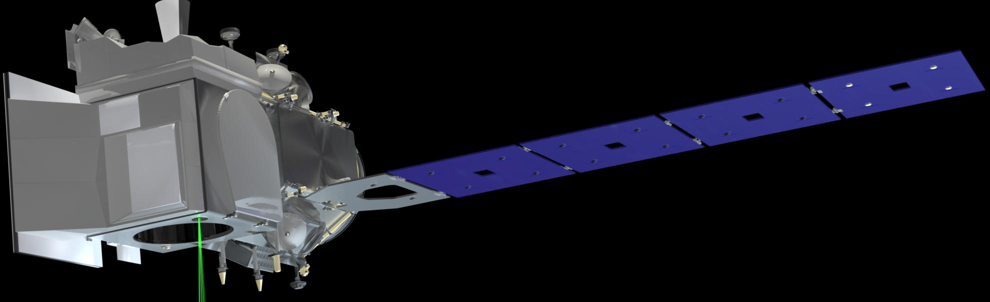


Tyler Sutterley*

UW Applied Physics Laboratory

email: tsutterl@uw.edu

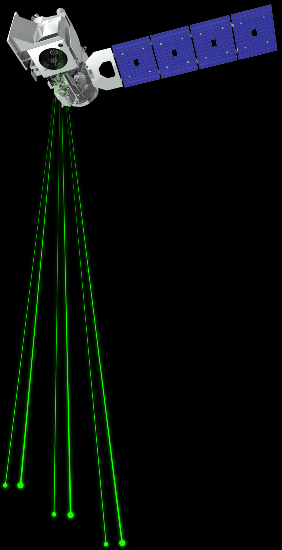
ICESat-2 Products: *from photons to grids*

* **with help and materials from ICESat-2 PSO, Science Team and collaborators**

Part 1

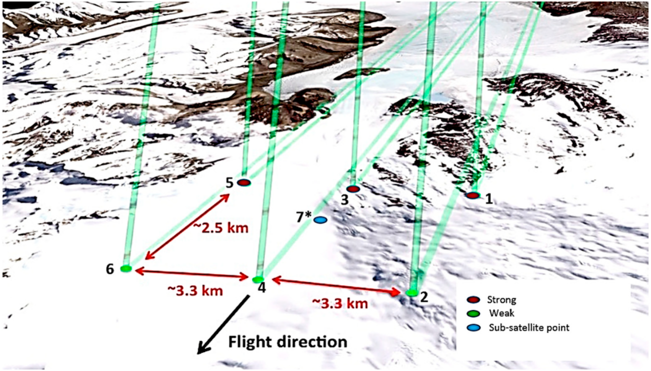
Mission and Instrument Overview

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
  - 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

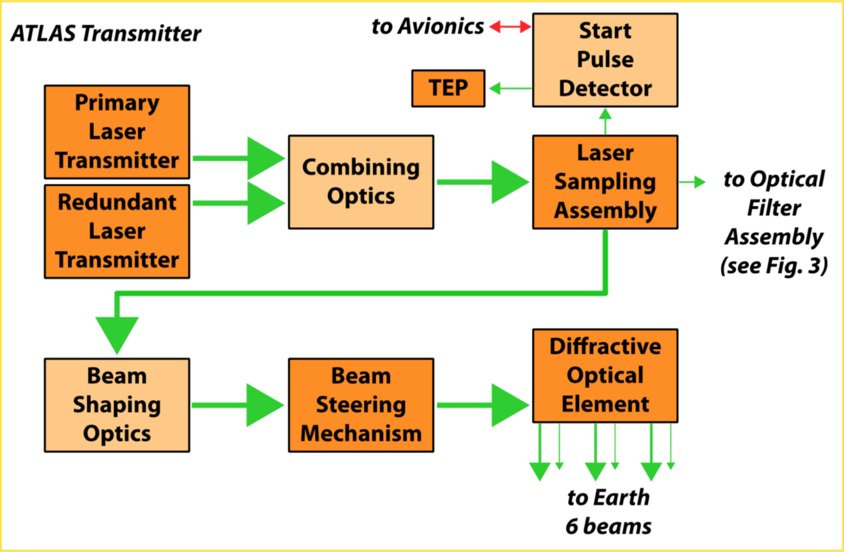
Advanced Topographic Laser Altimeter System (ATLAS)



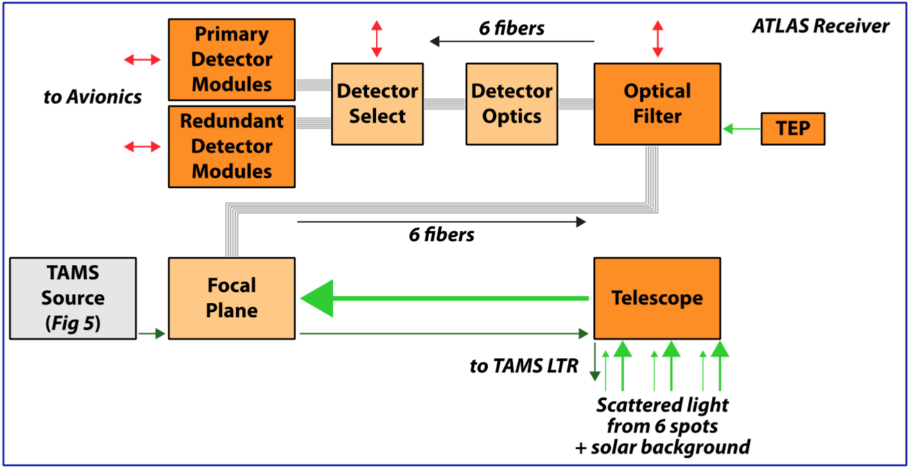
- Single 10kHz 532nm laser micro-pulse → split into 6 beams
- Detectors sensitive to green light returns at the single photon level
- On-the-ground 3 km spacing between pairs to increase spatial coverage
- On-the-ground 90 m pair spacing for slope determination
- Different beam energies to provide dynamic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

