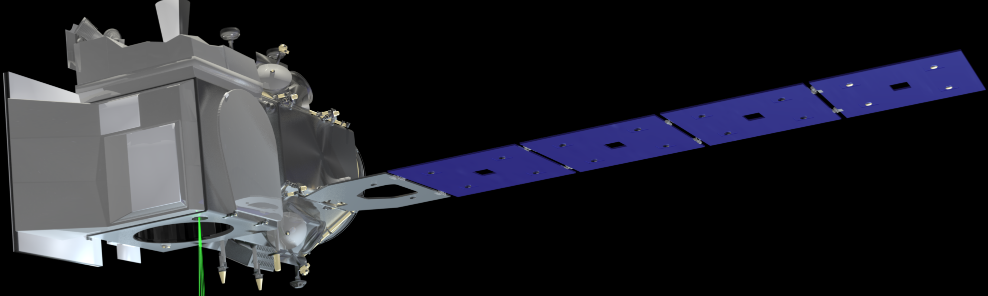
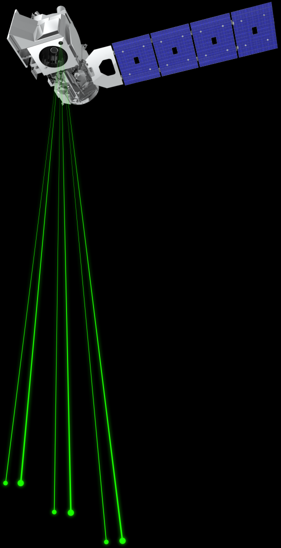


Tyler Sutterley[1*]
Nathan Kurtz[2]
Ben Smith[1]
[1]*UW Applied Physics Laboratory*
[2]*NASA Goddard Space Flight Center*
email: tsutterl@uw.edu

ICESat-2 Products: *from photons to grids*

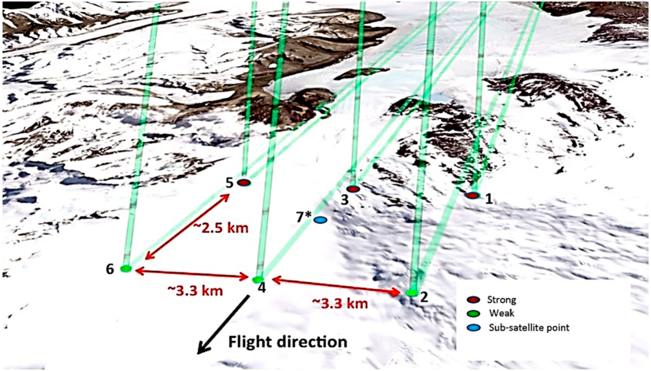
[*] with materials from ICESat-2 PSO, Science Team, SlideRule team, and collaborators

ICESat-2 Science Objectives



- Quantify polar ice sheet contributions to current and recent sea level change and the linkages to climate conditions
- Quantify regional signatures of ice sheet changes
  - Quantifying the regional evolution of ice sheet change
  - Assess mechanisms driving recent changes
  - Improve predictive ice sheet models
- Estimate sea ice thickness to examine ice-ocean-atmosphere exchanges of energy, mass and moisture
- Measure vegetation canopy height as a basis for estimating large-scale biomass and biomass change

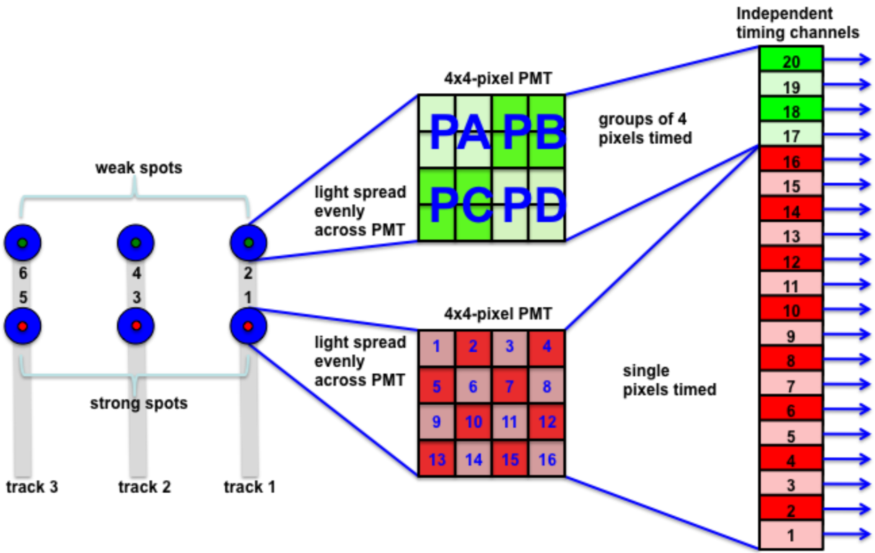
Advanced Topographic Laser Altimeter System (ATLAS)



- Single 10kHz 532nm laser micro-pulse $\rightarrow$ split into 6 beams
- Detectors sensitive to green light returns at the single photon level
- On-the-ground 3 km spacing between pairs to increase spatial coverage
- On-the-ground 90 m pair spacing for slope determination
- Different beam energies to provide dynamic range for varying surface reflectances

Figure 2 from Neuenschwander and Magruder [2019]

ATLAS Photon Timing



ICESat-2 Photon Geolocation

Position of observatory in space

- Precision Orbit Determination (POD) – NASA GSFC
- Based on Ruag GPS receivers
- Verified with Satellite Laser Ranging (SLR)
- Orbit known to <2 cm radial

Pointing vectors for ATLAS laser beams

- Precision Pointing Determination (PPD) – UT Austin Applied Research Lab
- Based on Sodern Star Trackers and Laser Reference System (LRS)
- Verified with cal/val data comparisons with photon returns

