ICE, CLOUD, AND LAND ELEVATION SATELLITE-2 (ICESat-2)

ATL19 Gridded Dynamic Ocean Topography Release 002

Application Notes and Known Issues

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Introduction

This document contains notes for the use of the ICESat-2 ATL19 Gridded Dynamic Ocean Topography product. It includes issues that are known to the developers, which may be fixed in future releases of this product. Feedback from the community will be added to future revisions of this document.

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1.0 INTRODUCTION AND BACKGROUND

The Introduction and Background Section 1 is taken mainly from the ATL19 ATBD Sections 1.1 to 1.2.3.

1.1 Background: ATL03 and ATL12

The Ice, Cloud and land Elevation Satellite 2 (ICESat-2) is a photon-counting pulsed laser altimeter intended primarily to map the heights of the Earth's ice and snow-covered and vegetated surfaces. Its Advanced Topographic Laser System (ATLAS) projects 3 pairs of strong and weak beams pulsed at 10 kHz. For each beam, it measures the time of flight of individual photons to the Earth's surface and back. This range combined with precision pointing and orbit determination is used to measure the height of the surface along ground tracks numbered from left to right (gt1L, gt1R, gt2L, gt2R, gt3L, and gt3R) across the path of ICESat-2 (Fig. 1 right). The 6 beams are arranged in 2 rows of 3 with the weak beams forward when flying in the forward direction. The track assignments of the beams are as shown in Figure 1 (when during half the year ICESat-2 is flying backward the ground tracks remain numbered left to right but the beam assignments flip left to right). With the spacecraft yawed slightly to the left the weak and strong beam tracks of each pair are separated by only 90 m with the tracks of the strong-weak pairs separated 3 km across track. Each pulse of each beam illuminates a patch on the surface about 14-m across, and with the spacecraft moving at 7 km s^{-1}, new patches are illuminated every 0.7 m, giving ICESat-2 unparalleled along track spatial resolution. The orbit of ICESat-2 extends to North and South 88° to capture the Polar Regions and repeats every 91 days.

Although ICESat-2 was not intended primarily as an ocean altimeter, its fine resolution and polar reach make it a uniquely exciting ocean instrument. Consequently, the ICESat-2 ATL12 along track ocean surface height product has been developed (Morison et al., 2019). It draws input data mainly from the ICESat-2 ATL03 Global Geolocated Photon heights product.

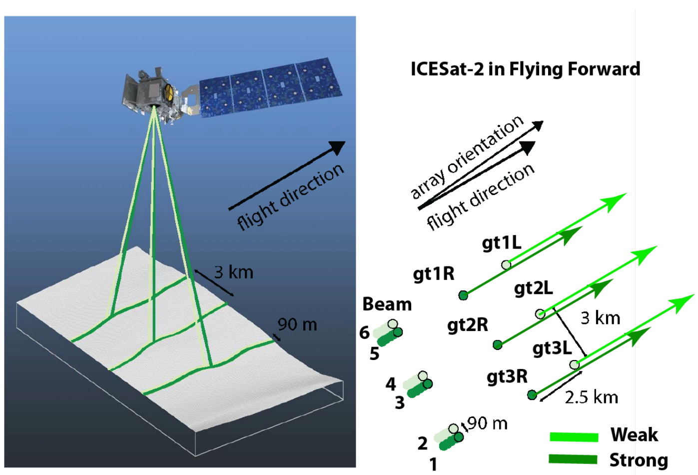

Figure 1 ICESat-2 spacecraft and beam configuration (left) and footprints flying in the forward direction.

The ICESat-2 ATL03 [Neumann et al., 2021a, 2021b] provides the photon reflection height (referred to as photon height) of the ocean surface relative to the

WGS84 ellipsoid for the downlinked data of each of the 6 beams. Originally, over the ice-free ocean and away from land only the strong beam data were downlinked to conserve downlink data volume, and weak beam data was only acquired over the ocean when near land or over sea ice. Beginning in the summer of 2021, this limitation has been relaxed so that strong and weak beam data everywhere is downlinked from the satellite. The raw photon heights are corrected for atmospheric delay and standard geophysical corrections such as such as solid earth tide of common concern to all the higher-level ICESat-2 products (e.g., land ice, sea ice and vegetation). A statistical approach is used to assign a confidence rating to the likelihood of each photon height being a surface height.

