Ice, Cloud, and Land Elevation Satellite 2 (ICESat-2)

Algorithm Theoretical Basis Document (ATBD)

for

Land - Vegetation Gridded Products (ATL18/ATL28)

Contributions by past and present Land/Vegetation Science Team Members and ICESat-2 Project Science Office

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ATL18/ATL28 ATBD prepared by

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(This ATBD Version corresponds to release 001 of the ICESat-2 ATL18/ATL28 data product)

Content reviewed: technical approach, assumptions, scientific soundness, maturity, scientific utility of the data product

1 INTRODUCTION

This document describes the theoretical basis and implementation of the processing algorithms and data parameters for Level 4 land and vegetation heights for the non-polar regions of the Earth. The ATL18/ATL28 product is comprised of several gridded heights for both terrain and canopy and is derived from the 20 m height measurements reported on ATL08. The ATL18 and ATL28 product will provide global estimates of terrain heights and canopy heights at a nominal 1 km resolution, however, this spatial resolution might increase as more data is acquired over time in future releases of the data products.

In this document, section 1 provides a background of the gridding scheme. Section 2 provides an overview of the gridded data products for both terrain and vegetation. Section 3 describes the basic methodology that planned to calculate the gridded data for ATL18/ATL28 as well as the processing steps, input data, and procedure to derive the grids. One of the objectives for ATL18/ATL28 is to have compatibility with gridded products from the GEDI mission.

1.1 Gridding Scheme

One objective of ATL08 and subsequently ATL18/ATL28 is for the data products to be a useable as possible such that they can be integrated in with data from other NASA missions. As such, the ATL18/ATL28 1-km data product will utilize the EASE 2.0 gridding scheme which has been adopted by the GEDI and SMAP missions. EASE 2.0 is defined with respect to the WGS84 ellipsoid (as is ICESat-2) and is compatible with the NetCDF file format as well as GeoTiff. EASE 2.0 consists of a nested, azimuthal gridding system with four projections. At the north pole EASE 2.0 uses a Lambert polar azimuthal projection (EPSG: 6931) and a cylindrical equal area global projection (ESPG: 6933) will be used for all latitudes (Figure 1). ATL18/ATL28 will consist of gridded data at a 1 km spatial resolution as specified in Table 1 from selected ATL08 derived surface heights.

ATL18/ATL28 will serve as the only terrain product for ALL latitudes, including the Canadian Arctic Archipelago that are not captured in the land ice data (ATL06 or ATL11) products. For latitudes higher than 59.5° North, the data will be placed into the EASE 2.0 Northern

Hemisphere grid (EPSG 6931). All data from latitudes (60°S – 73°N) will be placed into the EASE 2.0 Global grid (EPSG 6933).