Photon time of flight + POD + PPD $\rightarrow$ photon return bounce point

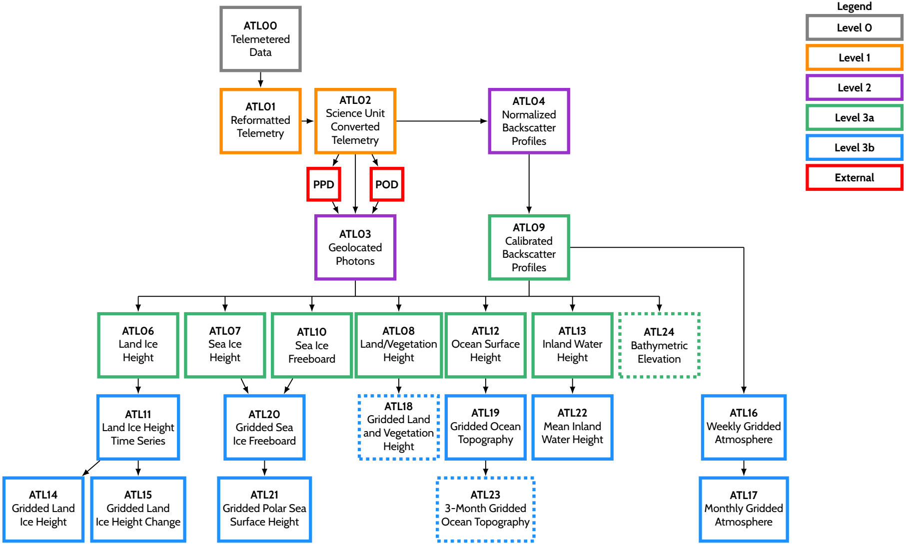
ICESat-2 Data Production

Level 0 Engineering Data → **Level 1** Reformatted Telemetry → **Level 2** Along-Track Data → **Level 3a** Along-Track Science Data → **Level 3b** “Gridded” Science Data

Data Production Keywords:

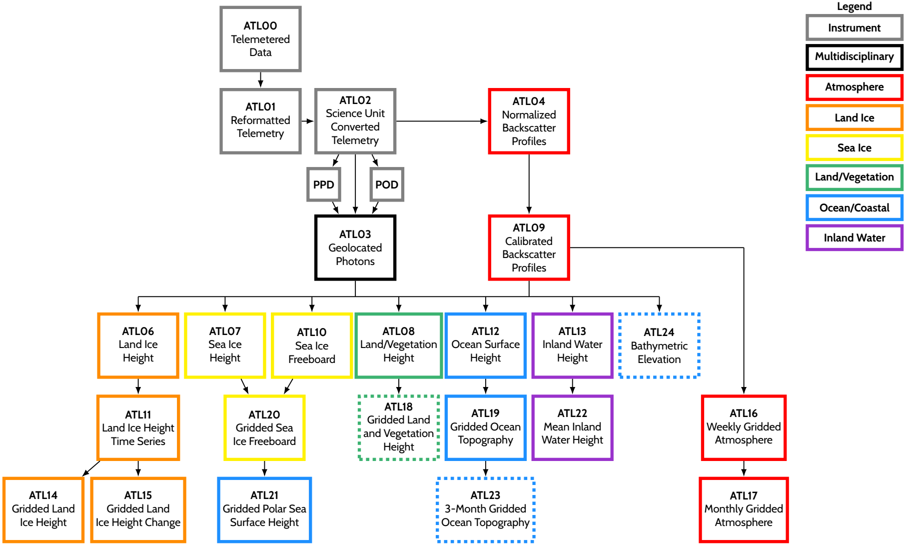
- **ATLAS:** Advanced Topographic Laser Altimeter System
- **ASAS:** ATLAS Science Algorithm Software
- **PGE:** Product Generation Executive
- **SIPS:** Science Investigator-led Processing System
- **SCF:** Science Computing Facility

ICESat-2 Product Chart



ANC: Ancillary Data, **CAL:** Calibration Product, **POD:** Precision Orbit Determination, **PPD:** Precision Pointing Determination

