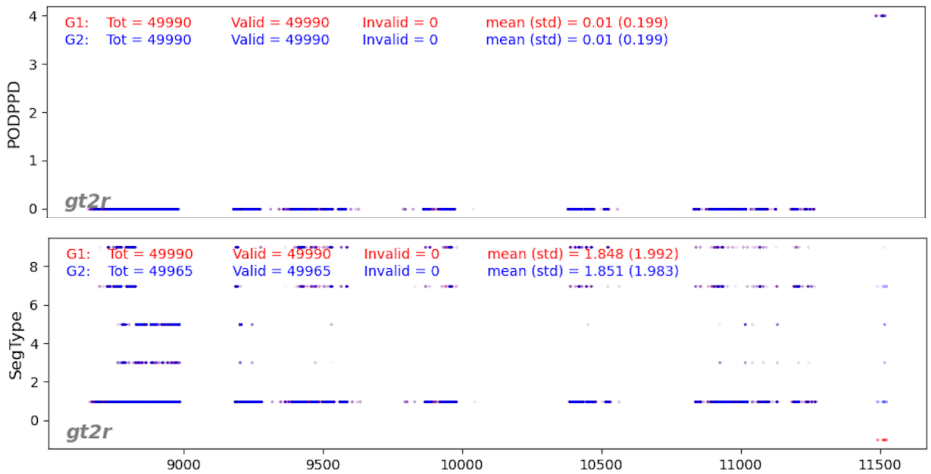

Figure 1*: G1: rel005 test data, G2: rel004 data. Note the PODPPD flag of 4 in both datasets around 11500 km (top panel, right) which in the rel005/G1 test data triggers an invalid surface segment type (SegType = -1).*

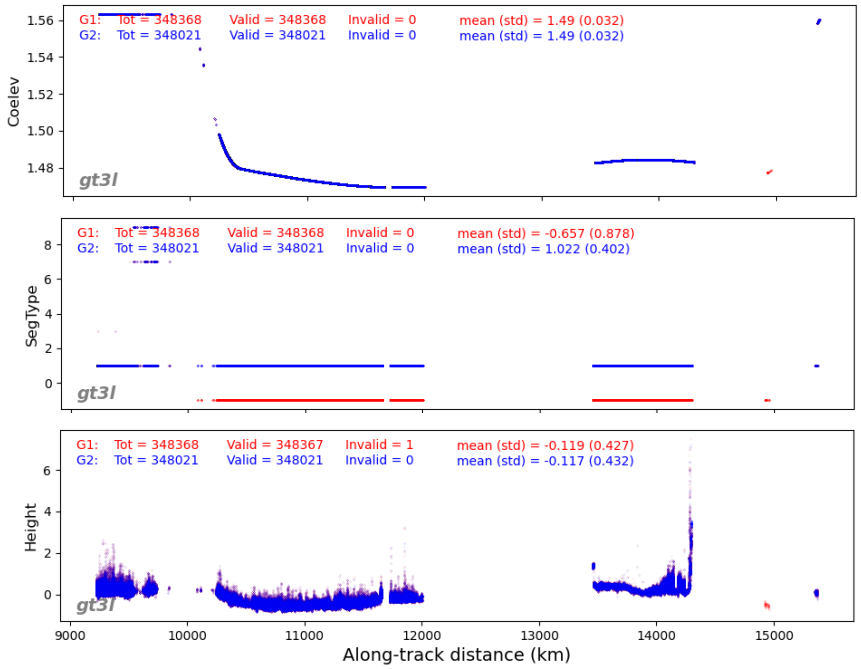

Figure 2: *G1: rel005 test data, G2: rel004 data. Note the lower coelev angle after ~10000 km (in radians, top panel) indicates off-pointing in both datasets which in G1 (test rel005) triggers an invalid surface segment type (SegType = -1) with heights (bottom panel) unaffected.*

