Snow depth from satellite laser altimetry

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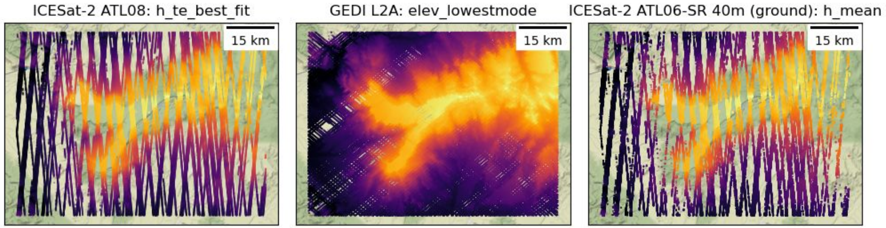
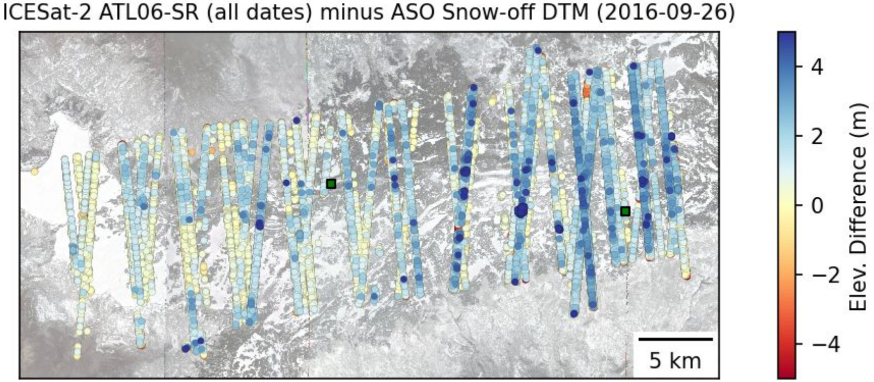
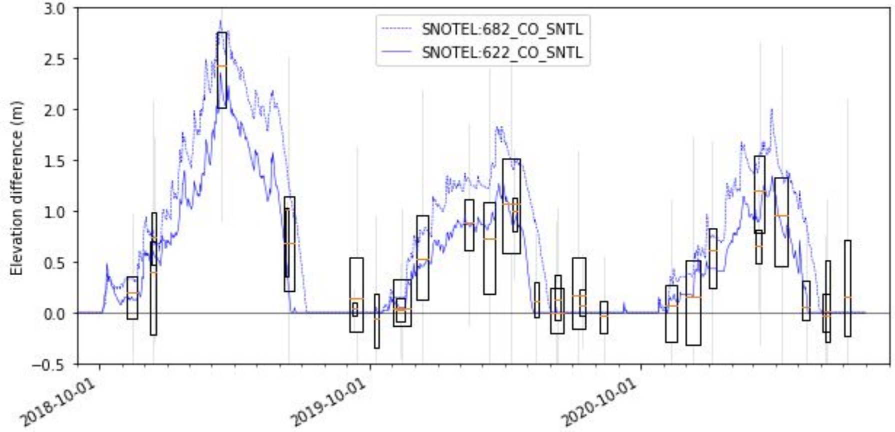
Fall AGU Meeting
December 15, 2021


ICESat-2 ATL08: h_te_best_fit
GEDI L2A: elev_lowestmode
ICESat-2 ATL06-SR 40m (ground): h_mean
15 km
15 km
15 km


ICESat-2 ATL06-SR (all dates) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
4
2
0
−2
−4


SNOTEL:682_CO_SNTL
SNOTEL:622_CO_SNTL
Elevation difference (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
2018-10-01
2019-10-01
2020-10-01

Motivation

Global snow observations require multi-sensor, multi-platform approach

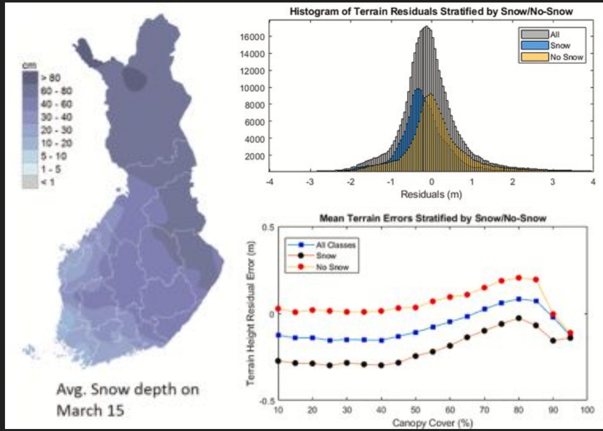
Satellite laser altimetry and commercial stereo photogrammetry (snow depth) will complement dedicated radar satellite missions (SWE)

Goal: Evaluate **currently available, on-orbit** lidar and stereo observations to measure seasonal snow depth

- Satellite laser altimetry data
  - ICESat-2
  - GEDI
- DEMs from commercial very-high-resolution (VHR) satellite stereo images
  - Maxar WorldView-1/2/3
  - Planet SkySat-C
  - Pleiades-HR
- LiDAR + stereo fusion

Satellite laser altimetry for snow: previous work

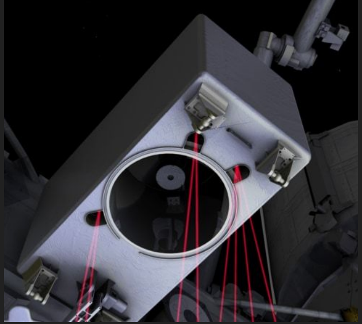
- *Treichler and Kääb* (2017) - ICESat snow depth for Norway, limited campaigns (March, June; 2003-2009)
- *Kwok et al.* (2020) - ICESat-2 snow depth on Arctic sea ice (freeboard)
- *Neuenschwander et al.* (2020) - ICESat-2 ATL08 validation in boreal forests (Finland)
- *Hu et al.* (2021) - ICESat-2 ATL08 crossovers for snow depth in flat, open areas (Altay, NW China)

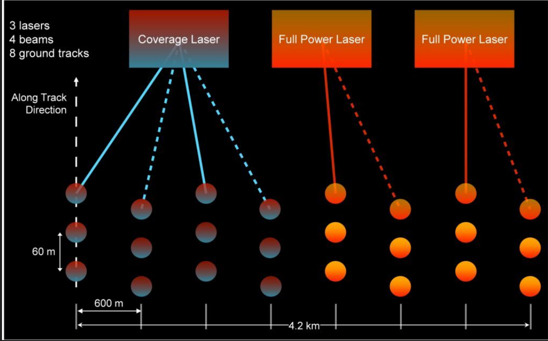


Neuenschwander et al. (2020)

Few studies for non-polar, terrestrial snow - especially challenging mountain and forest sites in Western U.S.

Global Ecosystem Dynamics Investigation Lidar (GEDI)





https://gedi.umd.edu/instrument/specifications/

Primary science: ecosystems, canopy structure, biomass

Orbit: International Space Station (ISS) orbit, 51.6° inclination

Launch: April 2019

Wavelength: 1064 nm (snow reflectance of ~0.8)

Type: Full waveform lidar

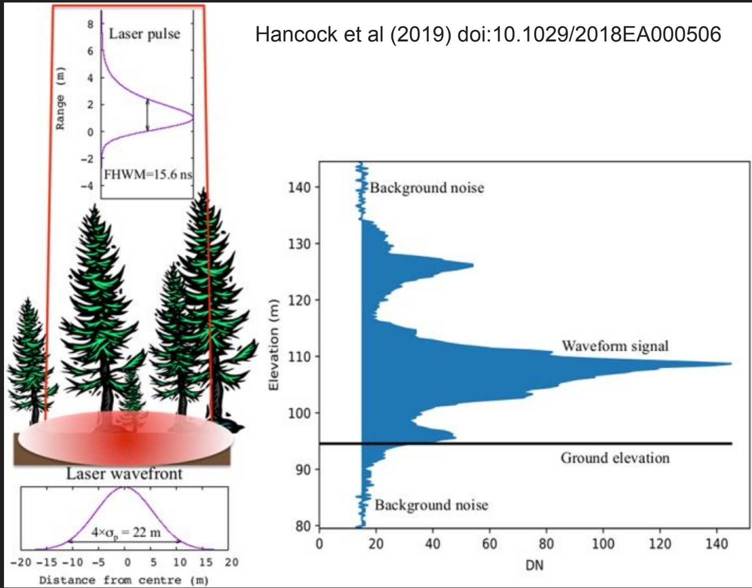
Pulse width: 15.6 ns (~4.7 m wide)

8 beams, ~25 m diameter footprint

Along-track spacing ~60 m, Cross-track spacing ~600 m

Total swath of 4.2 km

Geolocation accuracy ~10-20 m, <0.5 m vertical accuracy



Hancock et al (2019) doi:10.1029/2018EA000506

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

Primary science: ice sheet elevation change, sea ice

Instrument: Advanced Topographic Laser Altimeter System (ATLAS)

Orbit: Near-polar, 92° inclination

Launch: October 2018

Wavelength: 532 nm (snow reflectance of ~1.0)