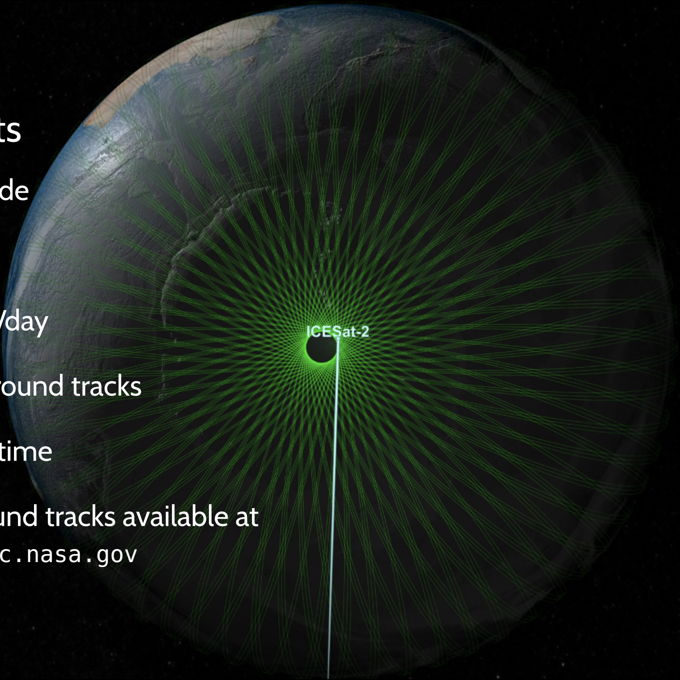
ICESat-2 Product Applications Chart



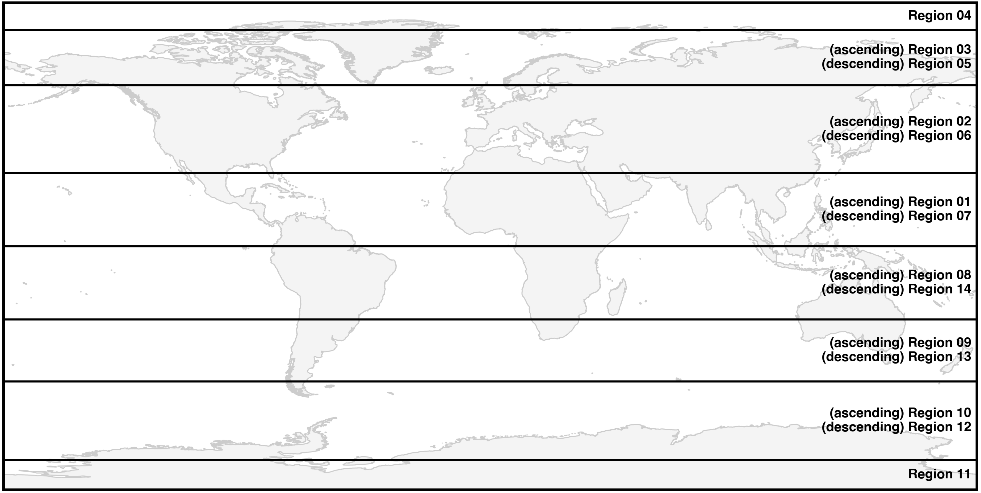
ANC: Ancillary Data, **CAL:** Calibration Product, **POD:** Precision Orbit Determination, **PPD:** Precision Pointing Determination

ICESat-2 Orbits

- 500 km altitude
- 88° S to 88° N
- 15 revolutions/day
- 1387 repeat ground tracks
- 91-day revisit time
- Predicted ground tracks available at `icesat-2.gsfc.nasa.gov`

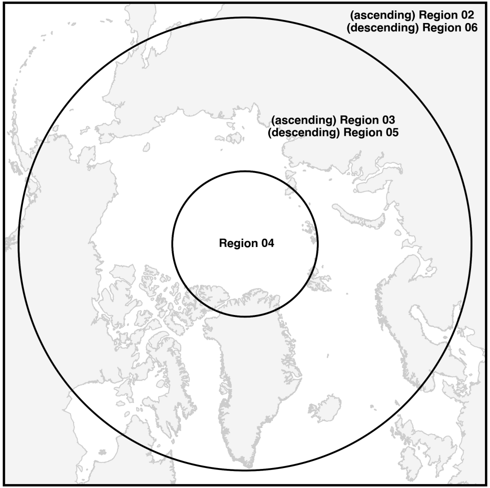


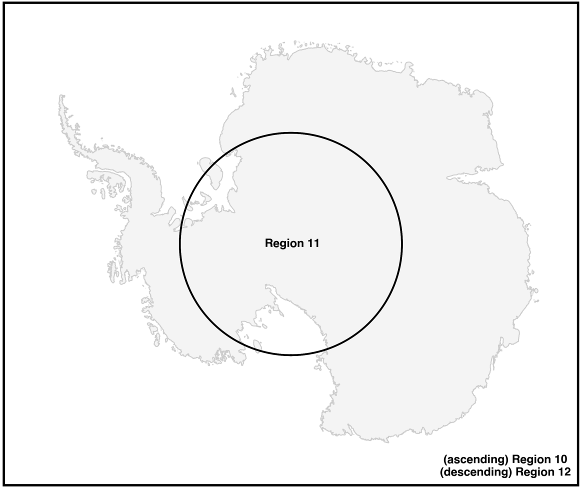
Granule Regions



Each orbit of ICESat-2 data is broken up into 14 granules in order to limit the overall file sizes and to reduce the number of files that need to be processed to create the higher-level science products

Granule Regions





Each orbit of ICESat-2 data is broken up into 14 granules in order to limit the overall file sizes and to reduce the number of files that need to be processed to create the higher-level science products

ICESat-2 Along-Track Sampling

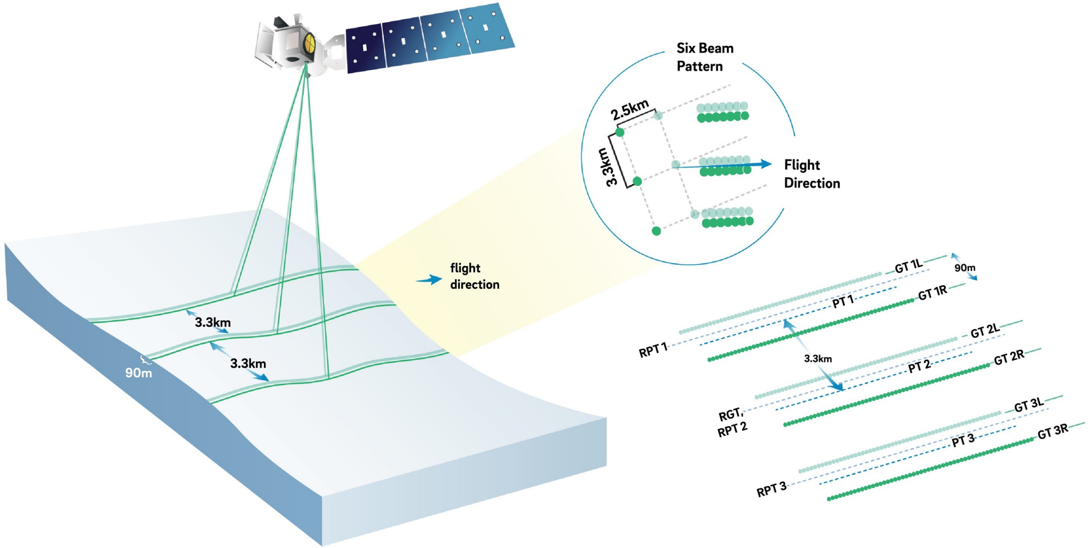
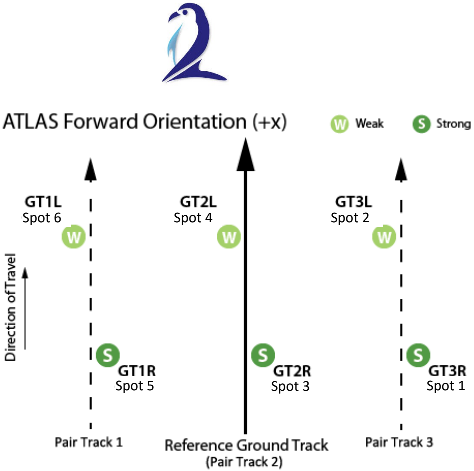
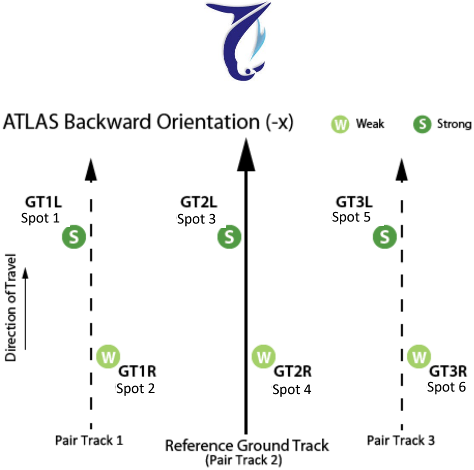