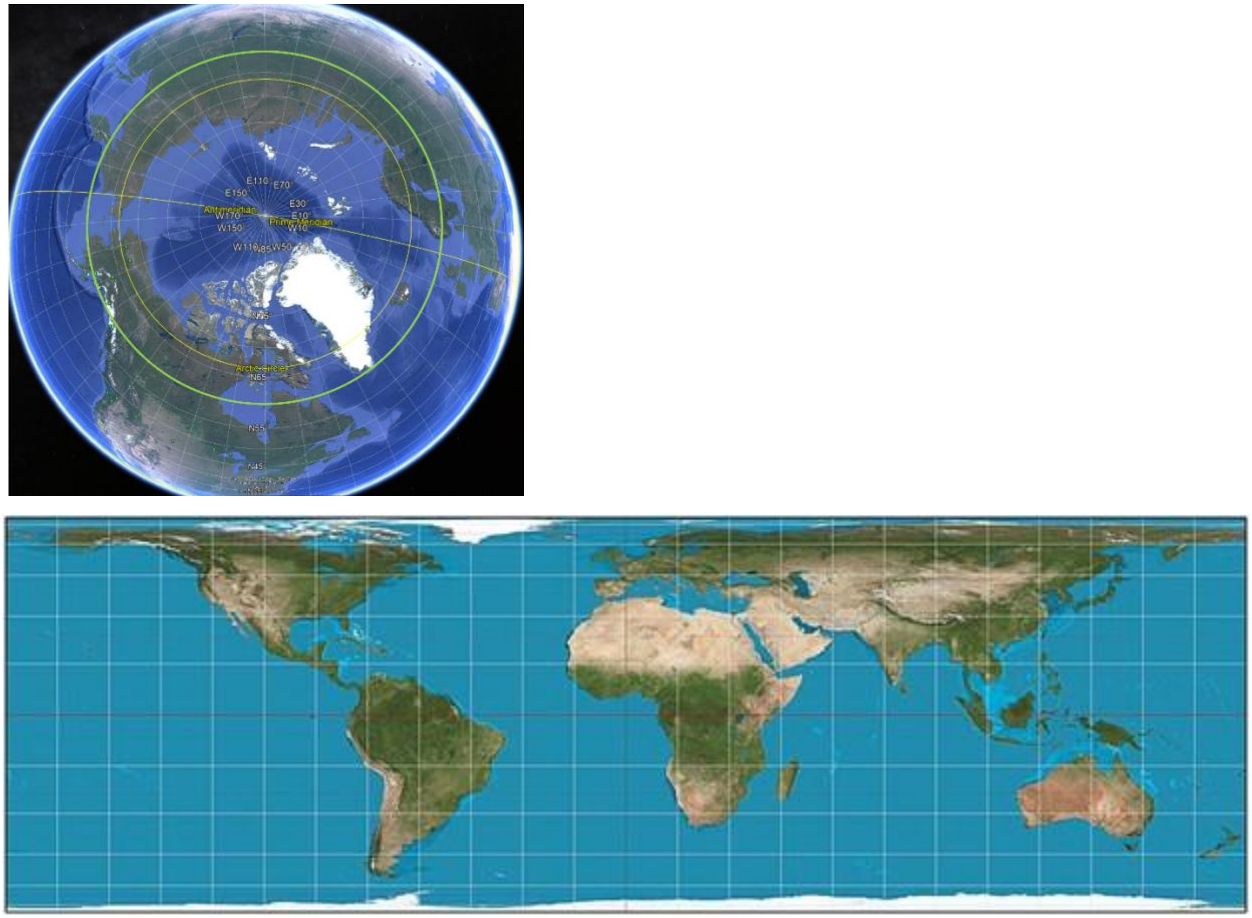

Figure 1. North Pole Projection for latitudes 59.5 to 90 degrees (top panel) and Cylindrical equal area projection for global projection 60S to 73N (bottom panel).

Table 1. EASE 2.0 gridding schemes for ATL18/ATL28 data products

Projection	**Resolution**	**Number of columns**	**Number of rows**	**Grid cell area (m)**	**x-axis map coordinate of the outer edge of the upper left pixel**	**y-axis map coordinate of the outer edge of the upper left pixel**
Global Equal Area	1 km	34,740	13,372	1000 x 1000	-17369532.4608	7019000.0

Northern hemisphere	1 km	6729	6729	1000 x 1000	-3364000.0	3364000.0

2 ATL18 ORGANIZATION

Several parameters were added to the ATL08 data product to facilitate the production of the gridded product. These include the best fit terrain height (h_te_bestfit_20m), the RH98 canopy height (h_canopy_20m), latitude_20m, longitude_20m, RH50 (i.e. median segment canopy height), segment_landcover, and the skill_score for terrain and canopy. Utilization of the terrain and canopy height every 20 m from the ATL08 data product should reduce any potential aliasing issues or edge effects associated with gridding the ATL18/ATL28 data products. Additional parameters from ATL08 that may be utilized in this version as well as future versions within the gridding scheme to filter the data include:

- h_te_bestfit_20m
- h_canopy_20m
- longitude_20m
- latitude_20m
- photon_rate_terrain
- photon_rate_canopy
- beam_num (1-6)
- solar_elev
- segment landcover
- apparent surface reflectance
- h_median_canopy
- canopy_openness
- top of canopy roughness
- h_dif_canopy
- terrain slope
- sigma_atlas_land
- date (yyyydoy)
- RGT cycle number
- Optical Depth
- Terrain and Canopy skill score