Figure 2 from Neuenschwander and Magruder [2019]

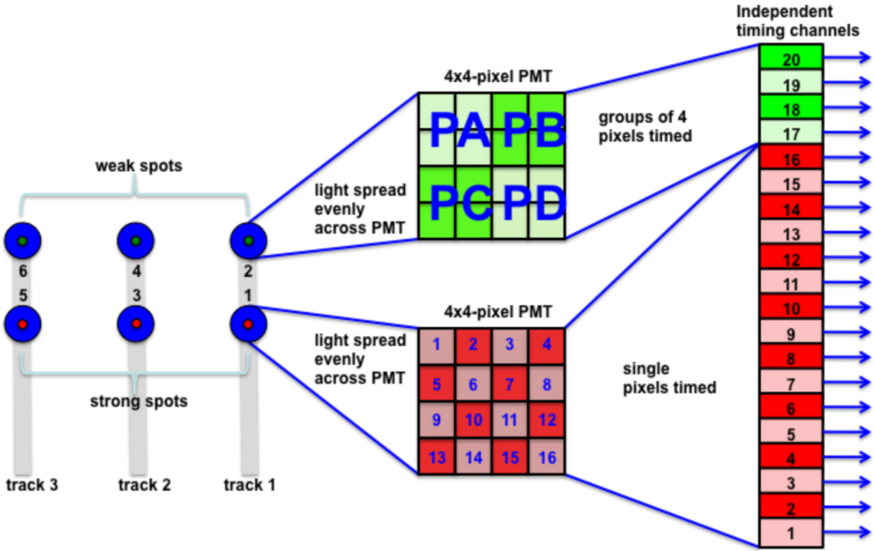
ATLAS Transmitter



ATLAS Receiver



ATLAS Photon Timing



ICESat-2 Photon Geolocation

Position of observatory in space

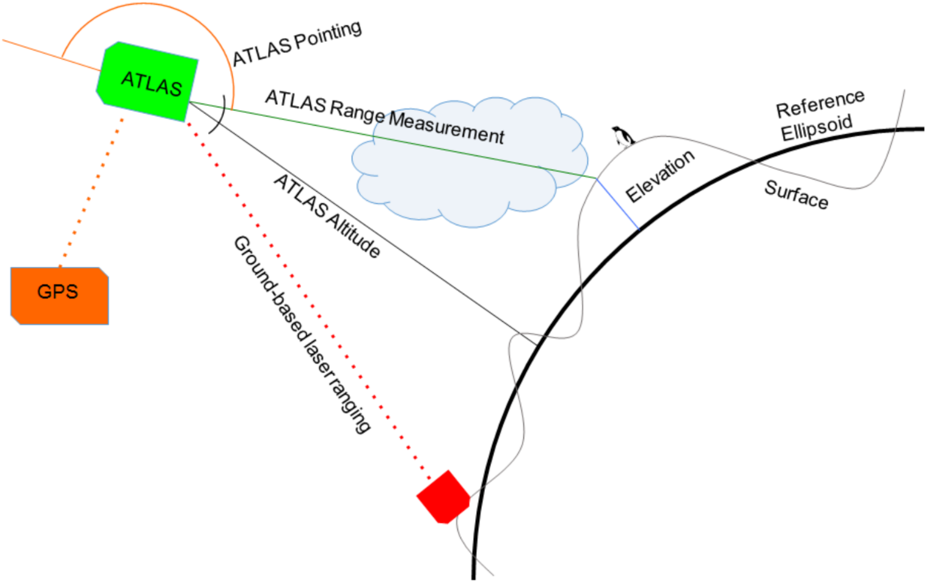
- Precision Orbit Determination (POD) – NASA GSFC
- Based on Ruag GPS receivers
- Verified with Satellite Laser Ranging (SLR)
- Orbit known to <2 cm radial

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

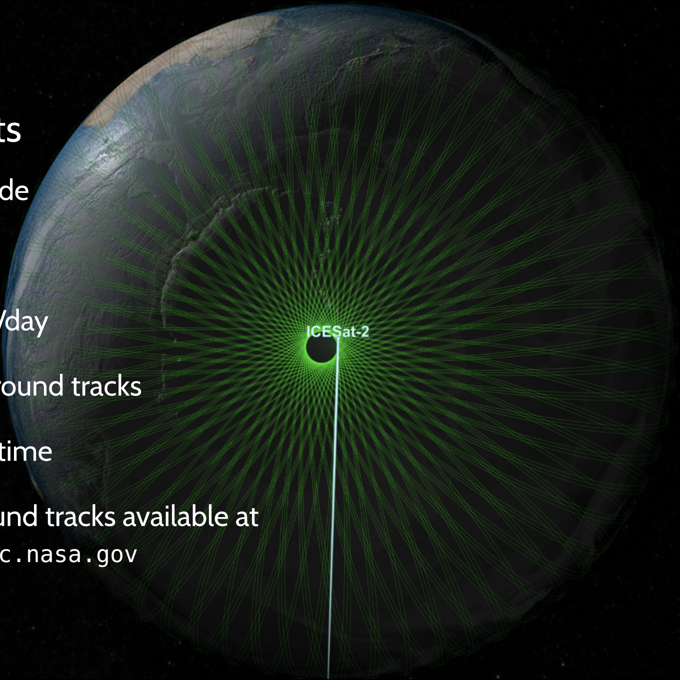
Photon time of flight + POD + PPD $\rightarrow$ photon return bounce point