Figure 1 from Smith et al. [2019]

ICESat-2 in its two orientations





Credit: NSIDC

File Naming Conventions

`ATL[xx]_[yyyymdd][hhmmss]_[tttt][cc][nn]_[vvv]_[rr].h5`

- `xx`: ATLAS product number
- `yyyymmdd`: year, month and day of data acquisition
- `hhmmss`: start time, hour, minute, and second of data acquisition
- `tttt`: Reference Ground Track (RGT, ranges from 1–1387)
- `cc`: Orbital Cycle (91-day period)
- `nn`: Granule number (ranges from 1–14)
- `vvv`: data version number
- `rr`: data release number

* used for ATL03, ATL04, ATL06, ATL08, ATL09, ATL10, ATL12, ATL13, ATL16, ATL17, ATL19, and ATL22

File Naming Conventions: Sea Ice

```
ATL[xx]-[hh]_[yyyymdd][hhmmss]_[tttt][cc][nn]_[vvv]_[rr].h5
```

- `xx` : ATLAS product number
- `hh` : Sea ice hemisphere flag (01=north, 02=south)
- `yyyymmdd` : year, month and day of data acquisition
- `hhmmss` : start time, hour, minute, and second of data acquisition
- `tttt` : Reference Ground Track (RGT, ranges from 1–1387)
- `cc` : Orbital Cycle (91-day period)
- `nn` : Granule number (for sea ice: 01)
- `vvv` : data version number
- `rr` : data release number

* used for ATL07, ATL10, ATL20, and ATL21

ATL03: Global Geolocated Photon Data

Contains:

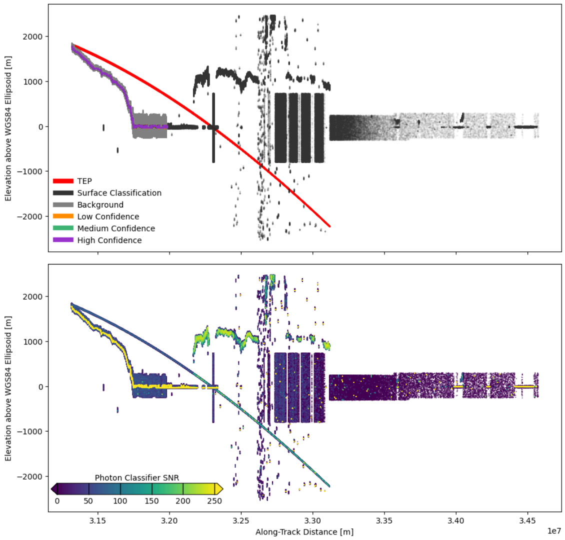
- Geolocation, time and elevation for all photons telemetered from ATLAS
- Photon classifications for each surface type
- Geophysical and atmospheric corrections
- Instrumental parameters

Advantages:

- Every photon is there, and every parameter
- Can derive information for all surface types

Use if you want to:

- Look at surfaces at a scale unresolved in higher-level products
- Look at processes the higher-level products were not designed to observe



ATL04 and ATL09: Atmospheric Backscatter Profiles

Contains:

- Atmospheric layer heights and optical properties

Advantages:

- Different channel of data from ATL03: can visualize cloud returns or Antarctic blowing snow

Use if you want to:

- Want to investigate cloud or suspended particle optical depths
- Want to try to understand atmospheric effects on ground returns
- Want to be able to mask cloud-affected segments

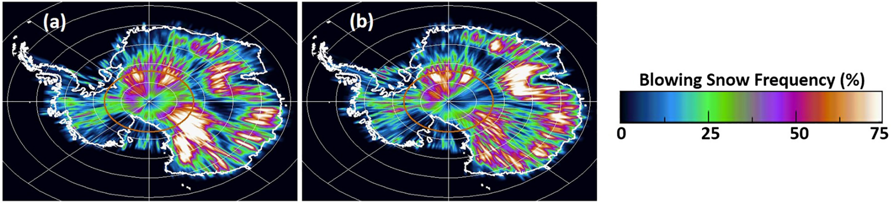


Figure 11 from Palm et al. [2021]

ATL06: Land Ice Height Data

Contains:

- Overlapping 40-meter linear segments fit to land-ice photons
- Height error and segment quality estimates

Advantages:

- Lighter product than ATL03
- Provides estimated surface heights with cm-level corrections

Disadvantages:

- 40 meters is too coarse for some applications
- Only designed for single surface returns