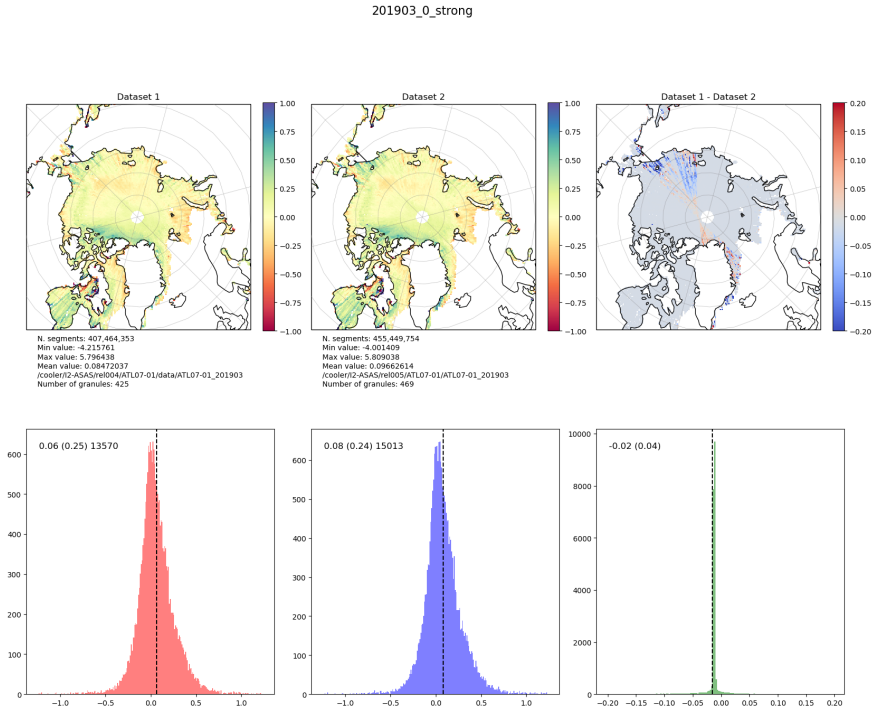

Figure 3: *gridded maps (top) and histograms (bottom) of Arctic sea ice heights (ssh_flag = 0) from ATL07 during March 2019. Dataset 1: rel004, Dataset 2: test rel005. Note the difference in regions*

where the PODPPD flag = 4. Due to the change in along-track distance/spatial sampling during off-pointing scans it is challenging to determine any underlying bias in these data.

As the sea ice products now contain information about orbit maneuvers, data can be appropriately filtered where necessary in the processing, meaning we no longer hold these granules as of rel005. This means we generally expect to see more granules hosted by the NSIDC than we had previously. While we have attempted to provide a comprehensive and automated filtering process, care must still be taken. For example, the ATL07 data will now include heights where the PODPPD flag indicates a maneuver is occurring, but the geolocation is 'nominal' (*height_segment_podppd_flag* = 4, CAL_NOMINAL) – data that would have been held previously as it would have been part of a calibration scan granule. See Figure 3 below for an example of this change.

Issue 6. Ocean tides and erroneous sea surface heights

The ATL07 algorithm applies various geophysical corrections, such as ocean tides, long period equilibrium ocean tides, and the inverted barometer (ATBD, Appendix J) to the photon heights obtained from ATL03. Currently (as of rel005) in regions where we are missing ocean tide data (obtained from the GOT4.8 ocean tide model) the ocean tide and long period equilibrium (LPE) tides are not applied but the segment heights are still calculated and included in the products. This is a bug, as it results in unphysical step changes in the ATL07 height anomalies where data is collected over regions with missing tides. These data can be filtered out by removing height segments with invalid ocean tide values. Work is on-going to fix this issue for rel006 (likely by invalidating the heights where the ocean/LPE tides are missing, and a new uncorrected height variable is also being introduced which could enable data to still be made available in these regions).

This issue can go undetected in regions where the ocean tide corrections are small, however we have noticed some large SSHA anomalies in the Weddell Sea, north of Berkner Island within the Filcher Ronne Ice Shelf, due to the lack of ocean tides available in GOT4.8 and the resultant unphysical increase in SSHA (See Figure 4). This appears to be the region with the most obvious lack of data from GOT4.8 data away from the coast. To avoid the issue, users can remove/invalidate segment heights where the ocean tide (*height_segment_ocean*) and the long period equilibrium tide (*height_segment_lpe*) are invalid.