ICESat-2 Primary Measurements



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`



ICESat-2 Along-Track Sampling

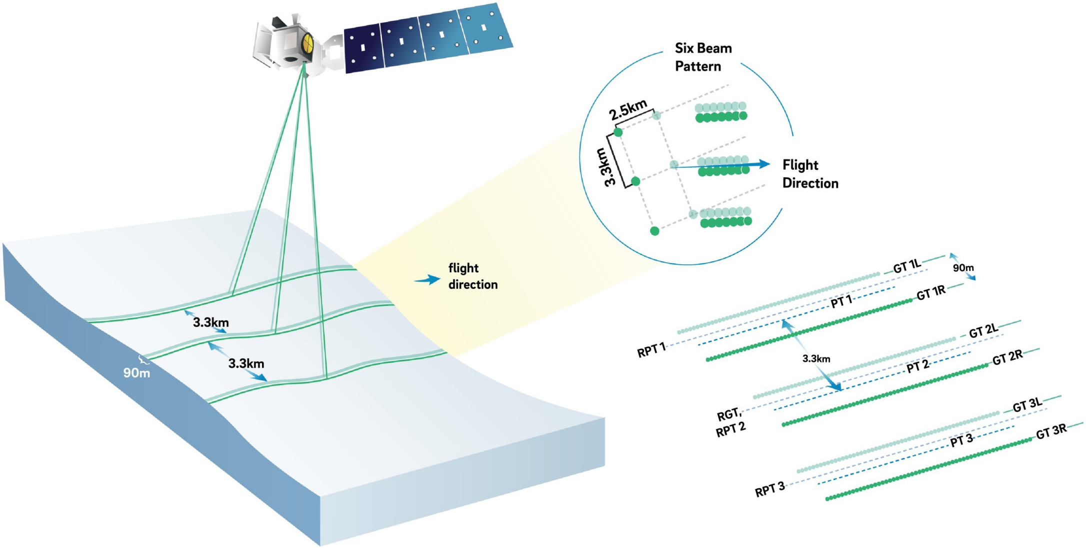
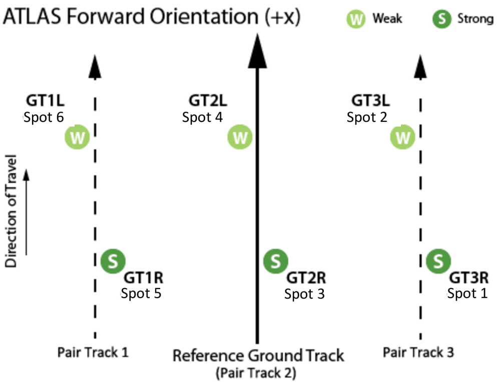
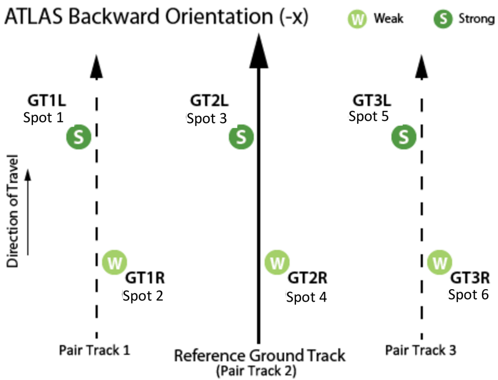


Figure 1 from Smith et al. [2019]

Spacecraft Orientation

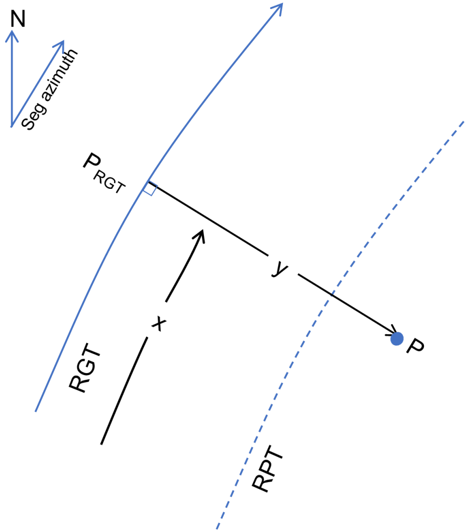




Provided by NSIDC

ICESat-2 Local Coordinate System

- Along-track coordinates, `x_atc`, are measured parallel to each RGT and are in reference to the equator
- Across-track coordinates, `y_atc`, are measured perpendicular to and in reference to the RGT
- Averaging Schemes:
  1. Measurements can be averaged over a set along-track distance
  2. Measurements can be averaged over a set number of photons and have a variable along-track length