Use if you want to:

- Make large-scale repeatable measurements of glaciers and ice sheets

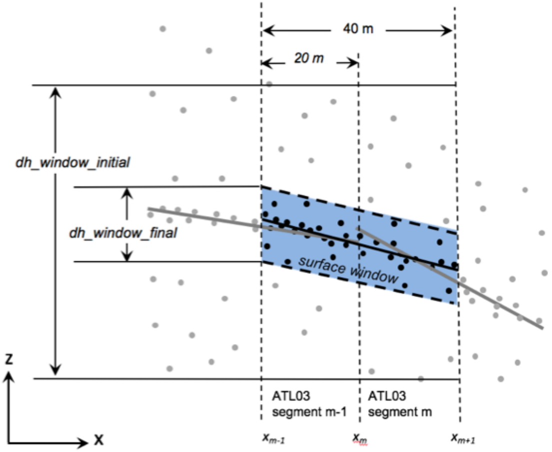


Figure 3 from Smith et al. [2019]

ATL11: Slope-Corrected Land Ice Height Time Series

Contains:

- 120-meter along-track segments for each beam pair corrected for across-track slope
- Crossover estimates from ATL06 at reference points

Advantages:

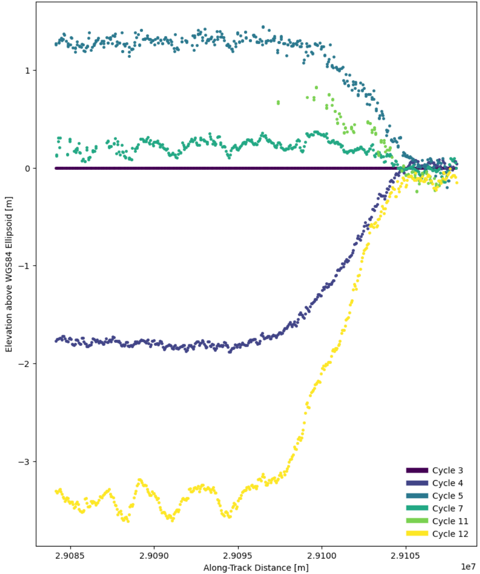
- Contains data for all cycles with along-track data following the Reference Ground Tracks (RGTs)
- Easy calculation of height change through time

Disadvantages:

- 120-m resolution is too coarse for some applications
- May not work well over complex surfaces

Use if you want to:

- Make large-scale estimates of glacier and ice sheet height change



ATL14 and ATL15: Gridded Land Ice Height and Height Change

Contains:

- ATL14: gridded digital elevation model (DEM) and height uncertainty at 100m posting
- ATL15: gridded land ice height change estimates at 1km, 10km, 20km, and 40km posting

Advantages:

- Gridded product combining all available along-track ATL11 data
- Simplifies volume change calculations using ICESat-2 data

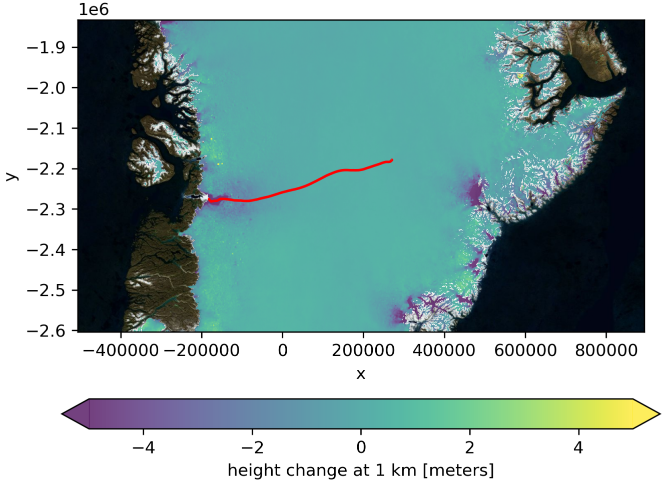
Disadvantages:

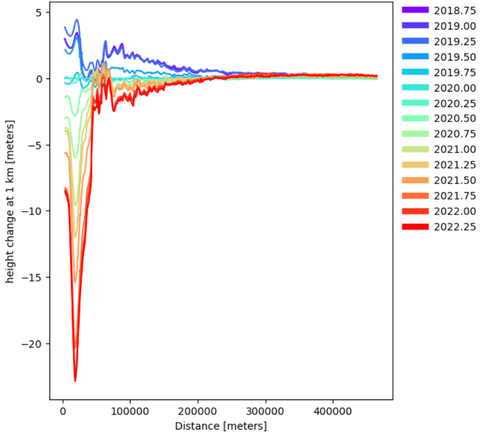
- ATL14 estimates degrade where measurements are unavailable
- Quarter-annual temporal sampling might not be high enough for certain applications

Use if you want to:

- Use gridded estimates of height change for ice sheet models
- Start creating land ice mass balance estimates from ICESat-2
- Extract land ice height change estimates along transects

Investigating ATL15 Gridded Land Ice Height Change Data

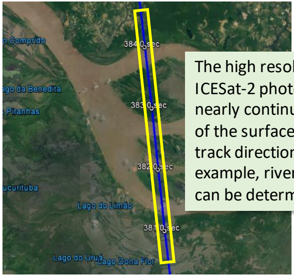




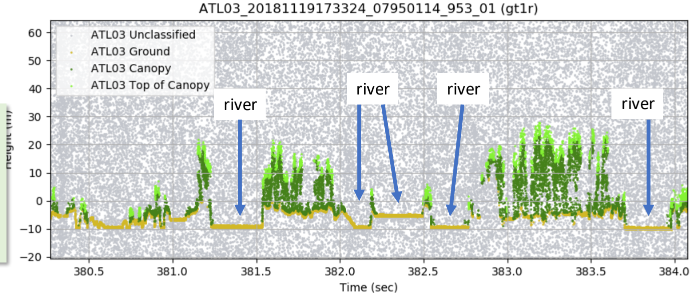
`IS2view` display of ATL15 height change data and extracted transect using glacier flowlines from Felikson et al. [2020]