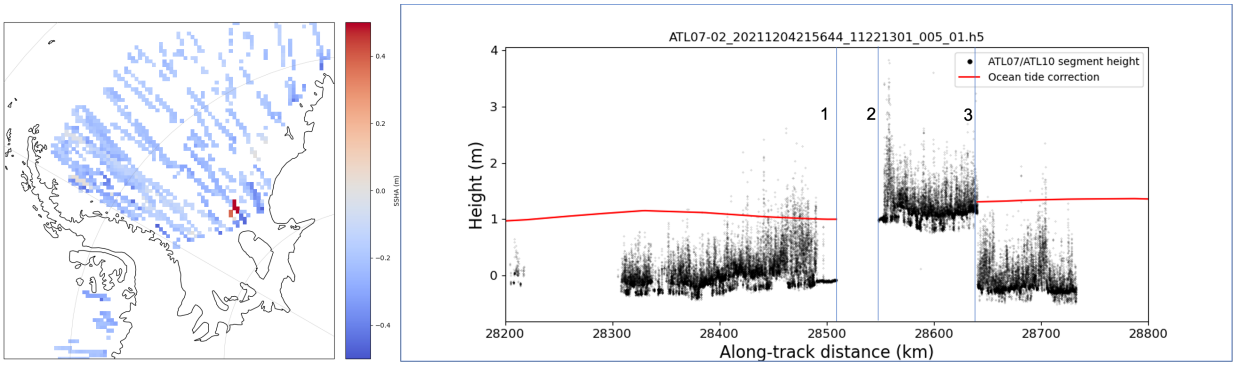

***Figure 4**: (left) gridded composite of ATL10 Sea Surface Height Anomalies (SSHA) from Dec 1-22, 2021, (right) ATL07 heights (black markers) for a granule extending over the Weddell Sea (over the positive SSHA shown on the left). ATL07 is missing between vertical lines 1 and 2 due to the presence of an iceberg and the effect of the coarse height filter (confirmed by ATL03) while the ocean tides (~1 m, red*

line) are missing between lines 1 and 3 resulting in the unphysical step-change in ATL07 between lines 2 and 3.

Note 1. ATL07/10 granule structure

The two panels (above, Figure 5) show the retrieved along-track surface heights (in ATL07, top right panel) and corresponding freeboards (in ATL10, bottom right panel) and their distributions (x-axis in meters, left panels) from a strong beam, in ~300 s (or ~2100 km) of ICESat-2 data. The gaps in the data are due to clouds. Retrievals (though of different resolutions) are available from both the strong and weak beams.

Granules. The ATL07 and ATL10 products each consist of approximately 32 files (granules) per day, 16 for the northern hemisphere and 16 for the southern hemisphere; each granule contains the sea ice retrievals (heights and freeboards) from data acquired over half an orbit. Six ground tracks within each granule span the width of the orbital swath with an across-track distance of 6 km.

Coverage. The ATL07 retrievals contain heights from the ice-covered oceans of the northern and