ATL06 ATBD Figure 3.5

Part 2

Data Products

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

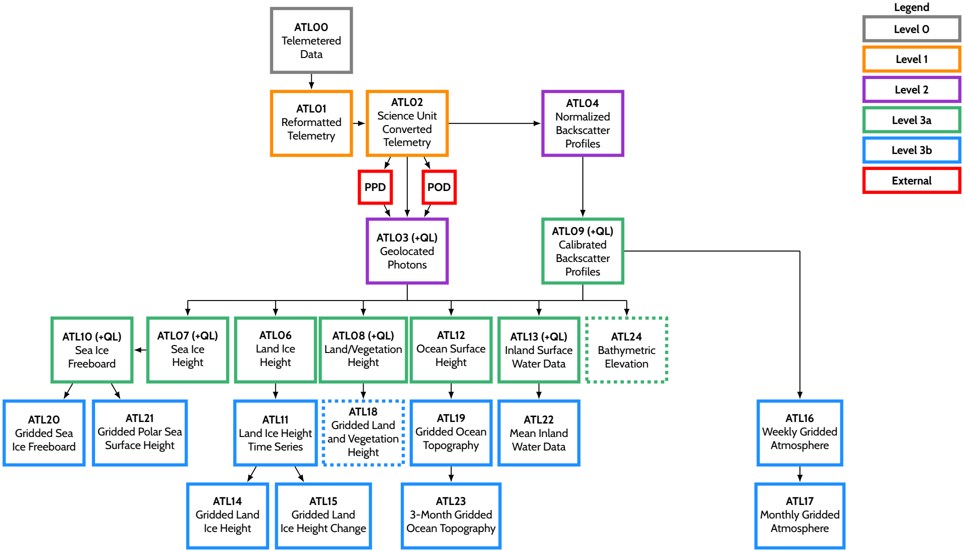
ASAS: ATLAS Science Algorithm Software

PGE: Product Generation Executive

SIPS: Science Investigator-led Processing System

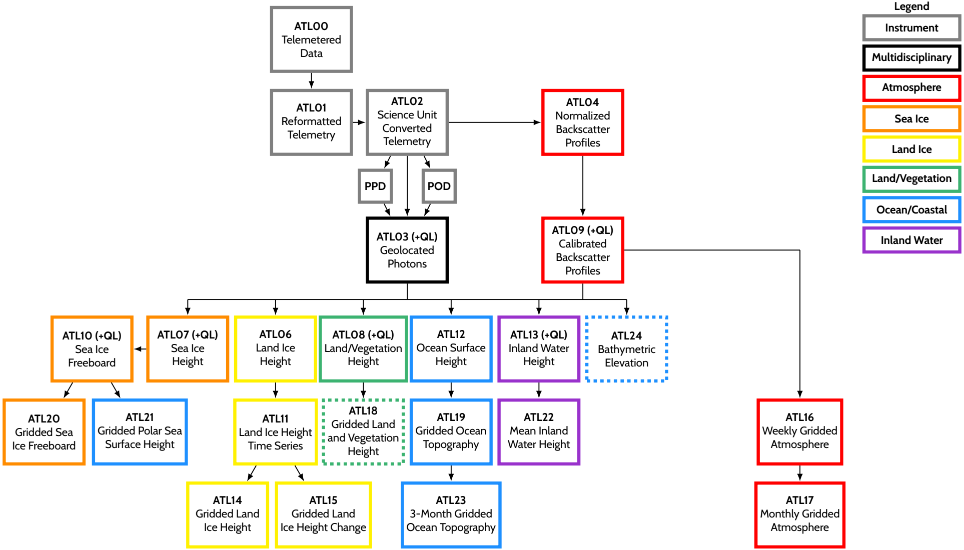
SCF: Science Computing Facility

ICESat-2 Product Chart



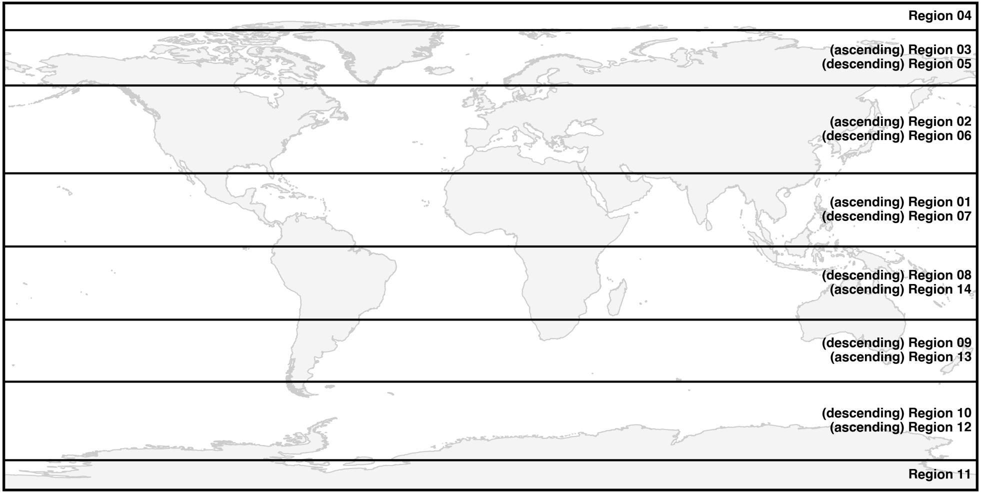
ANC: Ancillary Data, **CAL:** Calibration Product, **POD:** Precision Orbit Determination, **PPD:** Precision Pointing Determination; **QL:** Quicklook Available

ICESat-2 Product Applications Chart



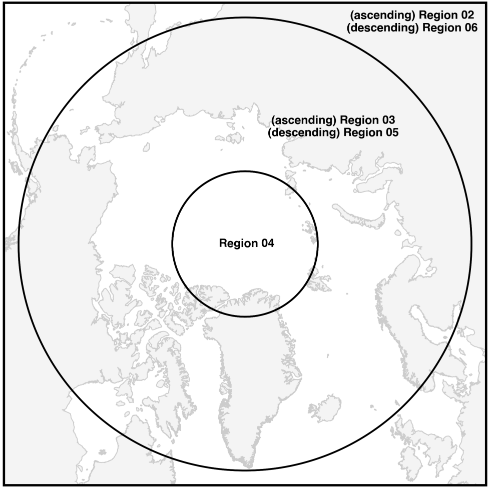
ANC: Ancillary Data, **CAL:** Calibration Product, **POD:** Precision Orbit Determination, **PPD:** Precision Pointing Determination; **QL:** Quicklook Available