Type: Photon-counting lidar

Pulse width: <1.5 ns (~0.45 m wide) - better range precision

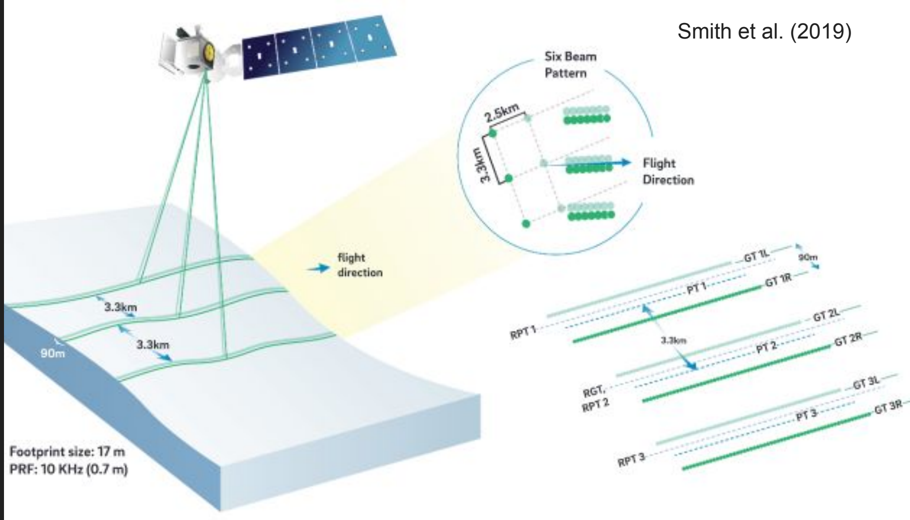
6.6 km swath, 3 beam pairs, ~11 m diameter footprint

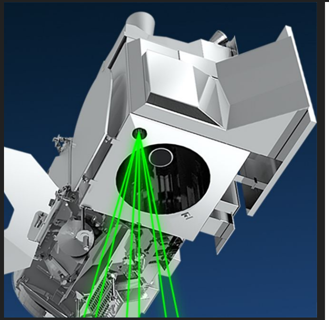
Along-track spacing of 0.7 m, Cross-track spacing ~3.3 km

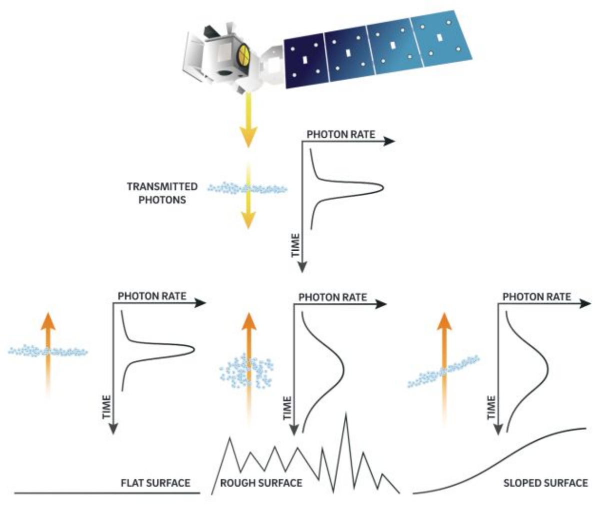
Geolocation accuracy <6.5 m, vertical accuracy <0.05-0.1 m

Repeat-track over polar regions, "vegetation" mode elsewhere: systematic off-pointing to fill gaps over time

Smith et al. (2019)





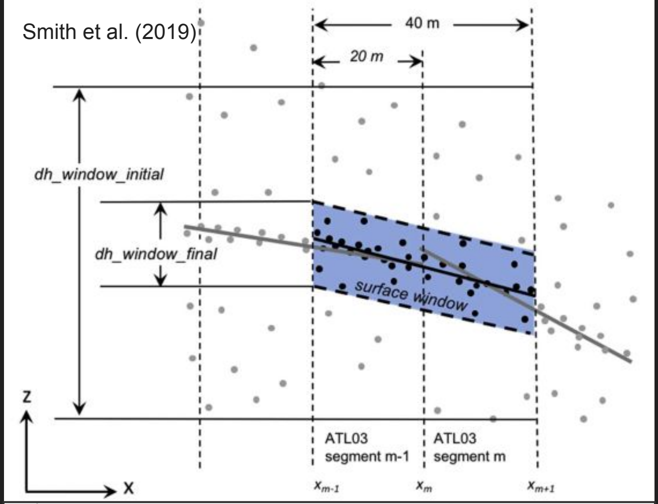


ICESat-2 ATL06

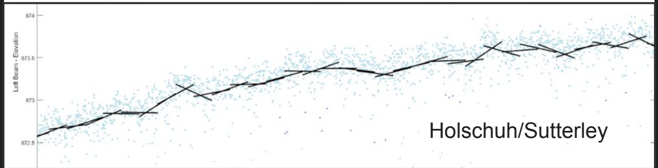
Land ice algorithm - good at finding the surface, but doesn't expect canopy

Overlapping 40 m segments every 20 m - linear fits to high-confidence surface photons

Available over ice sheets and glaciers



Smith et al. (2019)

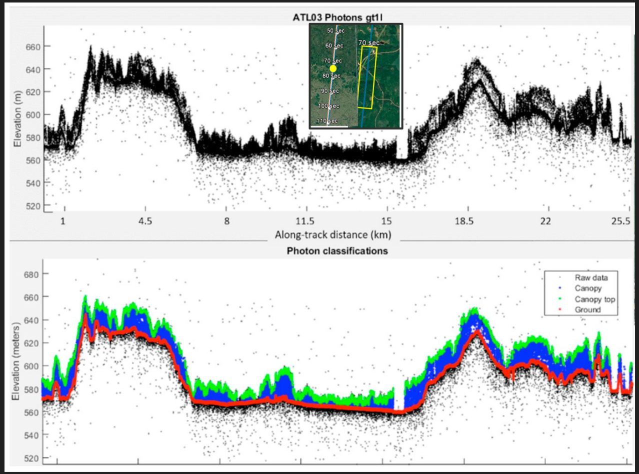


Holschuh/Sutterley

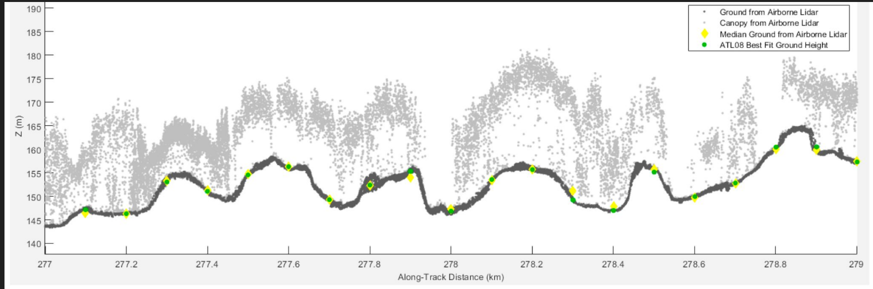
ICESat-2 ATL08

DRAGAN photon classifier (ground, canopy, canopy top)

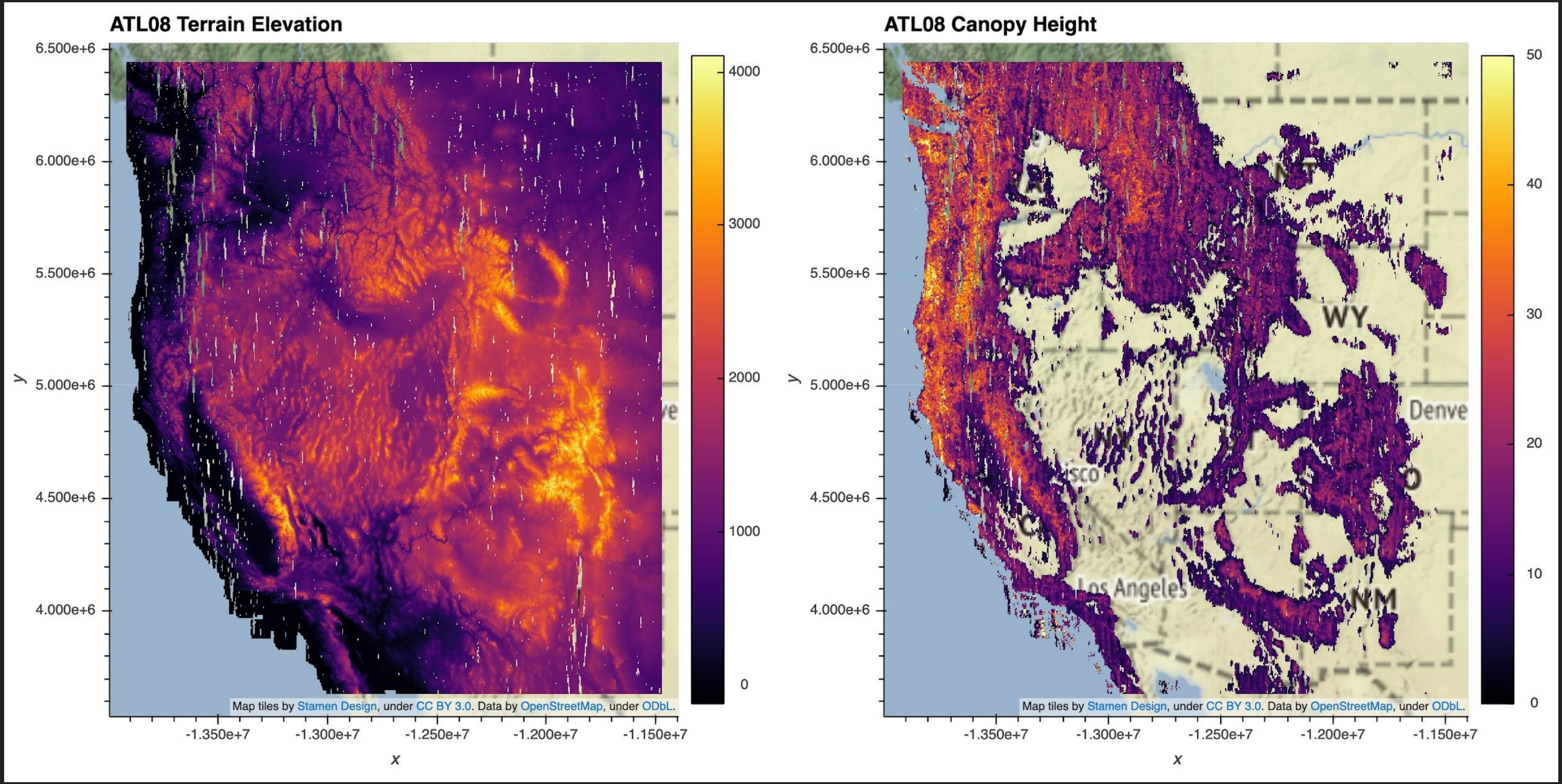
100 m segments - linear fit to ground photons and linear fit to canopy photons