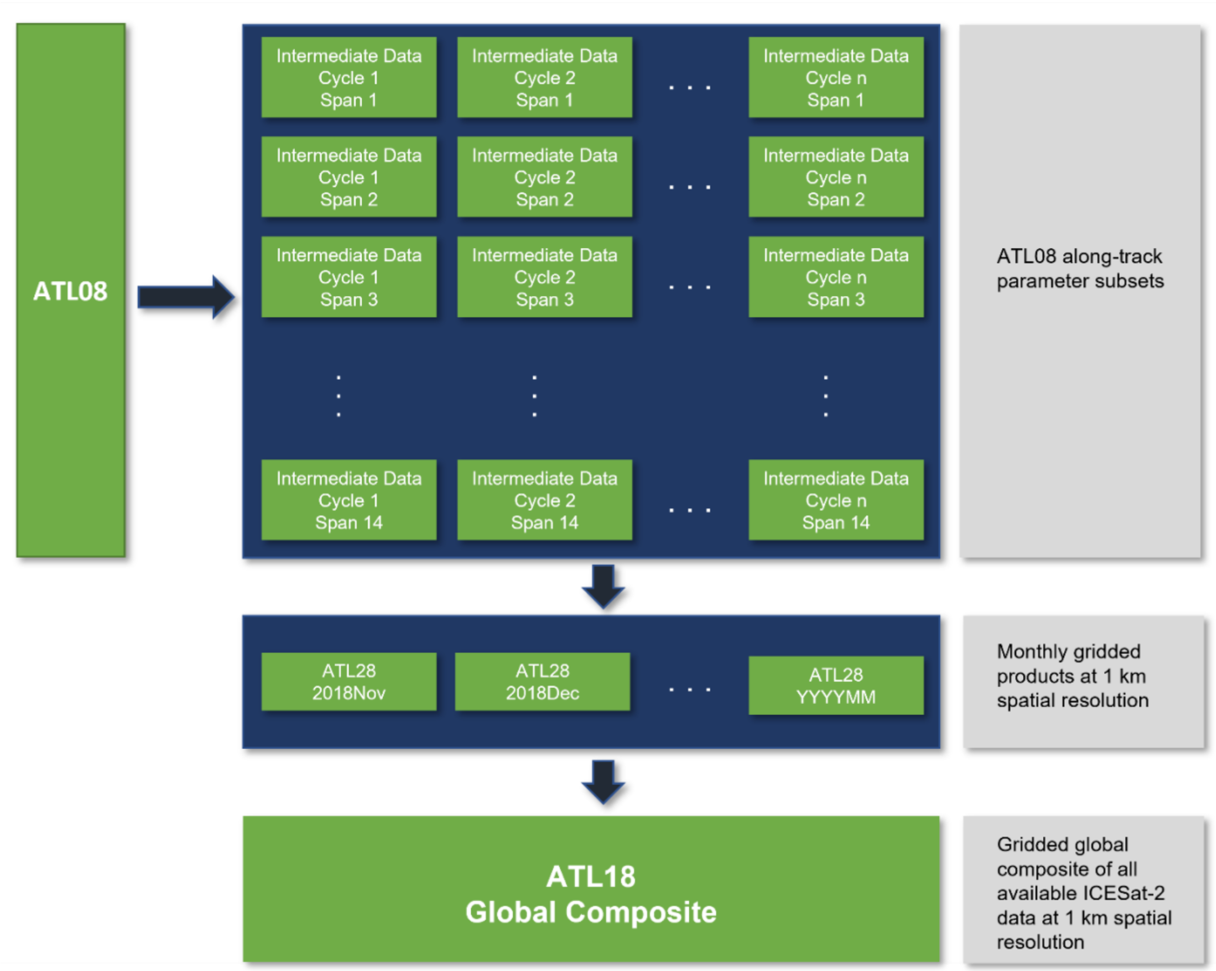

Figure 2. Organization of intermediate data, ATL28 monthly gridded product and final ATL18 gridded composite

Figure 2 depicts the internal organization going from the ATL08 along-track data products to the monthly ATL28 gridded products to the final ATL18 composite gridded product. A subset of parameters from ATL08 will be hashed into intermediate data products based on RGT cycle number and Span number. The span field may be equivalent to the region number used in ICESat-2 parsing of orbit granules or it may be defined as particular latitude/longitude bounds. ICESat-2 data with latitudes below 60° S are filtered out and will not be included within the intermediate data products nor as part of ATL28 or ATL18. From the intermediate products, monthly products (ATL28) will be created at 1 km spatial resolution in both the north polar and global projection. ATL28 will provide the high-end user with the maximum granularity and flexibility of creating customizable data products should that be desired. One scenario is a user could select a sequence of monthly products to create customized ATL18 products via SlideRuleEarth (slideruleearth.io). In addition to the monthly gridded products, a full composite (ATL18) will be computed at 1 km spatial resolutions for both the north polar and global projection. The composites, referred to here within as ATL18 data product, will be derived from all high quality ATL08 data since the start of the mission through a specified end date. ATL18 will be computed as the mean and standard deviation of each parameter pulled from the ATL28 monthly stacks. The ATL18 data product will be reprocessed quarterly or bi-annually as new ICESat-2 data are added to the stack.

As a caution to the user, it is feasible that the ATL28 monthly product may only have a few (e.g. 1 - 3) records in a given 1 km grid cell. The user is encouraged to examine nrecord parameter to ascertain their level of comfort regarding the quality/uncertainty for a given grid cell.

2.1 Naming Convention

All ATL18 and ATL28 data files will have the following naming conventions, with coverage = “gl” for global cylindrical projection and “np” for the north polar projection. Parameter descriptions are defined in Section 3.1, 3.2 and 3.3 for terrain, canopy, and radiometric parameters respectively. For ATL28, the date field will follow the year and month (YYYYMM). For ATL18, the date field will represent the end date of the composite (YYYYMMDD) as the start date is presumed to be the beginning of the mission (20181015) for all ATL18 data products.

Examples:

ATL28_np_te_mean_1000m_201901_001_01.tif

ATL18_gl_can_mean_1000m_20241231_001_01.tif

2.2 File Format

All data products will be written as individual cloud optimized geotiff (COG) files. Height based COG files will be written as 32-bit floating point values with centimeter precision. Count based data files will be written as 16-bit integers. Radiometric based COG files will be written as 32-bit floating point.

2.3 Mathematical Representation

The ATL28 and ATL18 gridded parameters are derived by computing the mean and standard deviation for the parameter within each grid cell. The mean and standard deviation computation for ATL28 are calculated as follows:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$\sigma = \sqrt{\sum_{i=1}^{n}\frac{(x_i - \overline{x})^2}{n}}$$

where x_i is a parameter value for a given grid cell, and n is the number of parameters falling within the grid cell to determine the calculation. The calculation of the mean and standard deviation for ATL18 will be based on the calculation for a series.

$$\overline{X}_{1,2,3\ldots j} = \frac{N_1\overline{X}_1 + N_2\overline{X}_2 + N_3\overline{X}_3 + \ldots N_j\overline{X}_j}{N_1 + N_2 + N_3 + \cdots N_j}$$

$$\sigma_{1,j} = \sqrt{\frac{N_1\sigma_1^2 + N_2\sigma_2^2 + \ldots N_j\sigma_j^2 + N_1 d_1^2 + N_2 d_2^2 + \ldots N_j d_j^2}{N_1 + N_2 + \ldots N_j}}$$

where $\overline{X}_{1,2,3,\ldots j} = combined\ arithmetic\ mean\ of\ all\ contributing\ ATL28\ months$