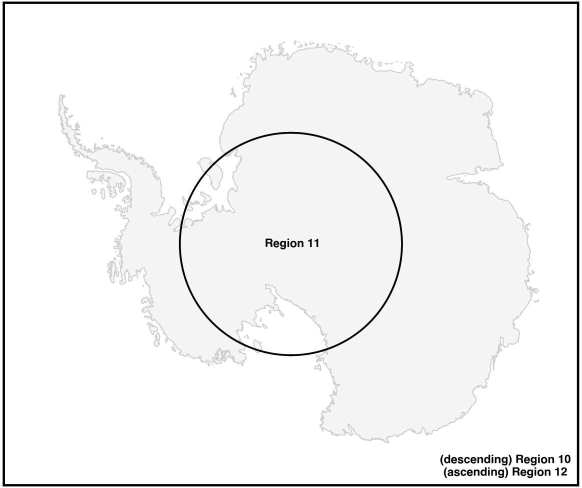
Granule Regions



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

File Naming Conventions

```
ATL[xx]_[yyyymmdd][hhmmss]_[tttt][cc][nn]_[rrr]_[vv].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, always 01 for atmosphere products)

`rrr` : data release number

`vv` : data version number

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

File Naming Conventions: Sea Ice

`ATL[xx]-[hh]_[yyyymmdd][hhmmss]_[tttt][cc][nn]_[rrr]_[vv].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 (always 01 for sea ice products)
- `rrr` : data release number
- `vv` : data version number

* used for ATL07, ATL10, ATL20, and ATL21

ATL03: Global Geolocated Photon Data

Contains:

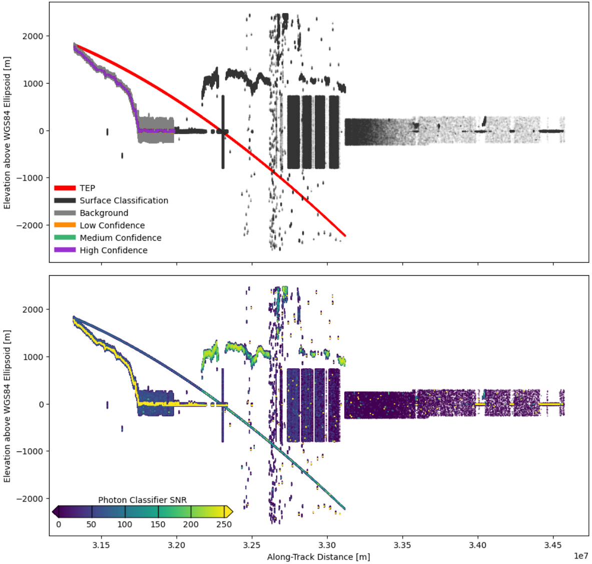
- Geolocation, time and elevation for all photons telemetered from ATLAS
- Photon classifications for each surface type
- Geophysical and atmospheric corrections
- Instrumental parameters

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:

- Much larger height window provided from the atmospheric data channel

Use if you want to:

- Want to investigate cloud or suspended particle optical depths
- Visualize cloud returns or Antarctic blowing snow
- Want to try to understand atmospheric effects on photon ground returns

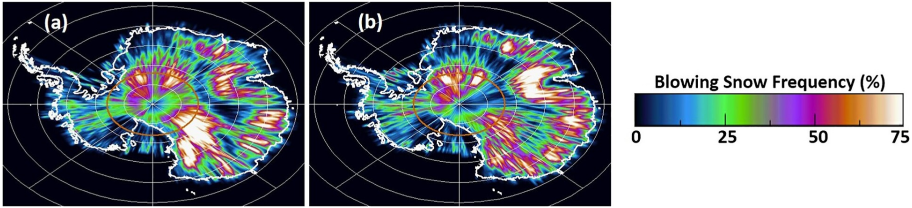


Figure 11 from Palm et al. [2021]

ATL06: Land Ice Height Data

Contains:

- Overlapping 40-meter linear segments fit to land and 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

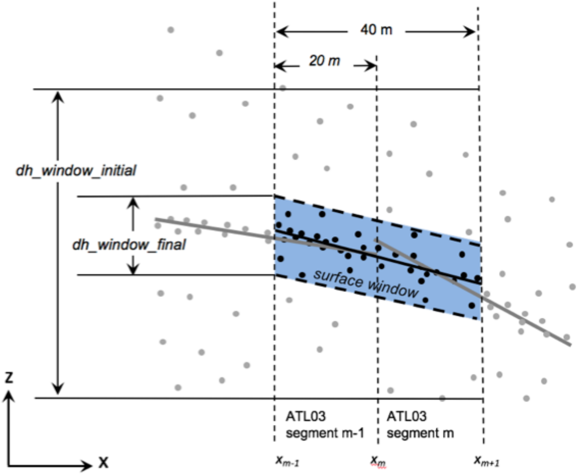


Figure 3 from Smith et al. [2019]

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:

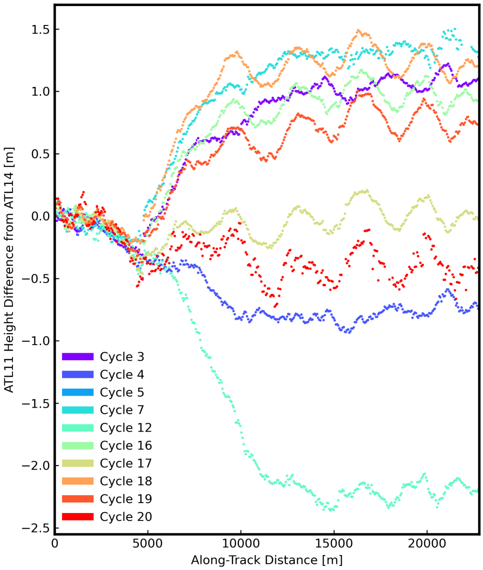
- Contains data for all cycles with along-track data following the Reference Ground Tracks (RGTs)
- Easy calculation of height change through time

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

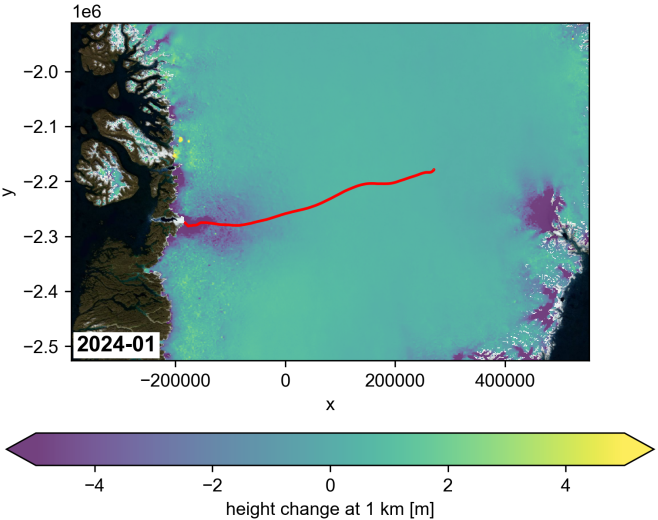
Disadvantages:

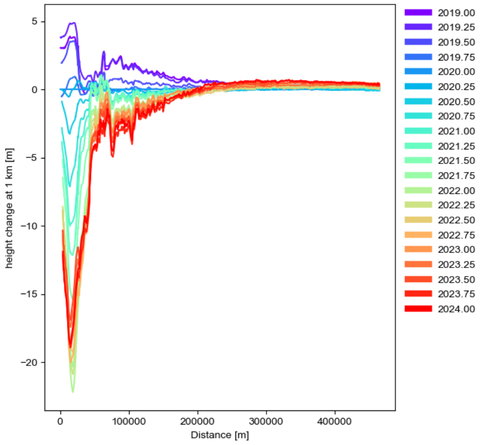
- ATL14 estimates degrade where measurements are unavailable
- Quarter-annual temporal sampling might not be high enough for certain applications