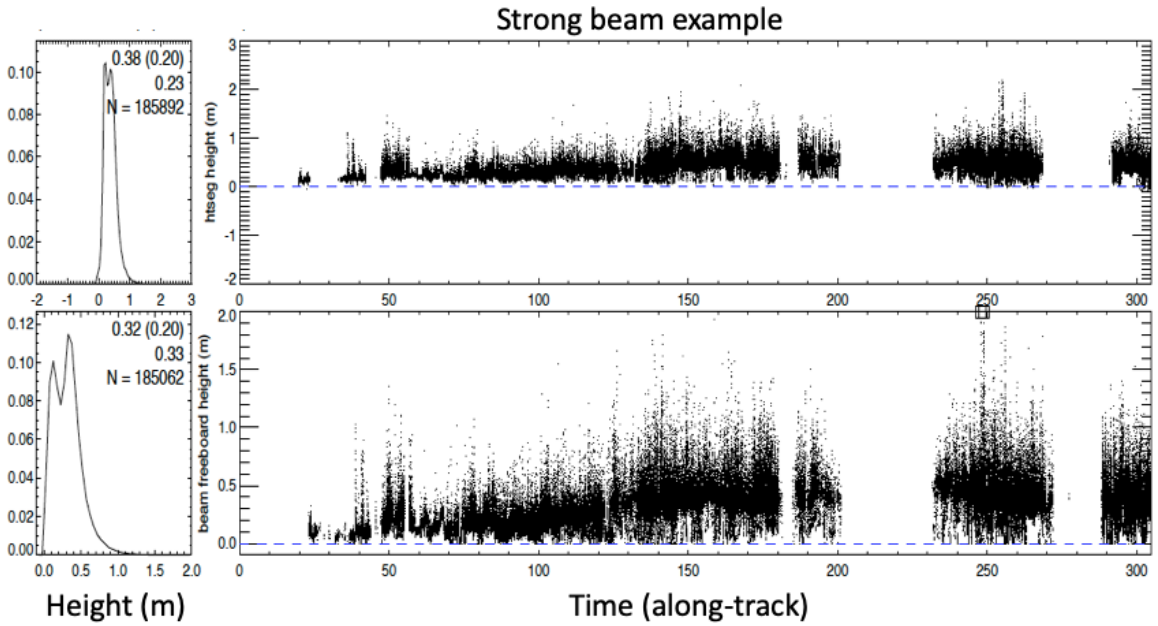

Figure 5: example ATL07 (top) and ATL10 (bottom) granule

southern hemispheres when the surface is visible (relatively cloud free) and the ice concentration > 15%. The ATL10 products are more restrictive, retrievals are provided only when the ice concentration >50% and 25 km away from the coast.

Note 2. Lower transmitted energy in Beam 3 (Strong Beam)

The transmit energy of Beam 3 (Strong beam 2R or 2L, depending on orientation of the ICESat-2 observatory) is approximately 80% that of Beam 1 and Beam 5. Thus, the segment lengths and photon return statistics are and will be different from the other two strong beams.

Added 03/20/21: Note that despite this, the reduced incidence angle of the middle beam compared to the outer beams generally increases the photon rate relative to the other beams (for the same surface) and can thus increase the potential for specular (high photon rate) lead classification, which partly (or perhaps fully, this is still being investigated) offsets the difference in beam energy.

Note 2. Variable segment lengths and spatial statistics

The ATL07 product contains profiles of surface heights of individual height segments along each of the six ground tracks. The variable along-track length of a height segment (L_s), associated with a height estimate, is determined by the ground distance travelled by the pulse footprints (number of pulses × inter-pulse distance) in the time it takes to aggregate 150 photons used for surface finding; thus, this length varies with surface reflectance. 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 ATL10 freeboards have the same segment lengths as those height segments in ATL07. This is an important characteristic to note in the calculation of spatial statistics.
The calculation of spatial statistics and distributions must account for the non-uniform and variable length sampling of height estimates. For example, the spatial mean ($\overline{h}$) and standard deviation (σ) of heights should be calculated as follows:

$$\overline{h} = \frac{\sum_N L_s^i h_s^i}{\sum_N L_s^i} \qquad \sigma^2 = \frac{\sum_N L_s^i (h_s^i)^2}{\sum_N L_s^i} - \overline{h}^2 \ .$$

That is, the height statistics should be weighted by the corresponding length of the height segment (L_s). This is taken into consideration when producing the gridded freeboard product ATL20.

Note 4. New sea surface designations: SSH flags 0, 1, 2 (in rel003 onwards)

In rel001 and rel002, the SSH flag is set to '1' (in both ATL07 and ATL10) if a particular height segment is a candidate height sample for use in the calculation of sea surface references.
In rel003, the SSH flag is incremented from '1' to '2' in ATL10 if that height sample were actually used in the calculation of sea surface references to distinguish the candidate from the selected samples.