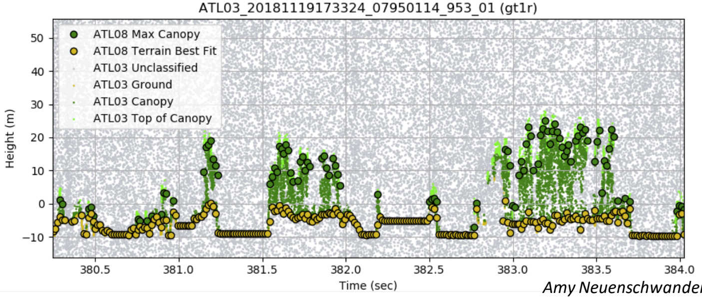
Example of ATL03 and ATL08

Amazon Floodplain



The high resolution of the ICESat-2 photons provide a nearly continuous sampling of the surface in the along-track direction. In this example, river stage levels can be determined.





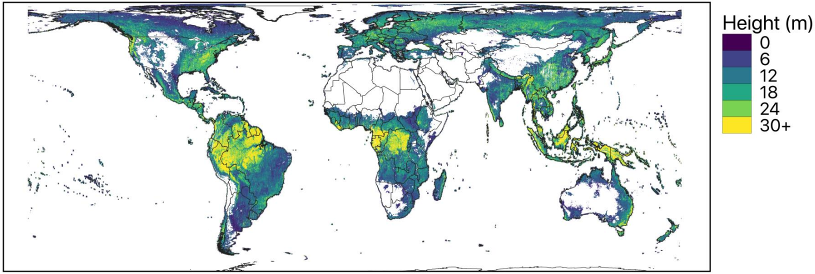
Photons from ICESat-2 are color-coded by the ATL08 (Land and Vegetation) algorithm. Data are from a day acquisition.

Bottom plot includes the same photons as the top panel, but the ATL08 100 m canopy height and terrain heights are superimposed

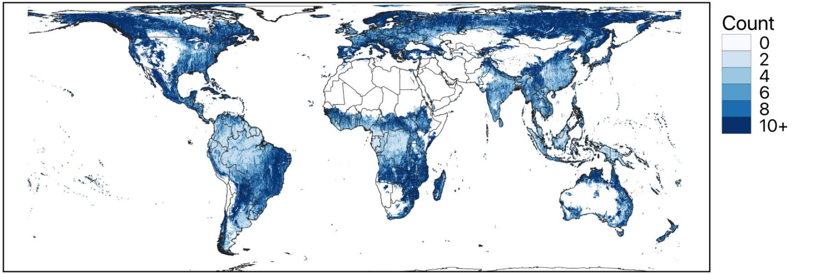
Amy Neuenschwander, U Texas

Gridded Canopy Heights from ICESat-2

The official ATL18 (gridded Terrain and Vegetation Heights) will be at a 1 km resolution and available with Release 007 of the data.



Using Machine Learning and the SlideRule architecture, we are also exploring methods to create on-demand terrain and vegetation products at user-specified resolutions.

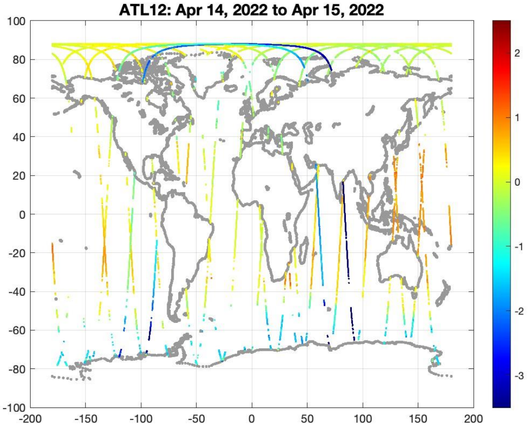


ICESat-2 ATL12 Along-track Sea Surface Heights (SSH)

ATL12 sea surface heights in files of 4-orbits over the world ocean >10-m deep. Include:

a) Ocean segment averages, the distribution, and first four moments of SSH for 6 beams plus the averages of pertinent geophysical variables and corrections. Ocean segments are 0.5 to 7-km long to reduce uncertainty over wave covered surfaces.
b) 10-m bin averages of DOT=SSH-geoid within ocean segments. In addition to higher resolution, 10-m bin statistics provide sea state bias, harmonic fits and wave statistics. Release 7 will add first photon bias and DOT in sea ice.

Ocean segment average DOT from four 4-orbit ATL12 files, April 14-15, 2022



J. Morison, Dickinson, Hancock, Roberts, Robbins, 7/29/2023

ICESat-2 ATL19 and ATL23 Gridded Dynamic Ocean Topography (DOT)

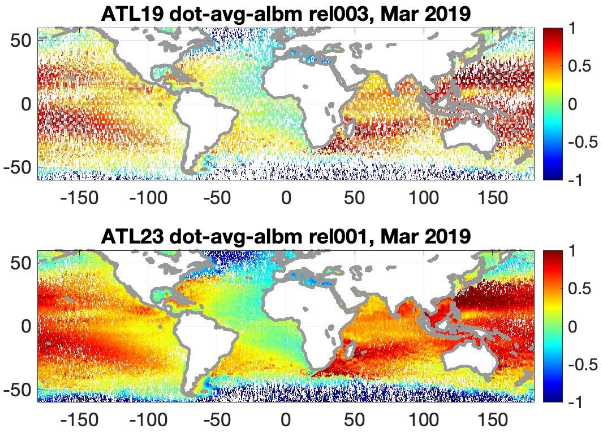
ATL19 are monthly grid-averages of ATL12 DOT plus related variables.

a) In ¼° Mid-Latitude Grid and 25-km polar stereographic N. & S. Polar Grids

b) Include individual beam averages (checks inter-beam bias), all-beam averages, cell-centered averages, and in Rel 4, minimum uncertainty centered averages.