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]

ATL07: Sea Ice Height Data

Contains:

- Along-track heights for sea ice and leads

Advantages:

- High precision (~2 cm) height retrievals from 150-photon aggregates
- Classifications for varying surface types
- Provides auxiliary information such as surface roughness and retrieval quality flags

Disadvantages:

- Surface retrievals have varying length scales
- Surface type flagging is still in development

Use if you want to:

- Have base level surface heights for freeboard or surface process studies

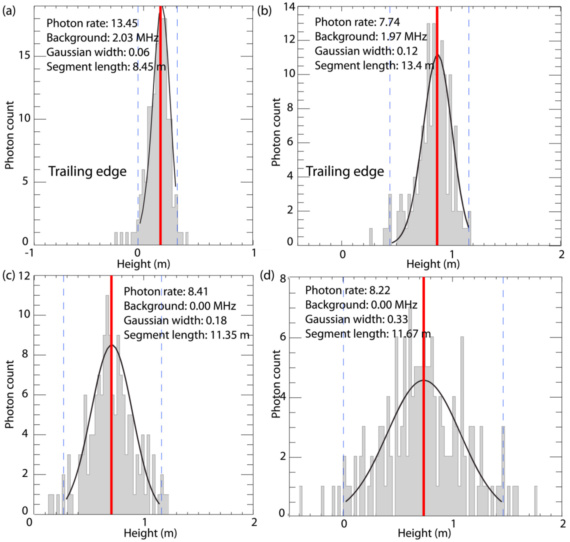


Figure 2 from Kwok et al. [2019]

ATL10: Sea Ice Freeboard Data

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 types

Disadvantages:

- Higher levels of missing/invalid data than ATL07
- Varying length scales of retrievals
- Summer sea ice retrievals still under investigation

Use if you want to:

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

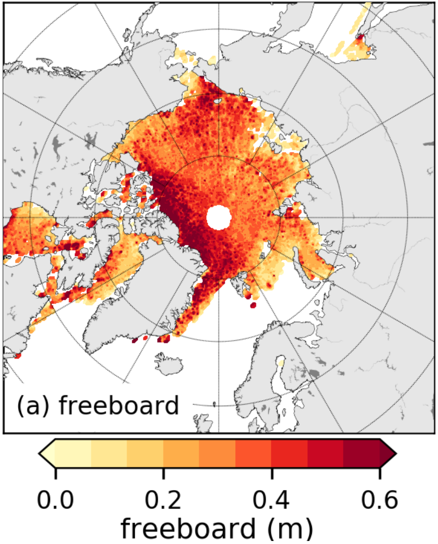


Figure 6 from Petty et al. [2020]

ATL20: Gridded Sea Ice Freeboard Data

Contains:

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

Advantages:

- Gridded product that is lighter 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

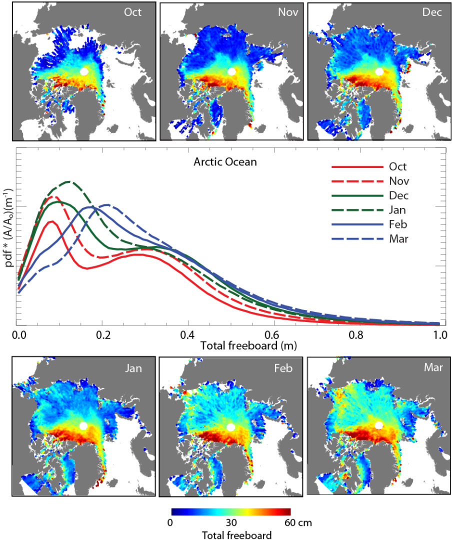


Figure 9 from Kwok et al. [2019]

ATL21: Gridded Polar Sea Surface Height Data

Contains:

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

Advantages:

- Gridded product that is lighter than ATL10
- Uses a sophisticated sea surface height retrieval algorithm to detect leads in polar oceans

Disadvantages:

- Coarse length scale, averages out the high resolution of the ICESat-2 data
- Only data from center strong beam available

Use if you want to:

- Look at large-scale gridded sea surface height anomalies or derive dynamic ocean topography

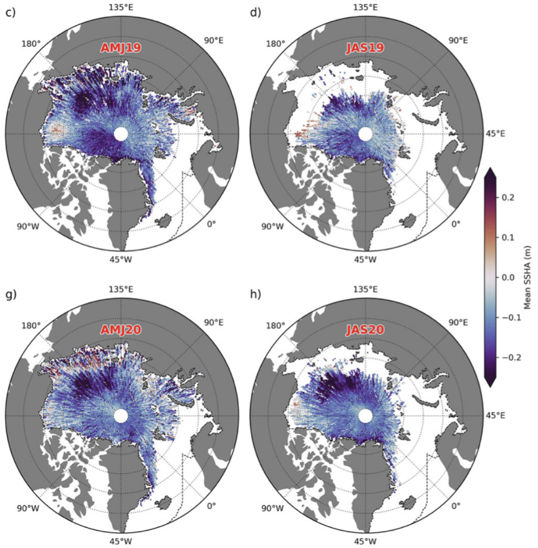


Figure 4 from Bagnardi et al. [2021]

ATL08: Land and Vegetation Height Data

Contains:

- Terrain surface and canopy heights from land photons

Advantages:

- Can handle surfaces with multiple returns (such as vegetated canopies)
- Provides photon-level classifications from ATL08 algorithm

Disadvantages:

- Can produce less reliable results over sloping surfaces

Use if you want to:

- Detect multiple surfaces, such as vegetated canopies or supraglacial lakes
- Look at vegetated terrain and need to detect the ground

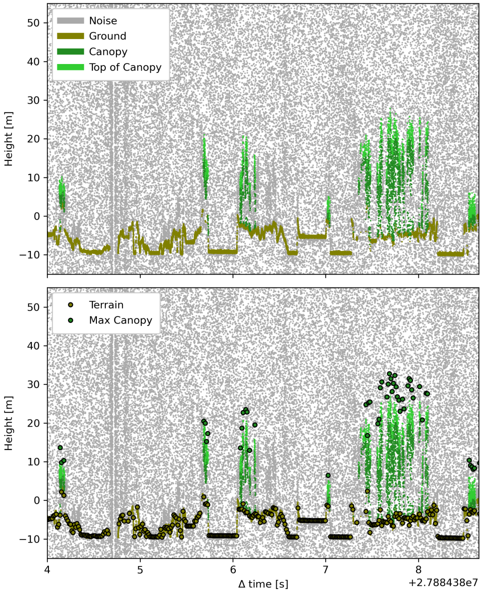


Figure recreated from Amy Neuenschwander (UT Austin)

ATL18: Gridded Land and Vegetation Height (in development)

Contains:

- Terrain and relative canopy height at 1km resolution

Advantages:

- Uses EASE2.0 grids for compatibility with other datasets
- Will be updated annually

Disadvantages:

- Low spatial resolution limits creating a temporal change product

Use if you want to:

- Analyze large-scale vegetation and land surface change

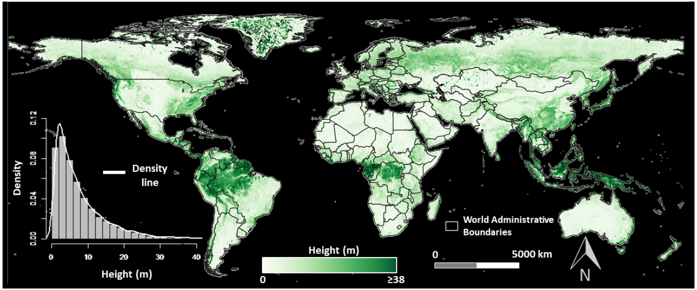


Figure from Amy Neuenschwander (UT Austin)

ATL12: Ocean Surface Height Data

Contains:

- Sea surface heights for oceans deeper than 10m
- Harmonic coefficients and statistics for waves
- Geophysical (e.g. sea state bias) corrections

Advantages:

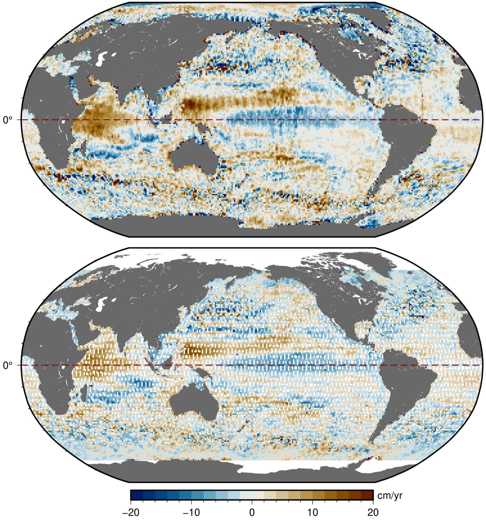
- Average height estimates reduce the effects of correlated noise due to waves
- Also provides sea surface heights with cm-level corrections at spatial resolutions up to 10m

Disadvantages:

- Does not represent the sea surface in ice covered areas

Use if you want to:

- Detect the instantaneous sea surface height



Comparison of ATL12 and JASON-3 from Buzzanga et al. [2021]

ATL19 and ATL23: Gridded Dynamic Ocean Topography

Contains:

- Rasterized DOT at $1/4°$ (mid-latitudes) and 25 km (polar) spatial resolution
- Monthly (ATL19) and tri-monthly (ATL23) temporal resolution

Advantages:

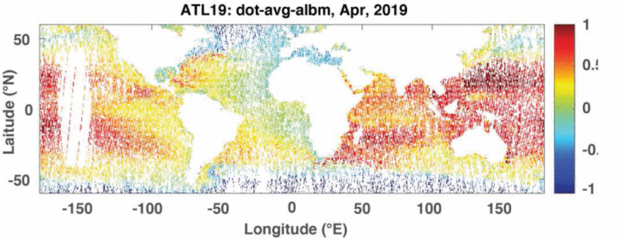
- Lighter product than ATL12
- Includes individual beam averages

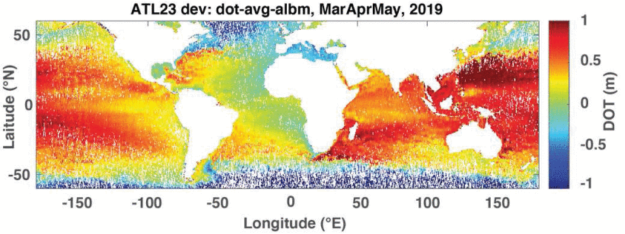
Disadvantages:

- Lower temporal resolution than ATL12

Use if you want to:

- Calculate the average DOT over time
- Look at large-scale oceanographic features





Figures 4 and 5 showing ATL19 and ATL23 from Morison et al. [2022]