Note 5. Increased coverage/sampling of the ice cover (in rel003 onwards)

There are three changes to the processing software that resulted in increased coverage of both the Arctic and Antarctic sea ice covers (See Figure 2):

1. Handling of returns in regions of overlapping land and sea ice masks
The procedures in rel001 and rel002 neglected to take into account the additional photons in the larger telemetry window (used for land ice) in the zone of overlap between land and sea ice masks. As a consequence, a large number of shots were treated as saturated and discarded,

causing potential gaps in coverage in regions where the two masks overlap. This effect is especially acute in the weak beams and when the solar elevation is high in the spring and summer, and negligible when the sun is below the horizon. This issue was fixed in rel003 and an increase in coverage around the coast is expected.
Expected changes: we expect an increase in coverage around coastal Antarctica and the Arctic coastline – especially around the Arctic shelves and in the passages of the Canadian Arctic Archipelago (see Figure 2).

2. Including h_fit_quality_flag=4 in the calculation of ATL10 freeboards
In rel001/rel002, we included only height segments with *h_fit_quality_flag* ≤ 3 in the calculation of freeboards in ATL10 (low values of *h_fit_quality_flag* are of better quality statistically). In the subsequent investigations, we decided to add height estimates with *h_fit_quality_flag=4* because the smaller population captures the higher freeboards in areas of higher surface roughness. In relaxing this filter, we expect an increase in the number of freeboards in ATL10.
Expected changes: we expect a small increase in overall coverage and only in areas of relatively rough ice (rough as measured by the Gaussian width of the surface finder). In these areas, the quality is low because the broad photon height distributions are noisy realizations of the surface when sampled by a 150 photon-aggregate. They are more random spatially.

Note 6. Changes in the ATL10 freeboard determination (introduced in rel003)

The two changes implemented are described below.
1. Correction of height filter
In rel001/rel002, the height filter used in the selection of reference surfaces for freeboard calculations was set to be overly stringent due to an incorrect parameter setting that eliminated a number of sea surface height segments. This is now fixed in rel003.

2. Use of only height segments with specular returns for reference height estimation
In rel001/rel002, candidate height segments that were selected to estimate reference heights for freeboard calculations included surface types 2 to 7. Surface types 2-5 are height segments with specular returns and types 6-7 are segments with smooth surfaces and low surface reflectance (dark leads). We found that the photon rates, used as a proxy for surface reflectance, are attenuated due to clouds (leading to incorrect classification of dark leads) and surface heights from dark leads are less reliable than those of specular returns without a cloud filter; the consequence is a higher reference surface and a lowering the estimated freeboards. Cloud flags from ATL09 are low resolution (~400 m) and thus not an effective filter at the lengths scale of potential leads detected by the sea ice classifier.

In rel003, we have modified the surface reference calculations so that only leads with specular returns (surface type 2-5) are used. The consequence of the changes can be seen in the freeboard composites of the Arctic Ocean (Figure 6) and of the Antarctic (Figure 7). Broadly, coverages have decreased by ~10-20% because there are fewer leads (by excluding the dark leads), and the composite means have increased by 0-3 cm because of the use of higher quality surface heights