Neuenschwander and Magruder (2019)



ATL08 for Western U.S. (h_te_best_fit, h_canopy)



100 m fits in mountain terrain?

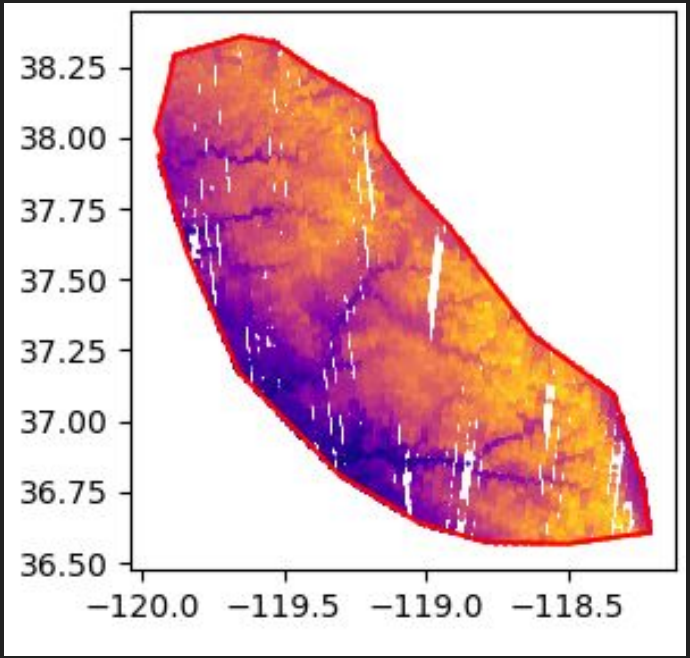
ICESat-2 SlideRule

On-demand processing of ICESat-2 photon data in the cloud using customizable ATL06 processor

Define an AOI and parameters (e.g., segment length), get results in seconds to minutes

Python client, C++/Lua server, efficient parallel read of ATL03 HDF5 granules on NSIDC S3

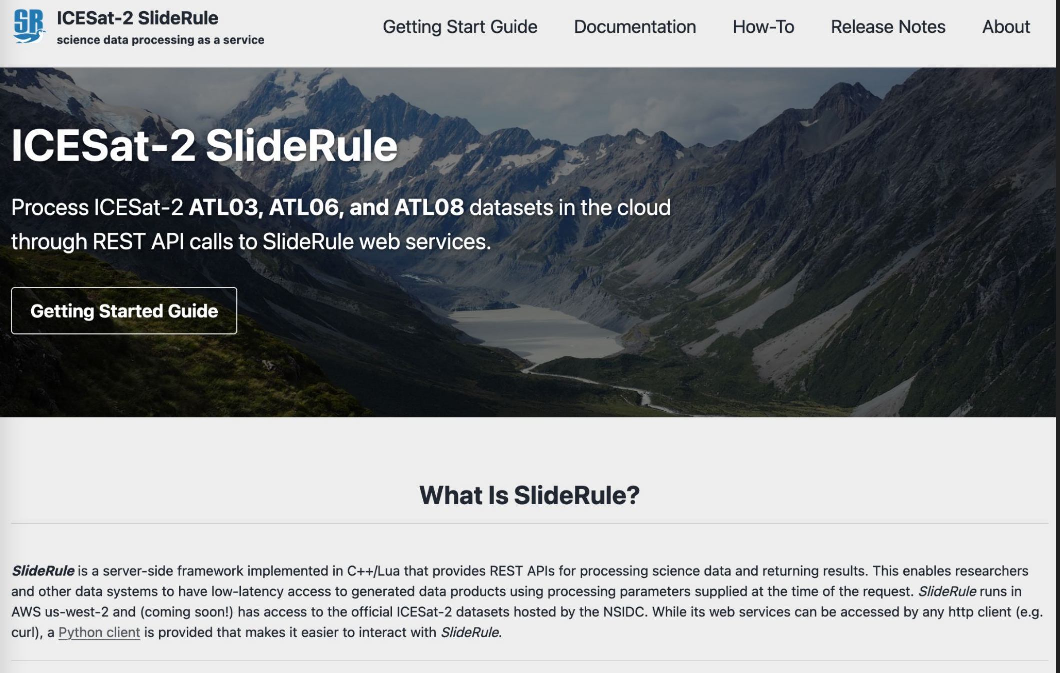
Open, reproducible science

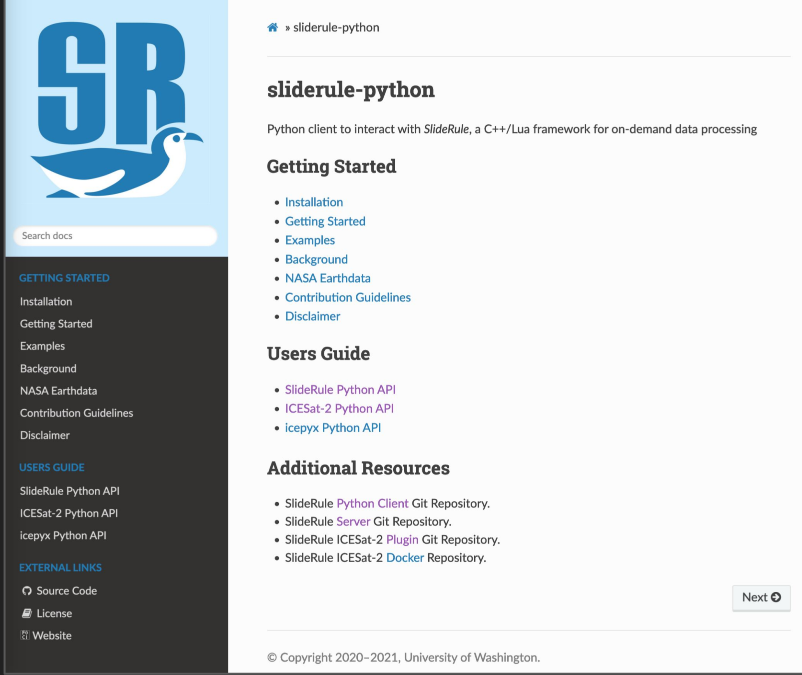


Example output for Sierra Nevada, CA

(1.44M elevations, 177 ATL03 granules, 142 seconds to process)

~2 minutes!