and

$\sigma_{1,j} = combined\ standard\ deviation\ for\ the\ entire\ series$

$\sigma_1 = standard\ deviation\ of\ the\ first\ ATL28\ composite$

$\sigma_j = standard\ deviation\ of\ the\ jth\ ATL28\ composite$

$$d_1 = \left(\overline{X}_1 - \overline{X}_{1,2,3,\ldots j}\right)^2$$

$$d_2 = \left(\overline{X}_2 - \overline{X}_{1,2,3,\ldots j}\right)^2$$

$$d_j = \left(\overline{X}_j - \overline{X}_{1,2,3,\ldots j}\right)^2$$

$$\overline{X}_1 = arithmetic\ mean\ of\ the\ first\ ATL28\ month$$

$$\overline{X}_2 = arithmetic\ mean\ of\ the\ second\ ATL28\ month$$

$$\overline{X}_j = arithmetic\ mean\ of\ the\ jth\ ATL28\ month$$

$$N_1 = number\ of\ observations\ in\ the\ first\ ATL28\ month$$

$$N_2 = number\ of\ observations\ in\ the\ second\ ATL28\ month$$

$$N_j = number\ of\ observations\ in\ the\ jth\ ATL28\ month$$

In addition to the mean and standard deviation, the number of records, N, using within each grid cell will be provided, enabling weighting, smoothing, and/or filtering by the user. For release 001 of ATL18 or ATL28, no spatial weighting within each pixel is considered.

3 THE ATL18/ATL28 DATA PRODUCT

The ATL18/ATL28 data product will consist of a gridded terrain height product and other relevant terrain metrics, a gridded canopy height product and other relevant canopy metrics, and gridded radiometric products where each cell represents the mean and or standard deviation value for a given parameter. The following list of rules will be implemented for release 001 of ATL18/ATL28.

- The ATL18 and ATL28 data products shall consist of all valid ATL08 records produced throughout the mission lifetime. For release 001, measurements from all dates will hold an equal weight in the gridding scheme, however, future releases may explore temporal weighting of various parameters.
- The ATL18 and ATL28 data product shall utilize the EASE 2.0 gridding scheme for the global equal area cylindrical projection and a north polar projection.
- The ATL18 and ATL28 data product shall have a spatial resolution of 1 km in the north polar projection and 1 km in the global equal area cylindrical projection.
- The ATL18/ATL28 terrain height and other terrain associated parameters will include data from all seasons and solar elevation conditions.
- The ATL18/ATL28 terrain height product and other terrain associated parameters will be derived from both the weak and strong beam.
- The ATL18/ATL28 canopy products will include data from all seasons.
- The ATL18/ATL28 canopy products will be derived from both strong beam (day and night acquisition) and weak beam (night acquisition: solar angle < 5 degrees).
- The ATL18/ATL28 radiometric products (i.e. terrain photon rate, canopy photon rate) will be derived from only the strong beam.
- For cells that do not have a sufficient number of samples, an invalid (or fill value) will be reported.

3.1 Gridded Terrain Parameters

Using the h_bestfit_20m from the ATL08 data product, the gridded mean terrain height and standard deviation of terrain height will be calculated. The gridded mean terrain slope and terrain uncertainty are calculated from those parameters on the ATL08 data product at the 100 m resolution. Slope will be converted into degrees by dividing the rise by 100 m of run (ATL08 step size) and calculating the absolute value. The mean will be calculated on the absolute value of slope. It is expected that the presence of snow on the surface could bias the estimated terrain heights high for certain locations and the impact of snow will be investigated for a future release of ATL18/ATL28**.**

Table 2: Standard ATL18/ATL28 Terrain Parameters

	Gridded Parameter Name	**Beams**	**Method**	**Input ATL08 resolution (m)**	**Units**
Mean Terrain Height	te_mean_all	All Beams	Mean of h_te_bestfit_20m values within each grid cell	20	m
STD Terrain Height	te_std_all	All Beams	Standard deviation of h_te_bestfit_20m values within each grid cell	20	m
Terrain Height Geosegment Count	te_20num_all	All Beams	Number of h_te_bestfit_20m records within each grid cell	20	unitless
Mean Terrain Slope	te_slope_all	All Beams	Mean of terrain_slope within each grid cell	100	degrees
Mean Terrain uncertainty	te_uncertainty_all	All Beams	Mean of sigma_atlas_land within each grid cell	100	m
Count of Terrain parameters (100 m)	te_100num_all	All Beams	number of 100 m terrain segment for all landcover classes within each grid cell	100	unitless