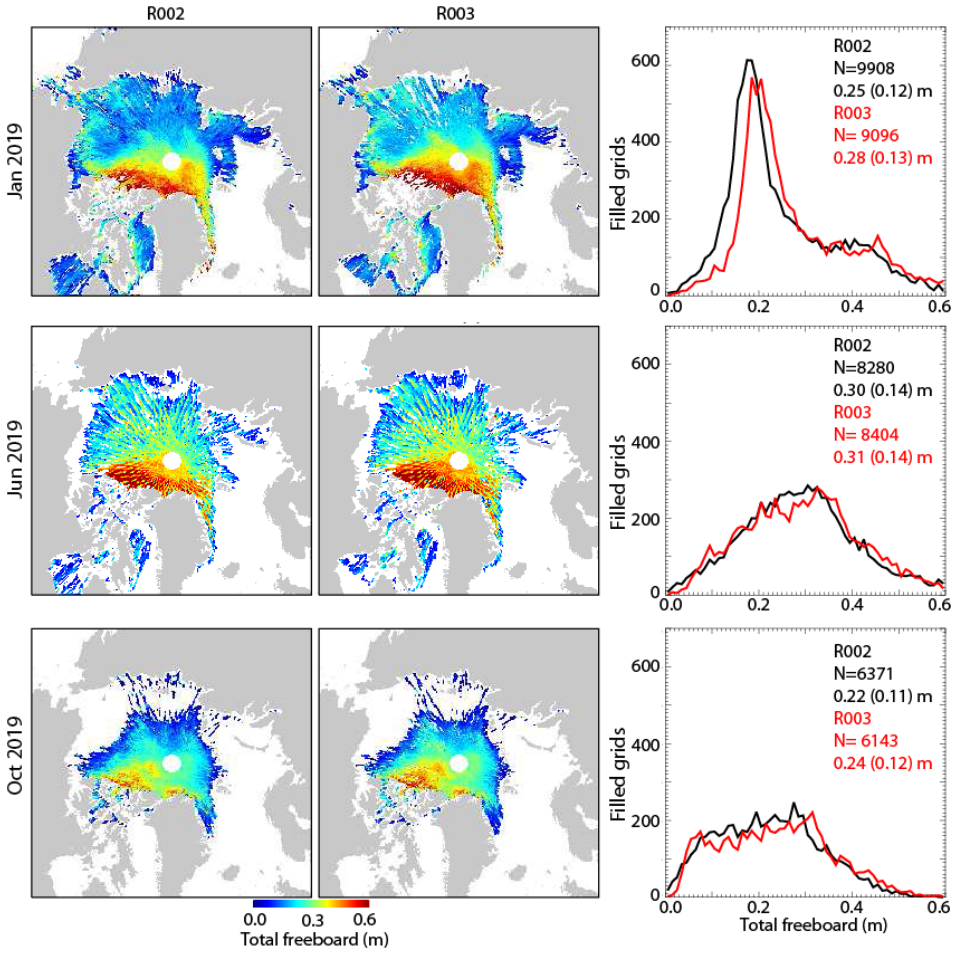

Figure 6: Changes in coverage and freeboard distributions of the Arctic Ocean sea ice cover in monthly composites of Jan, Jun, and Oct 2019. N is the number grid cells (25 by 25 km) that contains freeboard estimate. Numerical values are the mean (standard deviation) of the distributions. The distributions are not normalized and show actual population counts and provide an indication of the loss and gain of samples in each of the distribution bins.

(i.e., closer to the local sea surface) in freeboard calculations. A more detailed accounting and rationale for these changes – a refinement of freeboard calculations – has been detailed in a publication (Kwok et al., 2021). This also provides details of an alternate approach to filtering the cloud contaminated surfaces that is currently being tested and may be implemented in future releases.