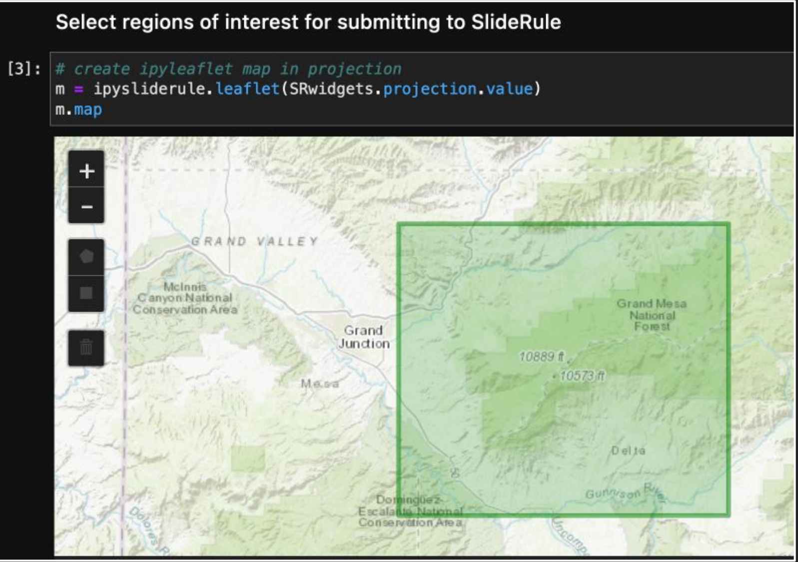


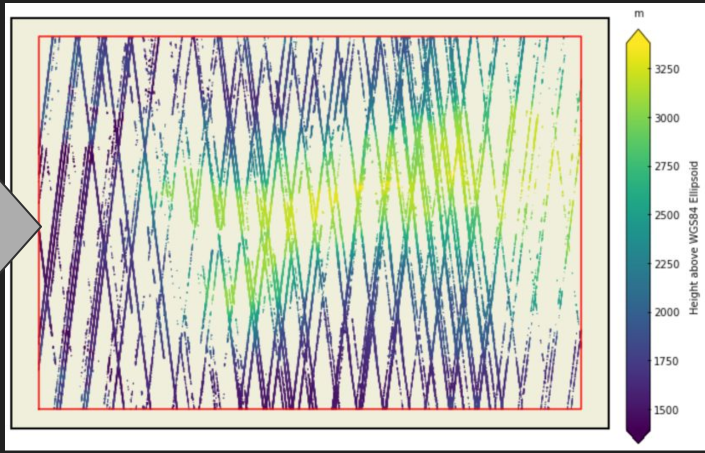
icesat2sliderule.org

http://icesat2sliderule.org/rtd/

Jupyter Notebook for Interactive Query

https://github.com/ICESat2-SlideRule/sliderule-python/blob/main/examples/api_widgets_demo.ipynb





GeoDataFrame with ~334K points, ready for analysis!

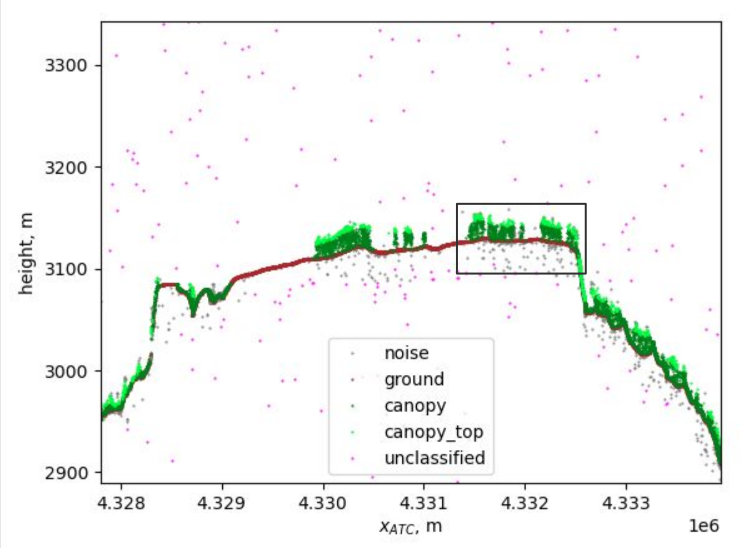
SlideRule parameter tests

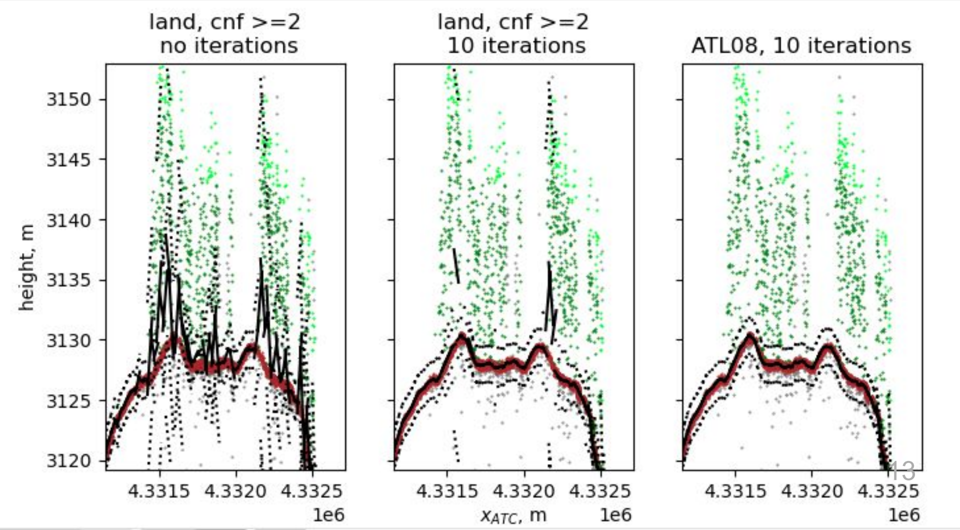
SlideRule lets us see how parameter choices influence recovered surface heights

Land classification with a single iteration (n_it=1) picks up vegetation photons

After 10 iterations, the surface window usually converges

Using the ATL08 classifications usually captures a narrow window around the ground on the first iteration





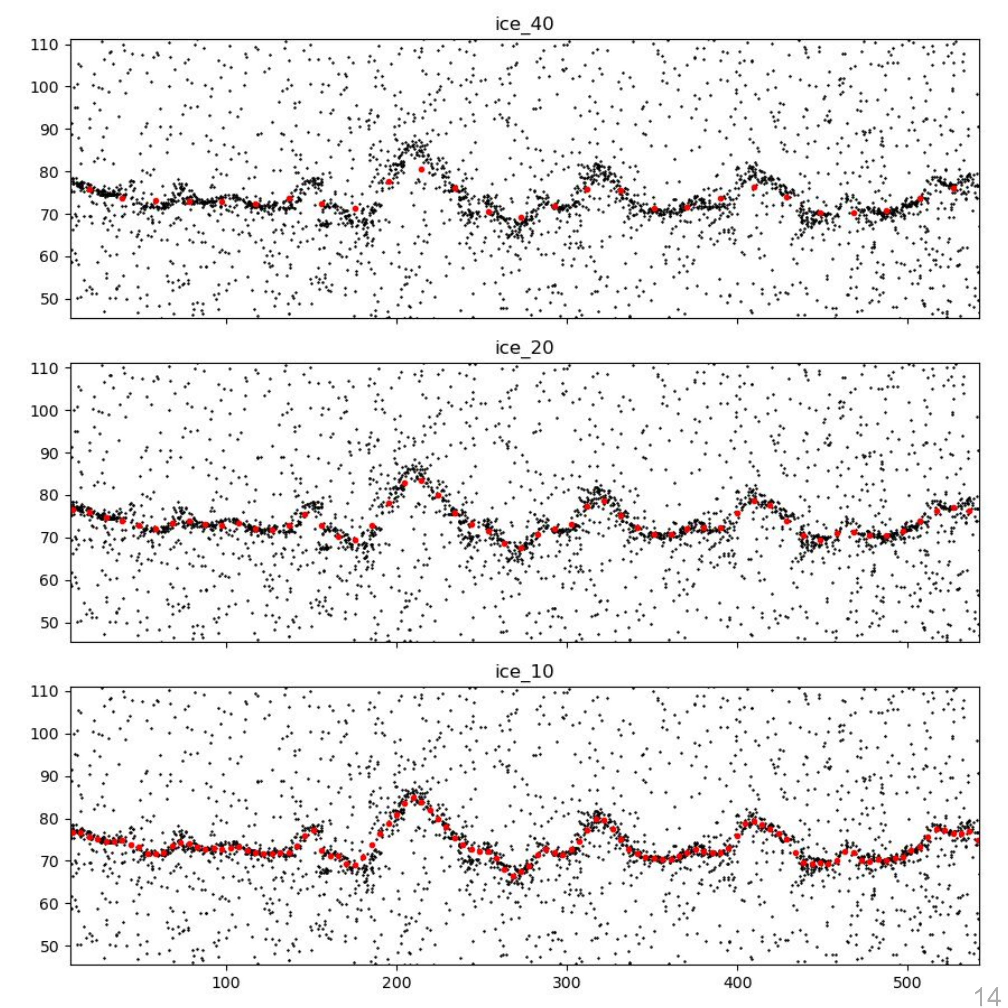
Segment length tuning over rough surfaces