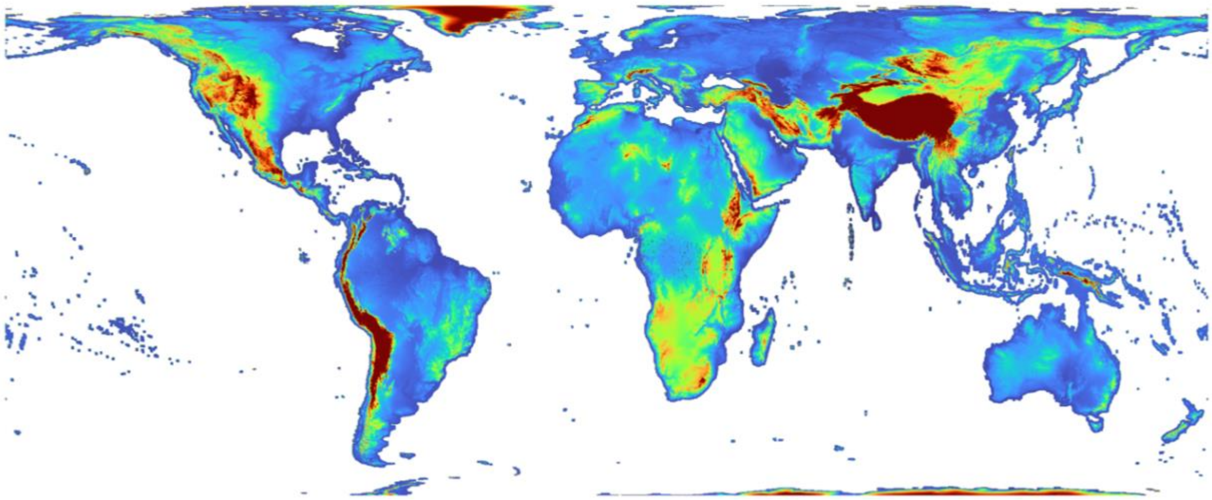

Figure 3. Example of ICESat-2 Global Terrain Height Product

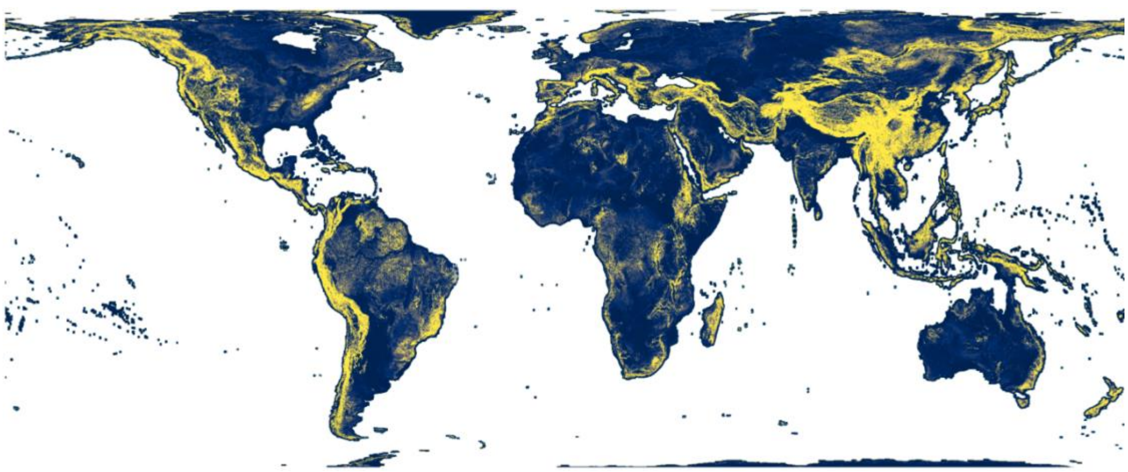

Figure 4. Example of ICESat-2 Global Terrain Uncertainty (Sigma Atlas Land)

3.2 Gridded Canopy Parameters

Although the generation of a gridded canopy product would ideally only include data collected in leaf-on conditions, version 1 of the composite **ATL18 data product will utilize all canopy heights for all seasons**. The detection of seasonal variation will be possible from the monthly ATL28 data products and that may factor into future versions of ATL18. The monthly products are provided such that a user can select the desired seasonality and temporal range for their area of interest to calculate the parameter estimates. Numerous validation efforts have shown poor determination of canopy height and canopy parameters on the weak beam during day acquisitions. For release 001 of ATL18/ATL28, only data from the strong beams and weak beam during night conditions (i.e. solar elevation < 5 degrees) will be utilized.