Product Information at the National Snow and Ice Data Center

- The NSIDC DAAC is the primary data manager for ICESat-2 data
    - On-prem data stores
    - Cloud-based data stores (AWS s3)

- Mission landing page for ICESat-2 →
  `https://nsidc.org/data/icesat-2`

- Product landing pages (e.g. ATL03) →
  `https://nsidc.org/data/atl03`

- Each product landing page includes:
    - User Guides
    - Algorithm Theoretical Basis Documents (ATBDs)
    - Data Dictionaries
    - List of Known Issues
    - Information for Data Access

Part 3

Mission Status and Future

2024 Safehold to Science Mode Timeline

- May 10: Massive solar storm (Largest since 1989!)
- May 10 – 17: Safehold
- May 14 – June 22: RGT excursion peaked at 286.526 km
- May 28 – June 18: Collected pure background
- June 18: Resumed RGT pointing on RGT 22
- June 21: Resumed Science Mode data collection on RGT 55
- June 22: Returned to nominal orbit
- June 25: Yaw flip to -X
- June 27: Resumed vegetation off-pointing and TOOs on RGT 145
- June 29: Completed on-orbit parameter optimization activities

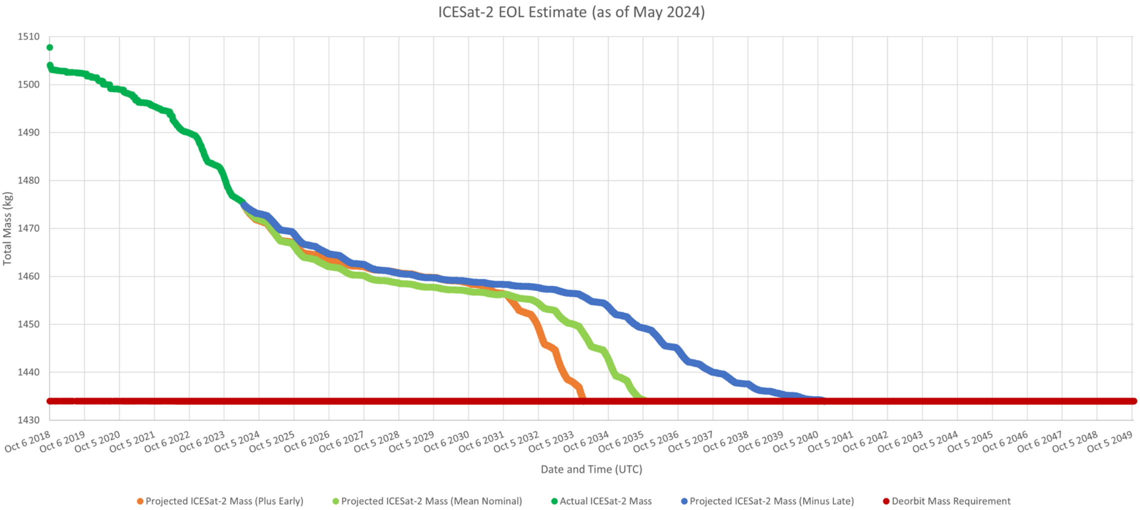
Future Mission Outlook

- Current Status: **Nominal**
- Performance metrics remain nominal and within mission requirements
- Over 2000 days in orbit
- Over 1.8 trillion laser pulses and 15 trillion photons returned
- Life-limiting factor is on-board fuel → dependent on solar activity

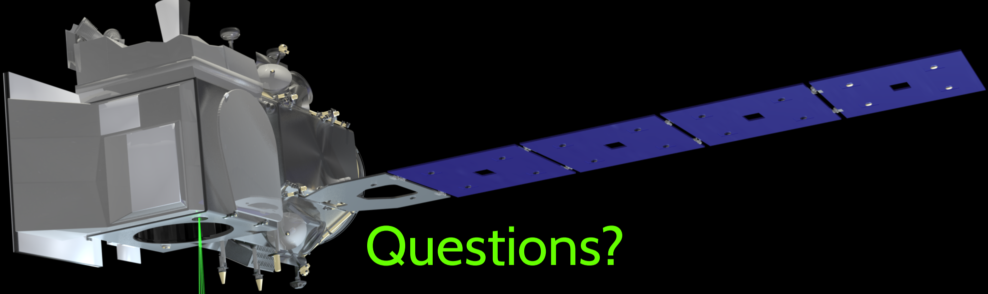
Mission Product Development

- Target publication date of release 007 products: spring 2025
- Target publication date of ATL24 bathymetry product: late 2024 or early 2025
- Gridded Land and Vegetation Height product (ATL18) in development
- Gridded Sea Ice Freeboard Quicklook product (ATL20-QL) in development
- Possible future standard products are under development

Mission Lifetime Estimates



Current estimate for mean nominal End of Life: November 2035



Questions?

Website: https://icesat-2.gsfc.nasa.gov

Data: https://nsidc.org/data/icesat-2

GitHub: https://github.com/icesat-2

Slack: https://icesat2-community.slack.com/