The processing of the ATL03 photon heights to produce the ATL12 ocean surface height [*Morison et al.*, 2019] first involves removing from the photon heights the expected high frequency variations due to tides from the GOT4.8 model and short period atmospheric forcing with a Dynamic Atmospheric Correction (DAC) based on the 6-h AVISO MOG2D. To further reduce the height variability of the raw photon heights, the EGM2008 geoid in the mean tide system is subtracted, so that processing begins with photon heights expressed as dynamic ocean topography (DOT) dealiased for tides and short period atmospheric forcing. The processing system then accumulates histograms of these dealiased and geoid-referenced photon surface heights along each ground track over ocean segments long enough to acquire 8,000 surface-reflected photons or up to a maximum length of 7 km. Minimum ocean segment lengths are usually 3 or 4 km. To better exclude subsurface returns under the crests of waves, surface finding is actually done on the basis of histograms of the photon height anomalies relative to a running 11-point average of the photon heights deemed high confidence surface photons in ATL03. The histogram of these anomalies is then trimmed of noise photons in the high and low tails of the distribution. Once the surface photons are so identified, their actual heights are used in subsequent processing.

To account for the instrumental uncertainty in photon time of flight due mainly to uncertainty in the start time of the photon flights within each laser pulse, the instrument impulse response histogram derived from the downlinked Transmit Echo Pulse (TEP) is deconvolved from the received height histogram to yield a surface histogram.

The ATL12 main outputs are the mean and next three moments of the resulting histogram. The 10-m along-track bin averages of photon heights are computed and used to determine electromagnetic (EM) sea state bias (hereafter referred to as SSB) and wave harmonics projected on to the ground track direction. Uncertainty in the mean surface height is largely due to sampling the wave covered surface and is proportional to significant wave height (SWH) and inversely proportional to the square root of ocean segment length divided by the correlation length scale. For ATL12 Release 4 and beyond, the 10-m along-track averages are used to yield the track-projected wave harmonics, correlation scale, and degrees of freedom.

In addition to data from ICESat-2 ATL03, ATL12 pulls in data from outside sources such ocean depth from GEBCO and in Release 5, ice concentration from NSIDC.

1.2 ATL19 Gridded Product

The ATL19 gridded product is intended to provide users with a realization of the height of the ocean surface mapped over the world ocean in 1-month (and ultimately 3-month) averages. This is in contrast to the ATL12 ocean surface height, which is an along-track record of sea surface height and related variables, each file of which covers only four ICESat-2 orbits representing 6 hours. The primary ATL19 gridded product is dynamic ocean topography (DOT), which is sea surface height relative to the WGS84 ellipsoid minus the height of the EGM 2008, mean-tide geoid [Neumann et al., 2021b] relative to the WGS84 ellipsoid. The ATL12 processing mainly works with DOT to avoid the large variations associated with the geoid, but consistent with prior NASA planning ATL12 outputs ocean segment averages of the SSH and the geoid required to compute ocean segment-averages of DOT. We chose the primary output of ATL19 to be DOT (with the corresponding geoid as an ancillary variable to enable determination of SSH) because the variations in DOT represent familiar circulation patterns and because being much smaller than SSH variations, inter-beam biases and error stand out sharply in DOT.

1.2.1 ATL19 Grids

ATL19 uses 3 grids, North and South polar stereographic 25-km grids as well as an overlapping mid-latitude curvilinear ¼° latitude-longitude grid between 60°S and 60°N. The gridding is done for each beam individually and for all beams for which the ocean segment-average positions are inside a grid cell.

1.2.2 The Basic Product

The basic product includes one-month simple averages and averages weighted by the estimated degrees of freedom for each beam ocean segment. Computing the individual beam averages provide a measure of relative biases among the six beams. The simple and degree-of-freedom weighted average grid or latitude-longitude positions of all the beam ocean segments in a grid cell are also output as are the simple and degree-of-freedom weighted averages of other key variables necessary to interpret DOT, such as the geoid and the sea state bias are also provided. Note that the most recent ATL19 ATBD dated 3/7/2022 goes so far as to include in DOT the sea state bias correction equal to subtracting the ATL12 ocean segment average of SSB, i.e., dot=*h-geoid_seg-bin_ssbias.* This should appear in ATL19 Release 3 and beyond. The effective average of SSB is also included in the event users want to apply their on SSB correction.

1.2.3 All-beam and running 3-month averages

The present release includes all-beam averages and planar fits over 9 cells to interpolate DOT to grid cell centers. In future releases of ATL19, monthly three-month running averages of the ocean segment DOT will provide more complete filling of grid cells and better interpolation of DOT to the center of the grid cells.

2.0 ISSUES

The issues below are those that could affect use of ATL19 presently or could affect changes in the way ATL19 data are used in the future.