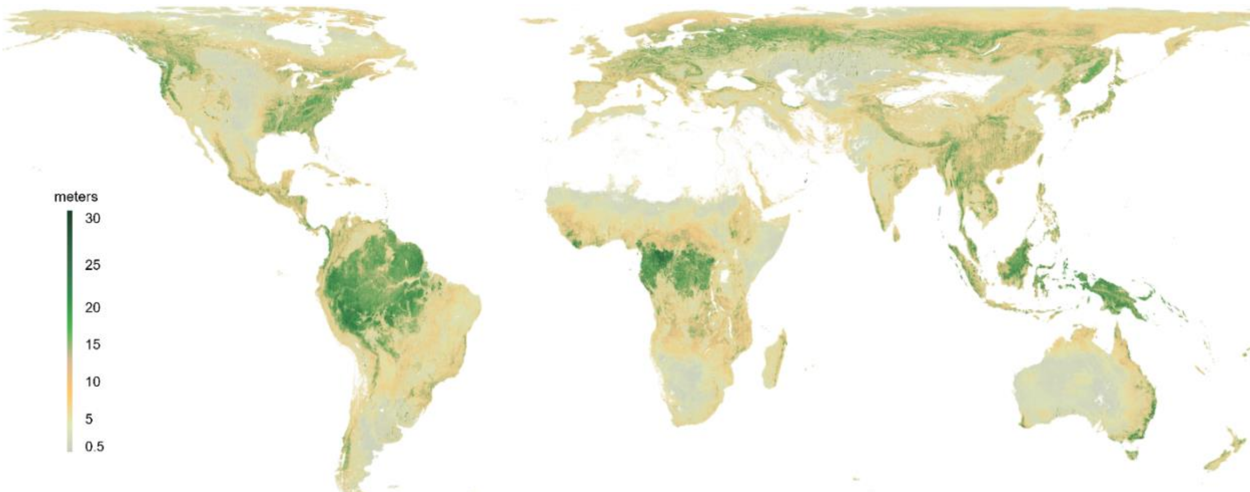

Figure 5. Example of ICESat-2 Global Canopy Height

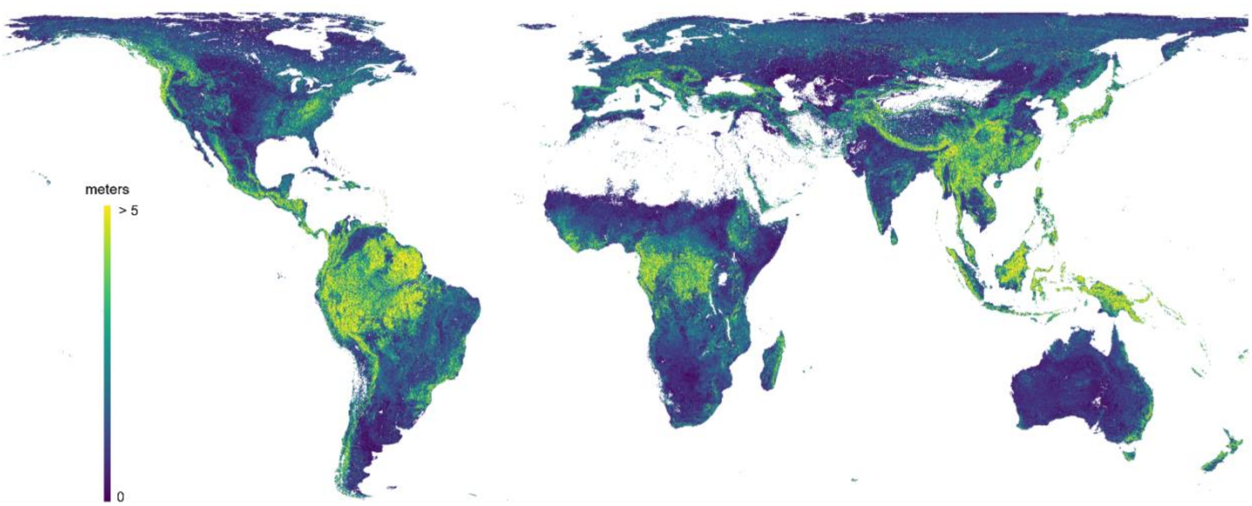

Figure 6. Example of ICESat-2 global Top of Canopy Roughness

The gridded canopy height will be computed using the h_canopy_20m records from ATL08. From ATL08, h_canopy_20m represents the 98^{th} percentile height at the 20 m geosegment level in the along-track direction. All h_canopy_20m heights within a grid cell will be used to report the mean of the h_canopy_20m canopy heights. In addition to canopy height, the mean value of several additional canopy parameters will also be gridded. These include the top of canopy roughness and the vertical distribution ratio. The ATL08 top of canopy roughness is defined as the standard deviation of the photons labeled as the top of canopy in the along-track direction. The vertical distribution ratio, with values ranging from 0 to 1, is defined as the ATL08 h_dif normalized by h_canopy, both at the 100 m rate.

$$VDR = \frac{h\_dif}{h_{canopy}} = \frac{rh98 - rh50}{rh98}$$

Table 3: ATL18/ATL28 Canopy Parameters

Description	**Gridded Parameter Name**	**Beams**	**Method**	**Input ATL08 resolution (m)**	**Units**
Mean of Canopy heights	can_mean_all	All Beams	Mean of h_canopy_20m heights for all landcover classes within each grid cell	20	m
STD of Canopy Height	can_std_all	All Beams	Standard deviation of h_canopy_20m for all landcover classes within each grid cell	20	m
Count of Canopy Heights (20m)	can_20num_all	All Beams	number of h_canopy_20m heights for all landcover classes within each grid cell	20	unitless
Mean of RH50 heights	can_meanrh50_all	All Beams	Mean of rh50 heights for all landcover classes within each grid cell	100	m
Mean Canopy Roughness	can_rough_all	All Beams	Mean of toc_roughness for all landcover classes within each grid cell	100	m

Mean Vertical Distribution Ratio	can_vdr_all	All Beams	Mean of h_dif normalized by h_canopy for all landcover classes within each grid cell	100	unitless
Count of Canopy parameters (100 m)	can_100num_all	All Beams	number of 100 m canopy segment for all landcover classes within each grid cell	100	unitless

3.3 Gridded Radiometric/Reflectance Parameters

In addition to terrain and canopy related products, a series of radiometric based products for both terrain and canopy will be produced as the average photon rate per grid cell for the strong beam within each grid cell. Since the radiometric products (e.g. te_photon_rate, can_photon_rate) on ATL08 are reported at the 100 m rate, an additional count of ATL08 strong beam segments will be utilized to produce the average radiometric data product. An example of the global terrain radiometry product, global canopy radiometry product, and the global apparent surface reflectance are illustrated in figures 7, 8 and 9, respectively.