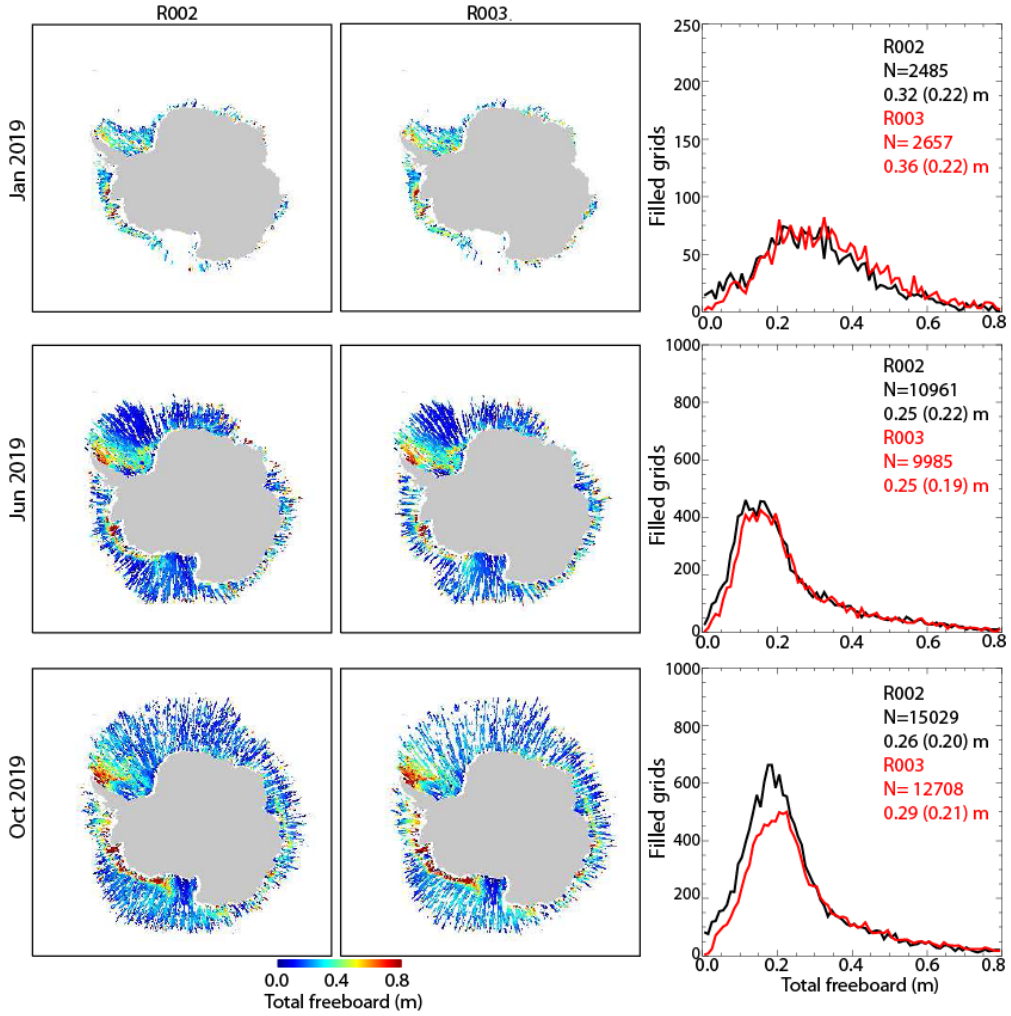

Figure 7: Same as previous figure except for the Antarctic.

Note 7. Hold files

Updated 10/26/21 for rel005

A hold process is in place for every new batch of ATL07/10 data generated by SIPS to prevent specific granules from being sent to the NSIDC, as determined by the ATL07/10 data product lead.

Prior to rel005 and the implementation of automatic PODPPD/off-pointing filtering (see Issue #5) the main reason for holding ATL07 and ATL10 granules was because of known ICESat-2 calibration maneuvers, in which the data quality is thought to be compromised due to issues with satellite off-pointing (see Issue #5). We held entire ATL07 and ATL10 granules in which a Round-The-World (RTW) or Ocean Scan has occurred within the period of a given ATL07/10

granule. These granules are now included as of rel005 but with data filtered where appropriate, which should result in increased data coverage (see Issue #5 above).

As of rel005 a minimum number of reference surfaces in ATL10 was also incorporated as an additional granule 'fail' filter (this was previous part of the manual hold process). Please refer to Section 9 of the ATBD for more information about granule filtering (fails and holds).

Our expectation as of rel005 processing is that ATL07/10 files are rarely held (manually checks will still be carried out prior to a new data delivery to check for obvious height/freeboard anomalies in gridded composites).

The ICESat-2 sea ice PSO maintains a list of held ATL07/10 granules that can be shared upon request.