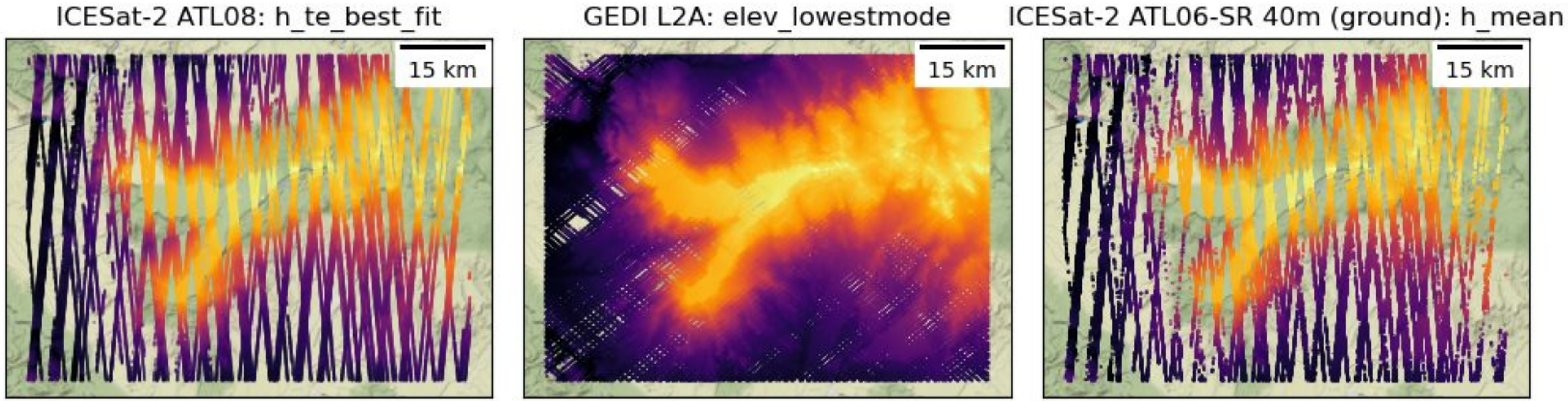
Stock ATL06 strikes a balance between data volume, accuracy, and resolution, with 40-m segments

SlideRule lets us see what's left out by the stock product

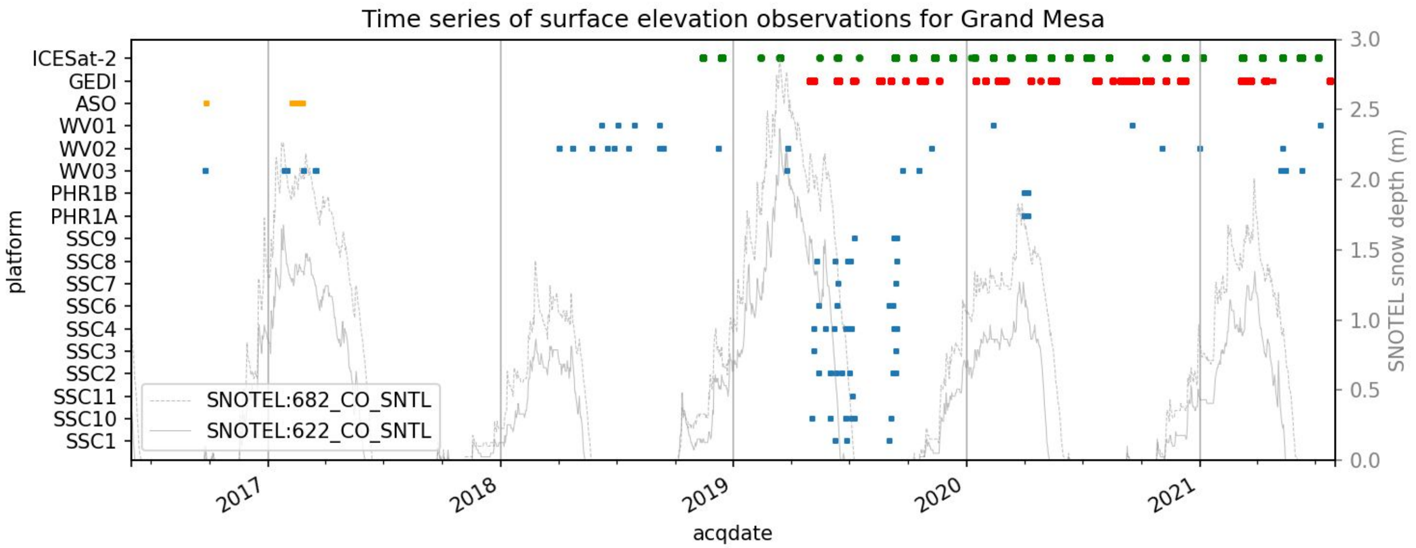
Example: A weak beam over a rough surface on Byrd Glacier with 40, 20, 10 m segment length

10 m best captures true roughness





ICESat-2 ATL08: h_te_best_fit
15 km
GEDI L2A: elev_lowestmode
15 km
ICESat-2 ATL06-SR 40m (ground): h_mean
15 km



Time series of surface elevation observations for Grand Mesa
platform
ICESat-2
GEDI
ASO
WV01
WV02
WV03
PHR1B
PHR1A
SSC9
SSC8
SSC7
SSC6
SSC4
SSC3
SSC2
SSC11
SSC10
SSC1
SNOTEL:682_CO_SNTL
SNOTEL:622_CO_SNTL
SNOTEL snow depth (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2017
2018
2019
2020
2021
acqdate

Elevation difference (snow depth) from crossovers

Repeat observations with same altimeter

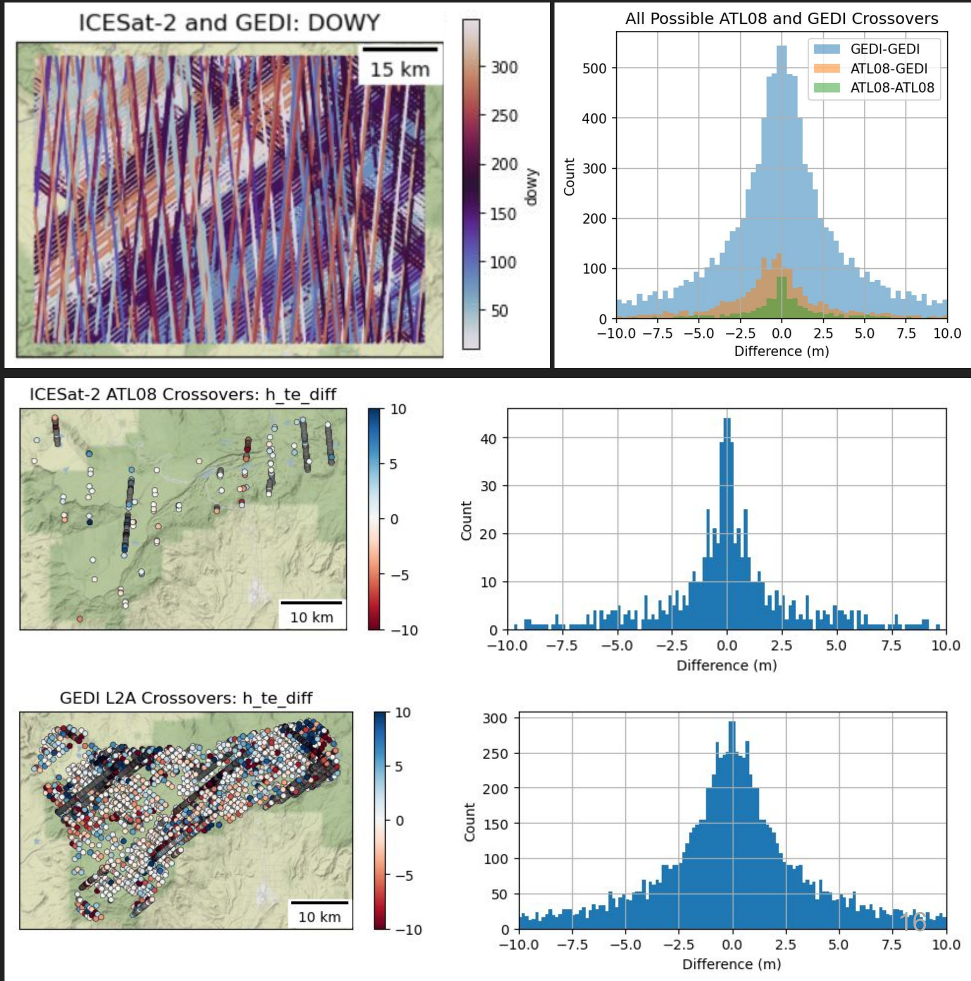
Snow-on (blue) minus snow-off (red) within some distance threshold

Need to account for footprint diameter, horizontal offset along local surface slope

Used for precise ice sheet elevation change measurement for repeat tracks

Harder at lower latitudes: no repeat, sparse tracks, clouds

Limited coverage at present, more opportunities as snow-free altimetry archive grows



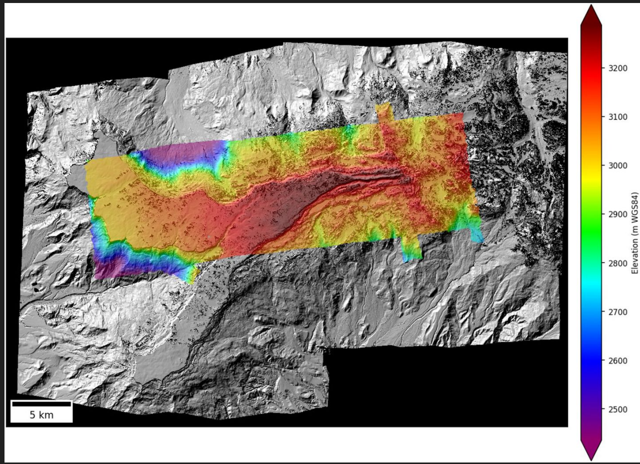
Elevation difference (snow depth) using reference DEM