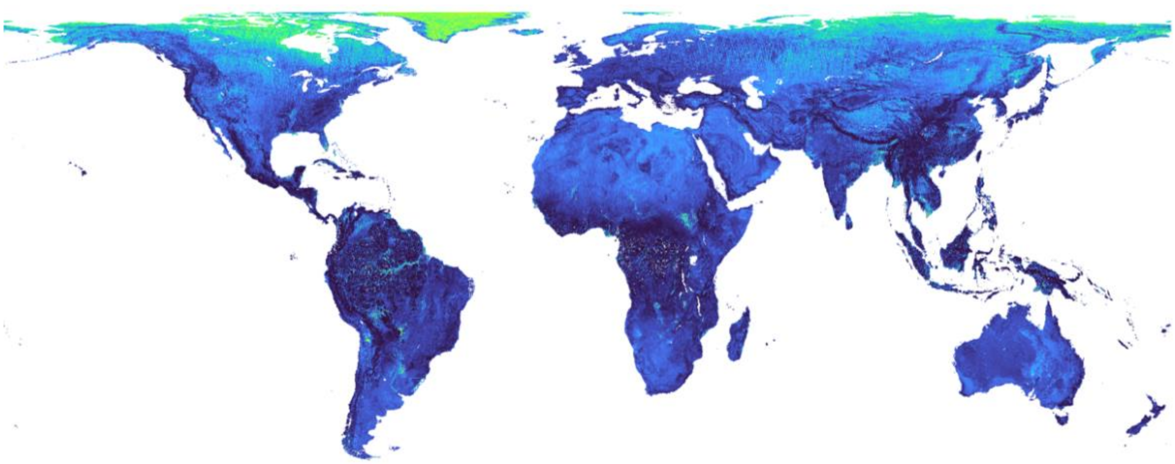

Figure 7. Example of ICESat-2 Global Terrain Radiometry. (this radiometric product was computed using both weak and strong beam radiometry rates). Moving forward, this will change to only strong beam

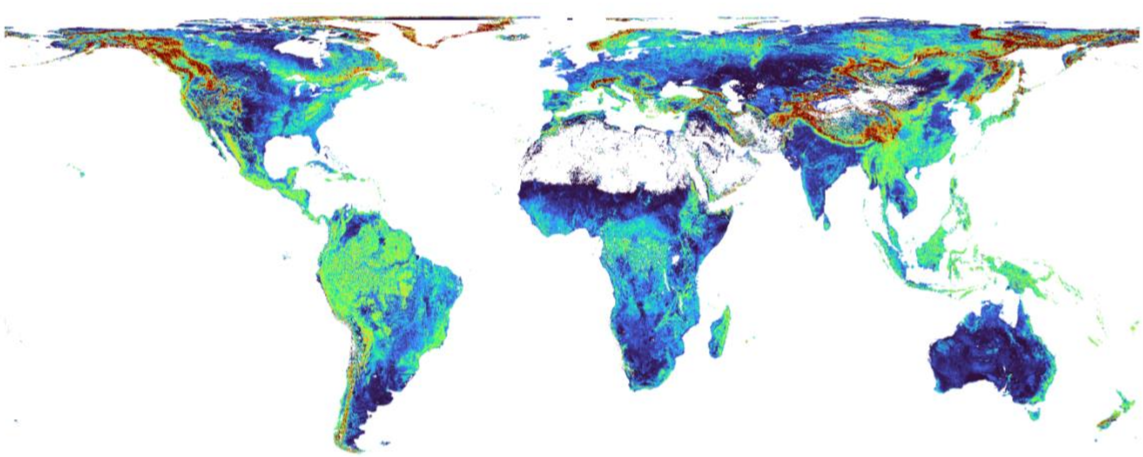

Figure 4. Example of ICESat-2 Global Canopy Radiometry (this radiometric product was computed using both weak and strong beam radiometry rates). Moving forward, this will change to only strong beam

Table 4: ATL18/ATL28 Radiometric Parameters

Description	Gridded Parameter Name	Beams	Method	Input ATL08 resolution (m)
Terrain Photon Rate	te_photonrate_sb	Strong Beams	Mean of terrain_photon_rate within each grid cell	100
Terrain Segment Count Strong Beam	te_100num_sb	Strong Beams	Number of ATL08 strong beam segments within each grid cell	100
Canopy Photon Rate	can_photonrate_sb	Strong Beams	Mean of canopy_photon_rate within each grid cell	100
Canopy Segment Count Strong Beam	can_100num_sb	Strong Beams	Number of strong beam canopy segments for all landcover classes within each grid cell	100

4 DATA FILTERING

Although a sequence of quality checks is implemented on ATL08, it is possible that an invalid canopy or terrain height exists. These invalid heights are predominately due to high levels of solar background noise and/or the presence of low-lying clouds and fog just above the surface. Data filtering and rejection of potential outliers will occur as the ATL08 are being read as the monthly ATL28 products are constructed; thus at the segment level. Initially, canopy heights, will be evaluated for filtering but the same procedure described in the following section could also apply to terrain heights. Additional filtering rules may be added in the future.

4.1 Segment Level Canopy Filtering via Outlier Rejection

4.1.1 Northern Latitudes

Many of the canopy height outliers are likely due to low clouds or fog. For the northern most latitudes, the following assumptions are made:

1. For a canopy height above a latitude of 73 degrees is false; thus the canopy height and other canopy parameters from that segment are rejected from consideration.
2. For a canopy height above a latitude of 64 degrees should be less than 25 m; thus the canopy height and other canopy parameters from that segment are rejected from consideration.
3. It is assumed canopy height above a latitude of 59.9 degrees is less than 40 m; thus the canopy height and other canopy parameters from that segment are rejected from consideration.

4.1.2 All Latitudes

4. For a canopy height < 0.5 m; reject the h_canopy_20 but do not reject other canopy parameters if other h_canopy_20 height in the 100 m span are valid.
5. For a h_dif_canopy value > 80 m; thus the canopy height and other canopy parameters from that segment are rejected from consideration.