ATL23 (new Rel. 1) are monthly 3-month grid-averages of ATL12 DOT plus related variables. Similar to ATL19 but extending over 3 months to cover the ~91 day repeat of ICESat-2 and fill more grid cells.

DOT over the Mid-Latitude Grid from (top) ATL19 for March 2019 and (bottom) ATL23 for average over, Feb-March-April 2019



J. Morison, Dickinson, Hancock, Roberts, Robbins, 7/29/2023

ATL07: Sea ice surface height

Contains:

- Along-track heights for sea ice and leads
- Geophysical corrections and preliminary surface type flagging
- Uses 150 photon aggregates to obtain surface heights

Advantages:

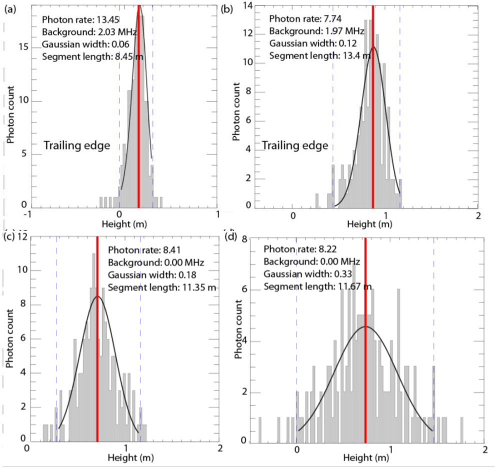
- Lighter product than ATL03
- Contains very accurate (better than 3 cm) height retrievals and ancillary information such as surface roughness and retrieval quality flags

Disadvantages:

- Surface height retrievals have varying length scales
- Surface type flagging not fully developed

Use if you want to:

- Have base level surface heights for development work such as freeboard or surface process studies (e.g. lead and floe lengths)



Kwok et al., 2019

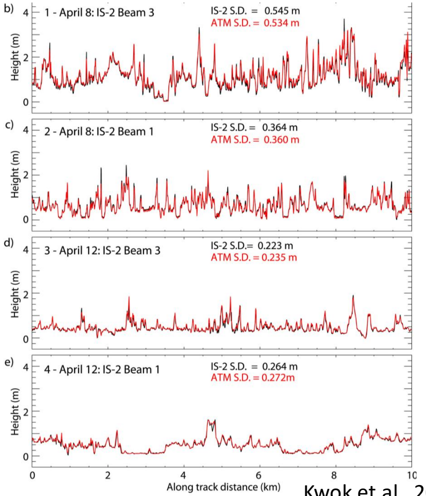
ATL10: Sea ice freeboard

Contains:
- Along-track sea ice freeboard and surface heights
- Surface type flagging and ancillary information

Advantages:
- Lighter product than ATL07 with higher level freeboard and surface type information

Disadvantages:
- Higher levels of missing/invalid data than ATL07 (low ice concentration, near-coastal)
- Varying length scales of retrievals
- Summer sea ice retrievals under investigation (July 2022 field campaign)

Use if you want to:
- Use along-track freeboard retrievals
- Use a highly accurate (3 cm or better over 25 km length scales) product



Kwok et al., 2019

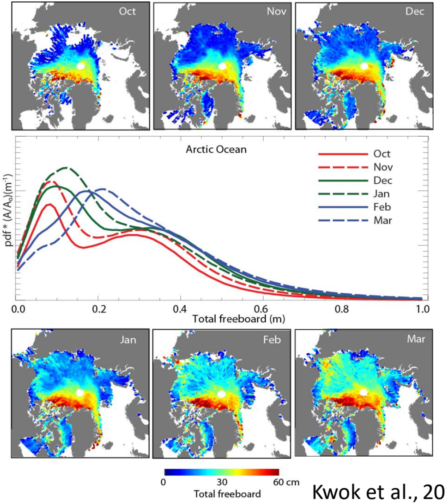
ATL20: Gridded sea ice freeboard

Contains:
- 25 km gridded sea ice freeboard at daily to monthly resolution

Advantages:
- Lighter product than ATL10

Disadvantages:
- Coarse length scale, averages out the high resolution of the ICESat-2 data

Use if you want to:
- Look at gridded sea ice freeboard data for large-scale determination of sea ice change
- Merge with other coarse-resolution data such as passive microwave products



Kwok et al., 2019

ATL21: Polar Sea Surface Height (SSH) anomalies

Contains:

- 25 km gridded sea surface height anomalies for sea ice covered regions

Advantages:

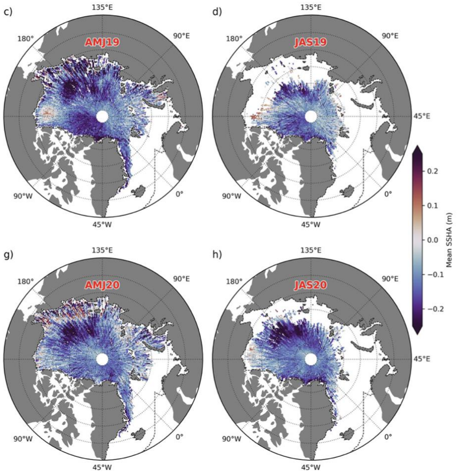
- Lighter product than ATL10
- Uses more sophisticated sea surface height retrieval algorithm to detect leads than ATL12 and higher level gridded ocean products
    - Work to reconcile ATL10 and ATL12 underway

Disadvantages:

- Coarse length scale, averages out the high resolution of the ICESat-2 data
- Only center strong beam available due to time and spatially varying biases of beams

Use if you want to:

- Look at large-scale gridded sea surface height anomalies or derive DOT



Bagnardi et al., 2021

ICESat-2 Science Requirements

4.1.1 Baseline Science Requirements

a) ICESat-2 shall produce an ice surface elevation product that enables determination of ice-sheet elevation change rates to an accuracy of better than or equal to 0.4 cm/yr on an annual basis.

b) ICESat-2 shall produce an ice surface elevation product that enables determination of annual surface elevation change rates on outlet glaciers to an accuracy of better than or equal to 0.25 m/yr over areas of 100 km^2 for year-to-year averages.

c) ICESat-2 shall produce an ice surface elevation product that enables determination of surface elevation change rates for dynamic ice features that are intersected by its set of repeated ground-tracks to an accuracy of better than or equal to 0.4 m/yr along 1-km track segments.

d) ICESat-2 shall produce an ice surface elevation product that enables resolution of winter (accumulation) and summer (ablation) ice-sheet elevation change to 10 cm at 25-km x 25-km spatial scales.

e) ICESat-2 shall provide monthly surface elevation products to enable, when sea surface height references (leads) are available and under clear sky conditions, the determination of sea-ice freeboard to an uncertainty of less than or equal to 3 cm along 25-km segments for the Arctic and Southern Oceans; the track spacing should be less than or equal to 35 km at 70 degrees latitude on a monthly basis.

f) ICESat-2 shall make measurements that span a minimum of three years.

g) ICESat-2 shall produce an ice surface elevation product that, in conjunction with ICESat-1, enables determination of elevation changes on a decadal time scale.

h) ICESat-2 shall produce elevation measurements, that enable independent determination of global vegetation height, with a ground track spacing of less than 2 km over a 2-year period.

i) The ICESat-2 Project shall conduct a calibration and validation program to verify delivered data meet the requirements in 4.1.1 a, b, c, d, e, g and h.

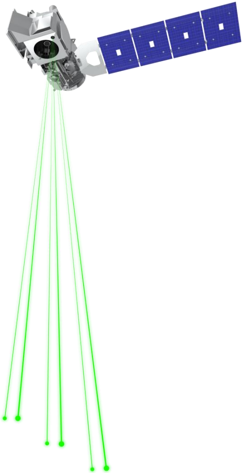
✅

ICESat-2 has been found to be meeting all Level-1 Science Requirements (Markus et al., 2017)

→ Science requirements paper in preparation

Future Mission Outlook

- Currently awaiting final guidance from Senior Review process with focus on:
  - Balancing repeat tracks for change detection vs. track densification
  - Planned international collaborations for 2024–2029
  - Continuing cloud and aerosol observations upon decommissioning of CALIPSO
  - Development of new bathymetric products and cal/val plans
  - Continuation of oceanography, coastal altimetry, and atmospheric data with mission budget cuts
- Development towards the next release (007) of data products in ~2024
- **Next science team meeting with new 2023 science team member selections in La Jolla, CA October 2–4**



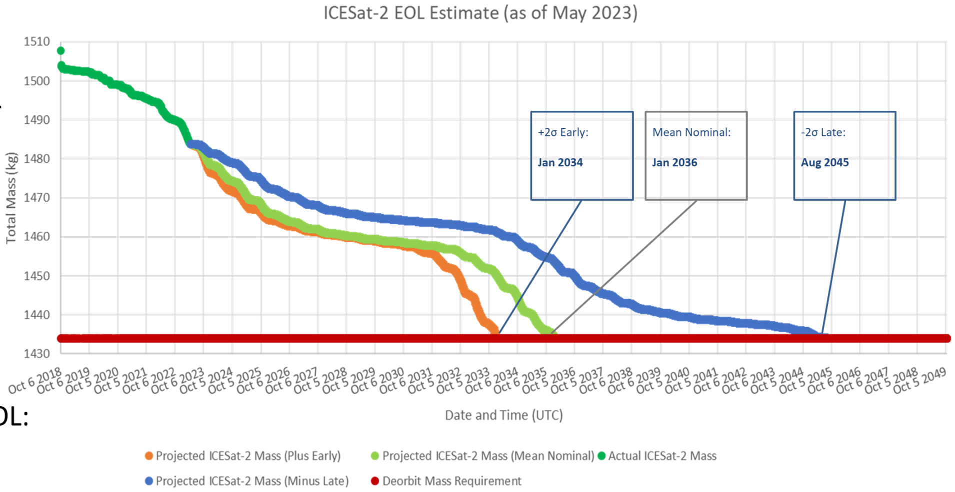
Future Mission Outlook: End of Life Estimates

ICE, CLOUD, AND LAND ELEVATION SATELLITE

Fuel for orbit-keeping may be life-limiting factor

Nov 2022

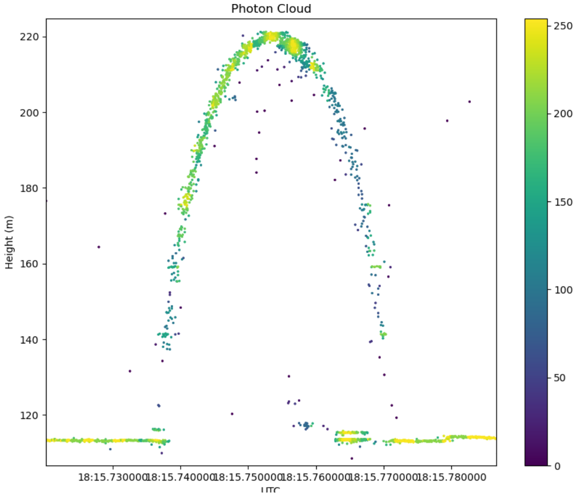
May 2023



Mean Nominal EOL: Jan 2036

ICESat-2 Feature Find!

https://demo.slideruleearth.io



Indoor bathymetry at Tropical Islands Resort
Former airship hanger at Brand-Briesen Airfield
Resort located at 52.0375°N, 13.748611°E
Original ATL03 feature find by Kelly Brunt (UMD)