2.1 Issue 1. ATL19 in Ice-Covered Regions

ATL12 surface height and consequently DOT make no allowance for sea ice freeboard. The heights include the top of the snow and sea ice surface in ice-covered regions. These will tend to be 10 to 40 cm higher than the DOT computed from ATL10 reference surface heights. As a result, DOT as provided by ATL19 Release 1 in ice covered oceans is also biased by the freeboard of the sea ice. In future releases of ATL19, we will account for this in two phases. First, we will work to reconcile any biases between ATL12-derived DOT and DOT from the ATL10 sea ice freeboard product in the low ice concentration regions of the marginal ice zone (MIZ). One possibility that shows initial agreement is to compare ATL10 to the lower of the two ATL12 surface height distributions in the 2-Gaussian mixture representation provided by ATL12 of the DOT distribution. At low ice concentrations, we expect this lower component of the Gaussian mixture represents the sea surface and the higher component the ice surface.

With respect to resolving differences in the open ocean and sea ice products, Release 2 of ATL19 is improved by the inclusion of average ice concentrations derived from ice concentration now included in ATL12 Release 5. With these data, the dependence on ice concentration will be determined for the differences among ATL19 DOT and gridded ATL10 DOT and ATL21 sea ice reference surfaces, and relation to ATL10 freeboard. This will help us to derive an appropriate scheme dependent on ice concentration for proper transition of ATL12 from the open ocean to ice covered regions.

2.2 Issue 2. Uncertainty in Gridded DOT

The Release 1 and 2 ATL19 gridded DOT standard deviation and uncertainty reflect only the variability within ocean segments due to waves. They do not include the variation due to temporal and spatial variability of ocean segment-average DOT. Similarly, because the height probability density functions, *Y*, from ATL12 represent only the distributions of the departure from mean DOT (*meonoffit2*) over an ocean segment, the grid cell aggregate distributions also only reflect the variability due to ocean waves. Future releases will quantify the variability among ocean segment average DOT in each grid cell.

2.3 Issue 3. Invalid Averages at Bin Centers

For reasons TBD, the average and DFW average DOT at bin centers have occasional errors in Release 1 and 2 of ATL19. The bin center averages are computed on the basis of a planar fit over 9 cells centered on the central point, and part of the reason for the erroneous values is undoubtedly occasional uneven distribution of tracks biased to one side of the 9-cell region. We have developed an editing scheme to eliminate such poorly conditioned fits, and we are debugging the final ASAS code for this as of 3/7/2022, too late for ATL19 Release 2. In the meantime, we suggest the user to not use bin center values in Release 1 of ATL19 or use them only with their own editing applied.

2.4 Issue 4. Pre-Grid Filtering

As discussed in Section 3.2.3.1 of the ATL19 ATBD, in the first release of ATL19, heights, *h*, that do not survive a 2-pass 3-sigma filter on dynamic ocean topography (DOT equal to *h-geoid_seg*) are edited out from being used in ATL19 computations. This results in rejection of some good data, particularly in the Southern Ocean where the mean DOT is low. We suggest Release 1 South Polar gridded data only be used with great caution and possibly with the user's own editing.

In the future, for each 4-orbit ATL12 file, data from all six beams will be concatenated. Means of dynamic ocean topography (DOT equal to *h-geoid_seg*) will be computed for each of the 18 ten-degree latitude bands for an ATL12 file. The latitude bands will be centered on the 5° marks and will not overlap, i.e. {90S° <= ATL12 latitudes < 80°S}, {80°S <= ATL12 latitudes < 70°S}, … {80°N <= ATL12 latitudes <90°N}). The standard deviation, σ, of the DOT from the entire ATL12 file will also be computed, and DOTs that are outside of $\pm\, 3\sigma$ from the associated latitude-band mean, will be removed. We have found this scheme does not erroneously reject good data in testing.

2.5 Issue 5. Data Sparseness in the Tropical Western Pacific Ocean Scan Region

Over most of the ICESat-2 data record, ocean scans have been performed over the tropical Western Pacific Ocean in order to refine the spacecraft pointing and orbit determination. DOT during ocean scans are edited out of ATL19 Release 1 for times when the magnitude of the reference angle is greater than 2°. As a result, for the first years of the program there is a virtual ATL19 data hole in the tropical Western Pacific. Starting in summer 2021, the number of ocean scans was reduced, which should lead to the some filling of the data hole going forward. Also releases after Release 2 will edit based the new POD/PPD flag being either 0, similar to reference angle <2°, or 4, meaning off pointing but in a stable orientation for which accurate DOT should be available. Also there are plans to spread ocean scans around to different parts of the ocean. These steps will greatly reduce the occurrence of ATL19 data holes due to ocean scans.