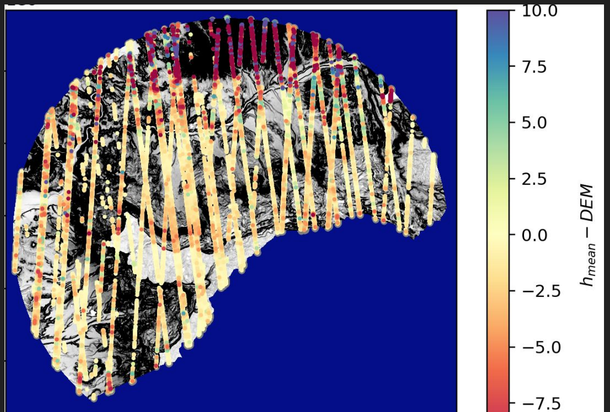
Sparse snow-on altimetry and accurate, high-resolution, snow-free DEM

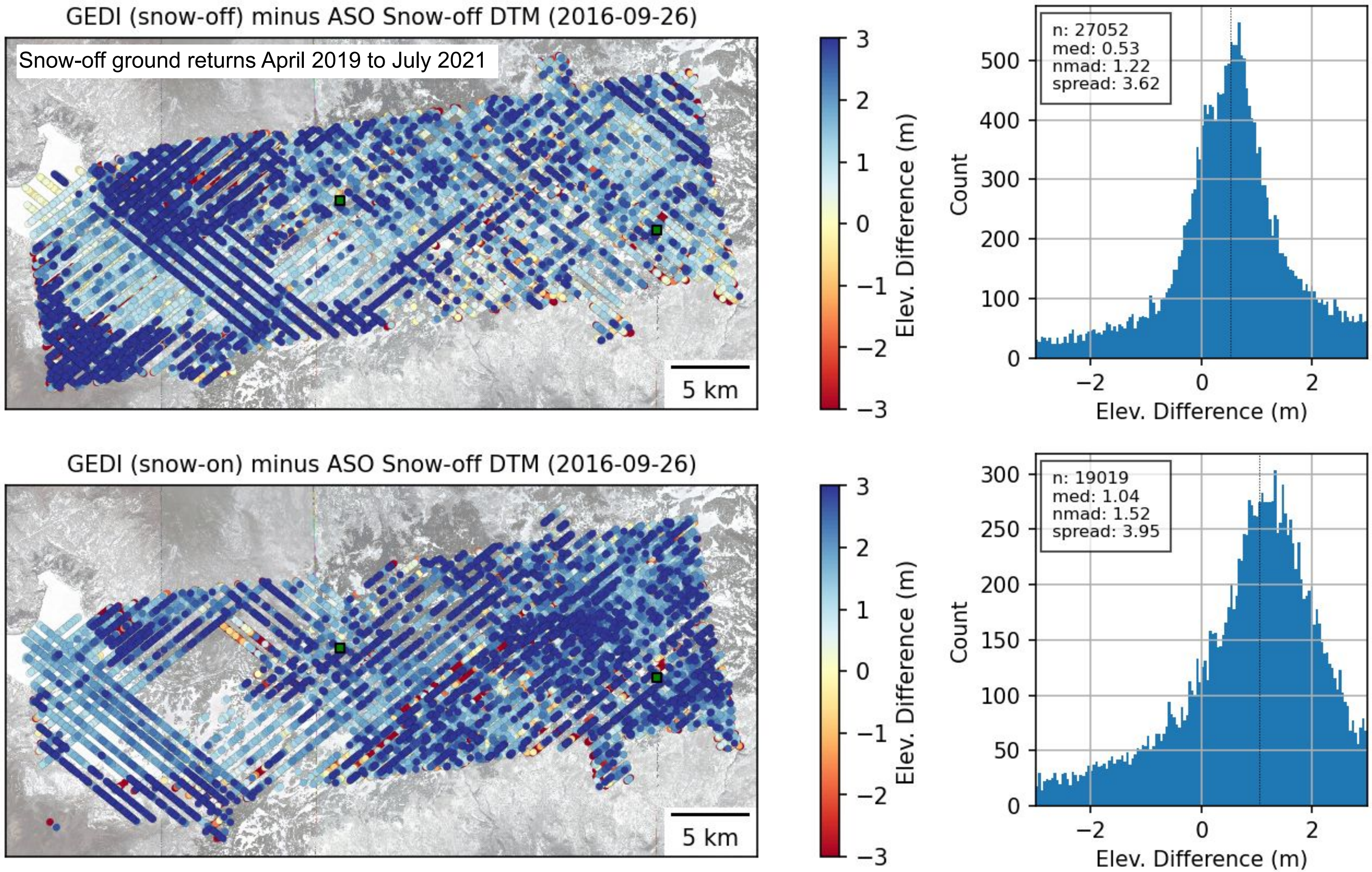
Ideally, LiDAR DTM (ASO, 3DEP)

Here, ASO Snow-free DTM for Grand Mesa (2016-09-26)

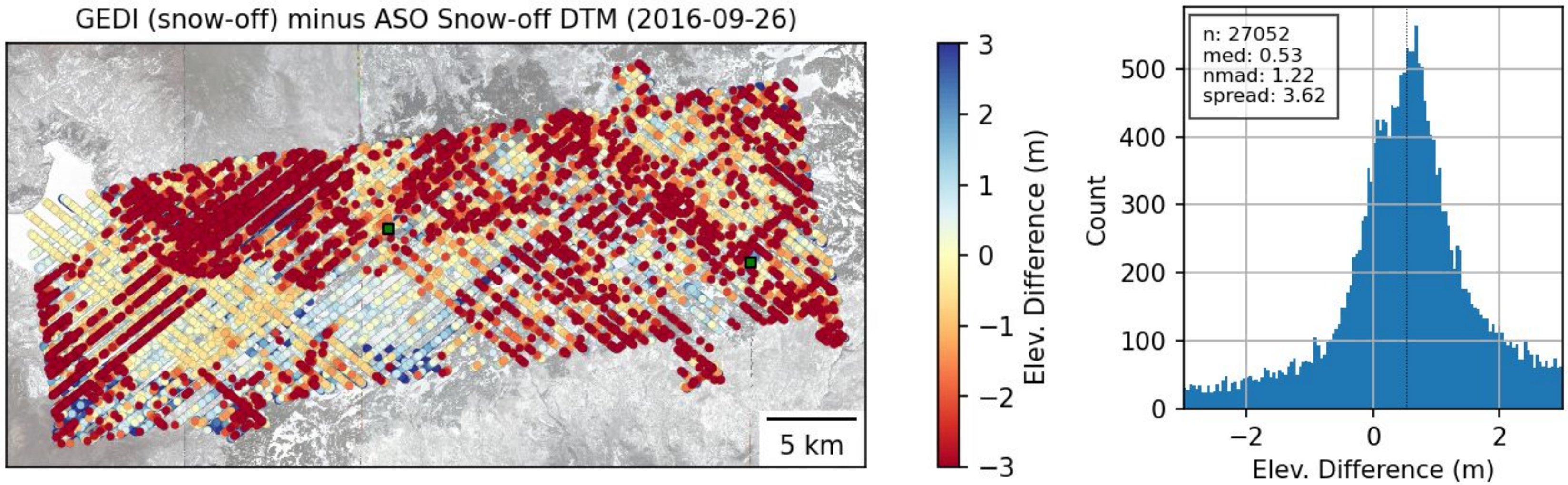
Patiently waiting for 3DEP release of 2015/2016 Delta Co. LiDAR (south of Mesa Co.)







GEDI (snow-off) minus ASO Snow-off DTM (2016-09-26)
Snow-off ground returns April 2019 to July 2021
5 km
Elev. Difference (m)
n: 27052
med: 0.53
nmad: 1.22
spread: 3.62
Count
Elev. Difference (m)
GEDI (snow-on) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
n: 19019
med: 1.04
nmad: 1.52
spread: 3.95
Count
Elev. Difference (m)


GEDI (snow-off) minus ASO Snow-off DTM (2016-09-26)
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Elev. Difference (m)
n: 27052
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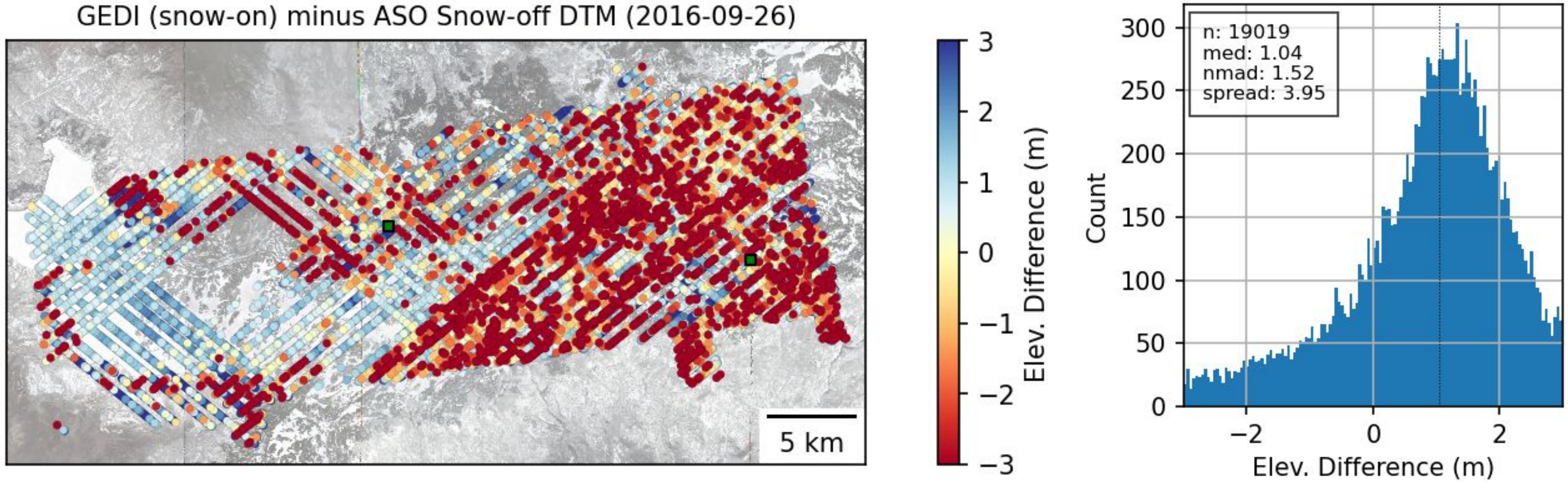
spread: 3.62
Count
Elev. Difference (m)