6. For an optical depth value > 1; the canopy height and other canopy parameters from that segment are rejected from consideration.
7. For a canopy photon rate on either the weak or strong beam < 0.1; the canopy height and other canopy parameters from that segment are rejected from consideration.
8. For ASR values > 0.9; the canopy height and other canopy parameters from that segment are rejected from consideration.
9. For canopy_openness > 15; the canopy height and other canopy parameters from that segment are rejected from consideration.
10. For landcover = class 60 (bare/sparse cover); the canopy height and other canopy parameters from that segment are rejected from consideration
11. Additional landcover canopy height limits are provided in Table 4.1. If these heights are exceeded, the canopy height and other canopy parameters from that segment are rejected from consideration.

Table 4.1 Maximum Allowed canopy height for given landcover class.

Map Code	**Max Allowed Canopy Height (m)**	**Copernicus Landcover Class**
0	N/A	No data
111	70	Closed forest, evergreen needle leaf
113	70	Closed forest, deciduous needle leaf
112	70	Closed forest, evergreen broad leaf
114	70	Closed forest, deciduous broad leaf
115	70	Closed forest, mixed
116	70	Closed forest, unknown
121	70	Open forest, evergreen needle leaf
123	70	Open forest, deciduous needle leaf
122	70	Open forest, evergreen broad leaf

124	70	Open forest, deciduous broad leaf
125	70	Open forest, mixed
126	70	Open forest, unknown
20	20	Shrubs
30	15	Herbaceous
90	15	Herbaceous Wetland
100	10	Moss and lichen
60	0.5	Bare/sparse vegetation
40	50	Cultivated and managed vegetation/agriculture
50	no limit	Urban/built up
70	5	Snow and ice
80	5	Permanent water bodies
200	5	Open sea

4.2 ATL18 Final filter (TBD)

The NOAA global self-consistent, hierarchical, high-resolution geography database (GSHHG) coastal shoreline at full resolution (Wessel and Smith, 1996) will serve as a water mask on the composite ATL18 data product. This shoreline is available at https://www.ngdc.noaa.gov/mgg/shorelines/.

Reference

Wessel, P., and W. H. F. Smith (1996), A global, self-consistent, hierarchical, high-resolution shoreline database, J. Geophys. Res., 101(B4), 8741–8743, doi:10.1029/96JB00104.

Supplemental Information

ATL08 release 005 includes the Copernicus landcover class which is derived from the IGBP classification scheme. In this classification scheme, there are 23 discrete landcover classes as follows:

Table 2: Copernicus Landcover values

Map Code	Landcover Class	Definition according to UN LCCS
0	No data	
111	Closed forest, evergreen needle leaf	Tree canopy >70%, almost all needle leaf trees remain green all year. Canopy is never without green foliage
113	Closed forest, deciduous needle leaf	Tree canopy >70%, consists of seasonal needle leaf communities with an annual cycle of leaf-on and leaf-off periods.
112	Closed forest, evergreen broad leaf	Tree canopy >70%, almost all broadleaf trees remain green year round. Canopy is never without green foliage
114	Closed forest, deciduous broad leaf	Tree canopy >70%, consists of seasonal broad leaf communities with an annual cycle of leaf-on and leaf-off periods.
115	Closed forest, mixed	Closed forest, mix of types
116	Closed forest, unknown	Closed forest, not matching any of the other definitions
121	Open forest, evergreen needle leaf	Top layer- trees 15-70% and second layer mixed of shrubs and grassland, almost all needle leaf trees remain green all year. Canopy is never without green foliage
123	Open forest, deciduous needle leaf	Top layer- trees 15-70% and second layer mixed of shrubs and grassland, consists of seasonal needle leaf tree communities with an annual cycle of leaf-on and leaf-off
122	Open forest, evergreen broad leaf	Top layer- trees 15-70% and second layer mixed of shrubs and grassland, almost all broad leaf trees remain green all year. Canopy is never without green foliage
124	Open forest, deciduous broad leaf	Top layer- trees 15-70% and second layer mixed of shrubs and grassland, consists of seasonal broad leaf tree communities with an annual cycle of leaf-on and leaf-off
125	Open forest, mixed	Open forest, mix of types

126	Open forest, unknown	Open forest, not matching any of the other definitions
20	Shrubs	Woody perennial plants with persistent and woody stems and without a main stem being less than 5m. The shrub foliage can be either evergreen or deciduous.
30	Herbaceous	Plants without persistent stems or shoots above ground and lacking firm structure. Tree and shrub cover is less than 10%
90	Herbaceous Wetland	Lands with a permanent mixture of water and herbaceous or woody vegetation. The vegetation can be present in salt, brackish, or fresh water.
100	Moss and lichen	Moss and lichen
60	Bare/sparse vegetation	Lands with exposed soil, sand, or rocks and never has more than 10% vegetation cover during any time of the year
40	Cultivated and managed vegetation/agriculture	Lands covered with temporary crops followed by harvest and a bare soil period.
50	Urban/built up	Land covered by buildings or other man-made structures
70	Snow and ice	Land under snow or ice throughout the year
80	Permanent water bodies	Lakes, reservoirs, and rivers. Can be either fresh or salt-water bodies
200	Open sea	Oceans, seas. Can be either fresh of salt-water bodies.