Note 8. Change to tide-free system

Updated 10/26/21
In rel001 to rel003 data there were inconsistencies in the permanent-tide system of the geophysical corrections applied to the ATL07/10 segments. ATL03 uses a conventional tide-free reference system where the solid earth tides (both permanent and time-varying displacements) have been removed, while the MSS used in ATL07 assumed a mean-tide system. This has now been rectified by moving the sea ice products into a consistent tide-free system by converting the MSS to a theoretical tide-free MSS. New free-to-mean conversion factors are now included in ATL07 and ATL10 to easily change from the tide-free system to the mean tide system:

In ATL07:
gtx/sea_ice_segments/geophysical/height_segment_earth_free2mean
gtx/sea_ice_segments/geophysical/height_segment_geoid_free2mean

In ATL10:
gtx/freeboard_beam_segment/geophysical/height_segment_earth_free2mean
gtx/freeboard_beam_segment/geophysical/height_segment_geoid_free2mean

Note that the ATL21 sea surface height anomaly product (https://nsidc.org/data/ATL21)is converted back to mean-tide to enable more physical interpretation of ocean circulation variability, as discussed in the ATL20/21 Known Issues document and ATBD.

Note 9. Updated sea ice concentration data

Passive microwave derived NOAA/NSIDC Climate Data Record (CDR) sea ice concentration data (daily, 25 km x 25 km, https://nsidc.org/data/g10016) is used to delineate/filter sea ice from open water (15% threshold in ATL07 and 50% threshold in ATL10). On June 14th, 2021, the near-real-time CDR sea ice concentration data was updated to Version 2, which has been used as the input concentration data starting from May 19th, 2021 (RGT 843).

There are notable, albeit small differences in concentration between these products which users should be aware of.

Work is also on-going with the ICESat-2 Science Team to better understand sea ice concentration data and filtering along coastlines/ice fronts.

Issue X1. Gaps in coverage near the coast especially in the weak beams (resolved in rel003)

The procedures in rel001 and rel002 neglected to take into account the additional photons in the larger telemetry window in the zone of overlap between land and sea ice masks. As a consequence, a large number of shots were treated as saturated and discarded, causing a gap in coverage in the overlapping land ice/sea ice masks. This effect is especially acute in the weak beams and when the solar elevation is high in the spring and summer, and negligible when the sun is below the horizon.

Issue X2. Negative segment lengths (resolved in rel004)

The segment lengths in rel001 to rel003 ATL07/10 data are calculated using the difference in distance between the first and last photon in a given height segment. Because the photon distance measurements are not provided in sequential along-track distance order, this can cause erroneous behavior, including negative segment lengths in some rare cases. The problem was fixed by finding the difference of the max and min of the along-track distances instead of the start and end, which will be included in rel004 data.

Issue X3. *Layer_flag* in ATL07 and ATL10 (resolved in rel002)

The computation of the *layer_flag*, which combines the information in *cloud_flag_atm*, *cloud_flag_asr* and *bsnow_con* into a consolidated flag for indication of cloud coverage, was implemented incorrectly in the current release (rel001 - ASAS 5.1). DO NOT USE.

Note X1. Hold files (resolved in rel004)

During rel003 testing, PSO investigations uncovered multiple ATL07/10 files at the NSIDC despite the presence of known calibration scans, especially in ATL10. A more comprehensive hold list was generated for the upcoming (rel004) data release (see Note #7). This list of held granules is available upon request.

Note X2. No July 9 through July 26 data in rel003 (resolved in rel004, see Issue #4)

ATL10s (freeboard product) were initially held during the period July 9 and July 26, 2019 pending timing issues (see Issue #7). These data have subsequently been released.

References

Bagnardi, M. N. Kurtz, A. Petty, R. Kwok (2021), Sea surface height anomalies of the Arctic Ocean from ICESat-2: a first examination and comparisons with CryoSat-2, Geophysical Research Letters, 48, e2021GL093155, doi:10.1029/2021GL093155.

Kwok, R., A. Petty, M. Bagnardi, N. T. Kurtz, G. F. Cunningham, A. Ivanoff (2021), Refining the sea surface identification approach for determining freeboard in the ICESat-2 sea ice products, The Cryosphere, 15, 821–833, doi:10.5194/tc-15-821-2021