GEDI (snow-on) minus ASO Snow-off DTM (2016-09-26)
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Elev. Difference (m)
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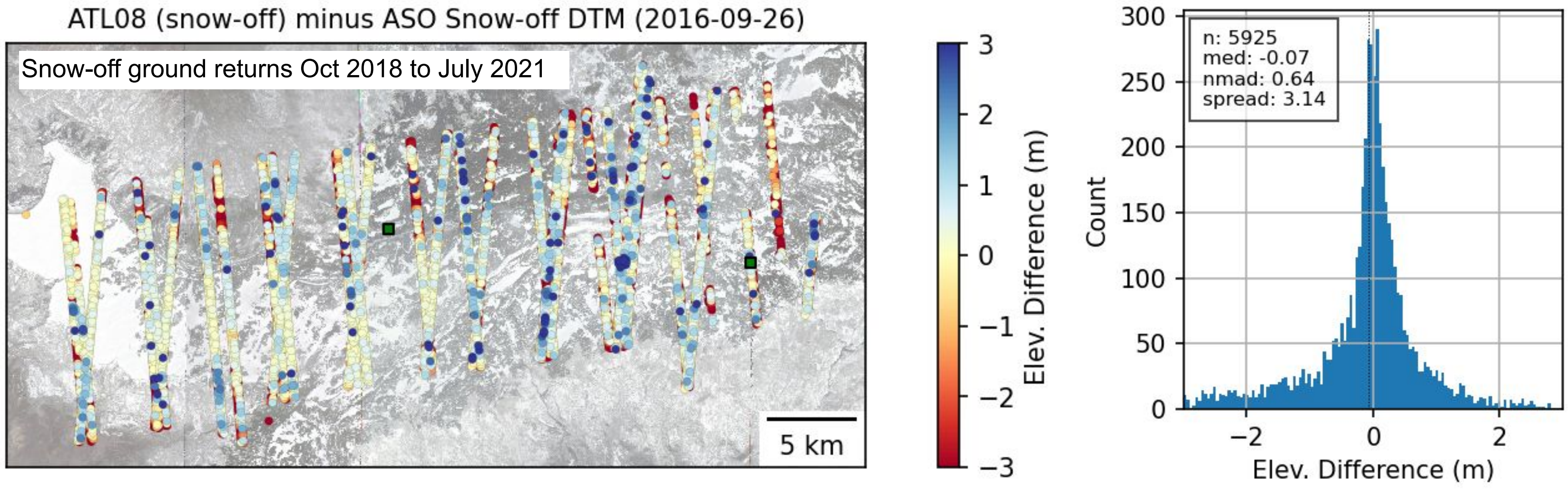
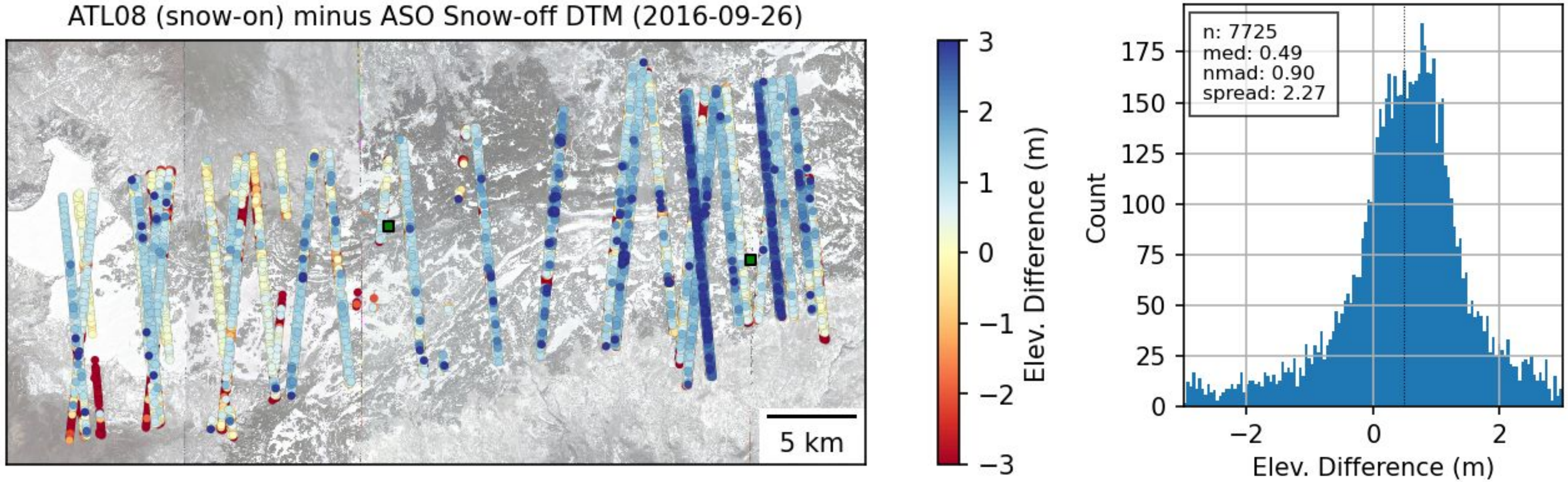
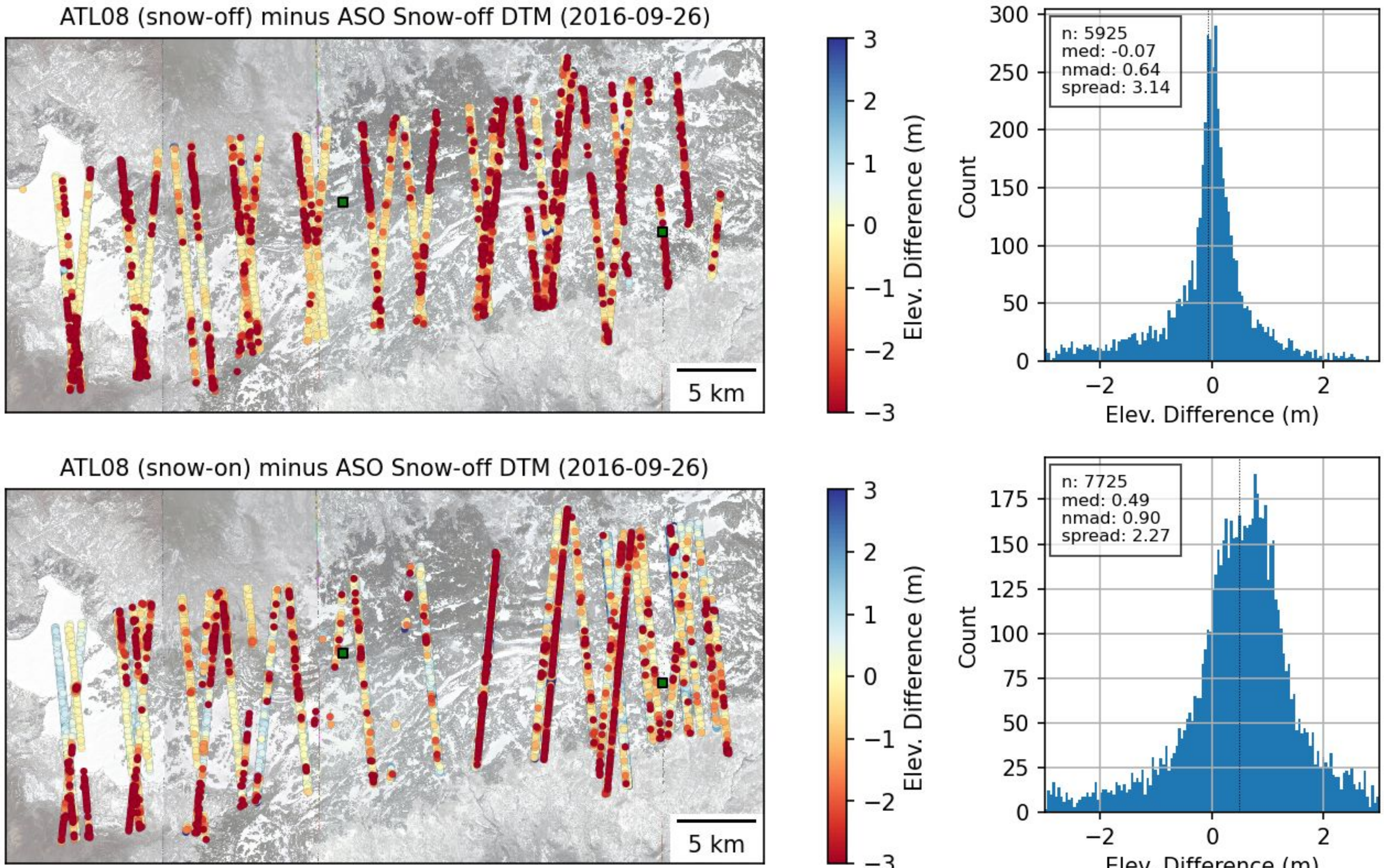
Count
Elev. Difference (m)

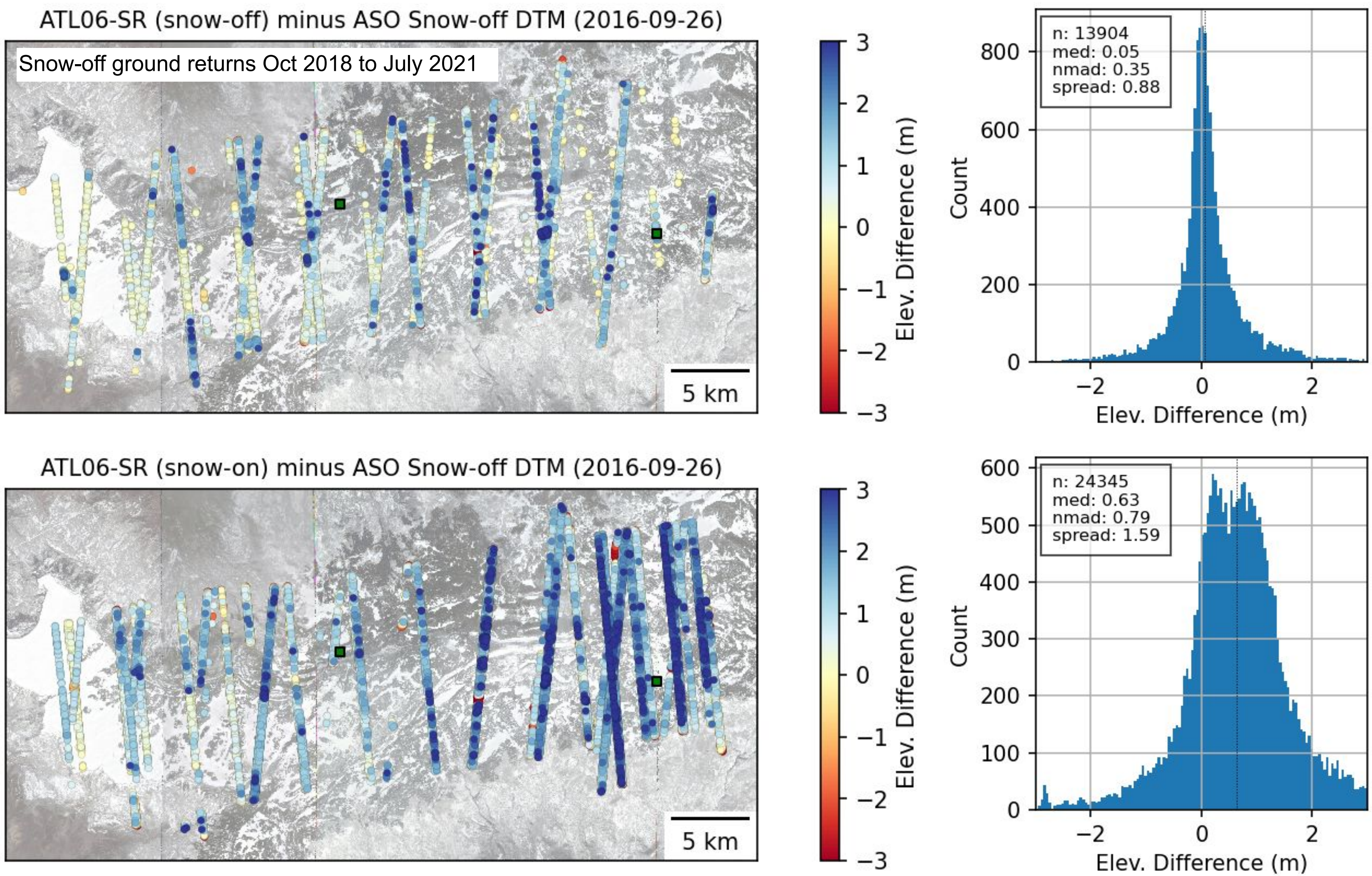


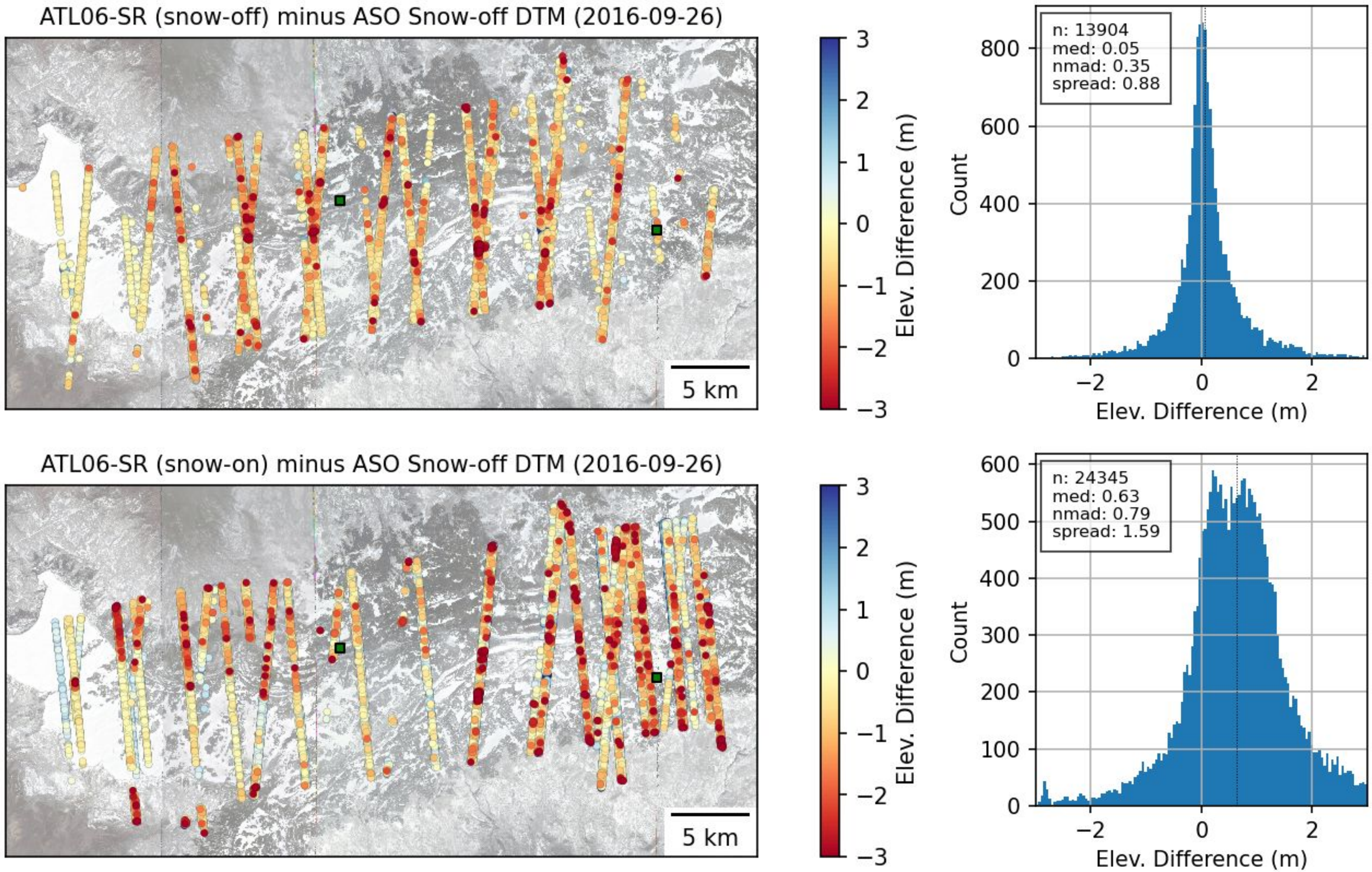
ATL08 (snow-off) minus ASO Snow-off DTM (2016-09-26)
Snow-off ground returns Oct 2018 to July 2021
5 km
Elev. Difference (m)
3
2
1
0
−1
−2
−3
Count
n: 5925
med: -0.07
nmad: 0.64
spread: 3.14
300
250
200
150
100
50
0
−2
0
2
Elev. Difference (m)



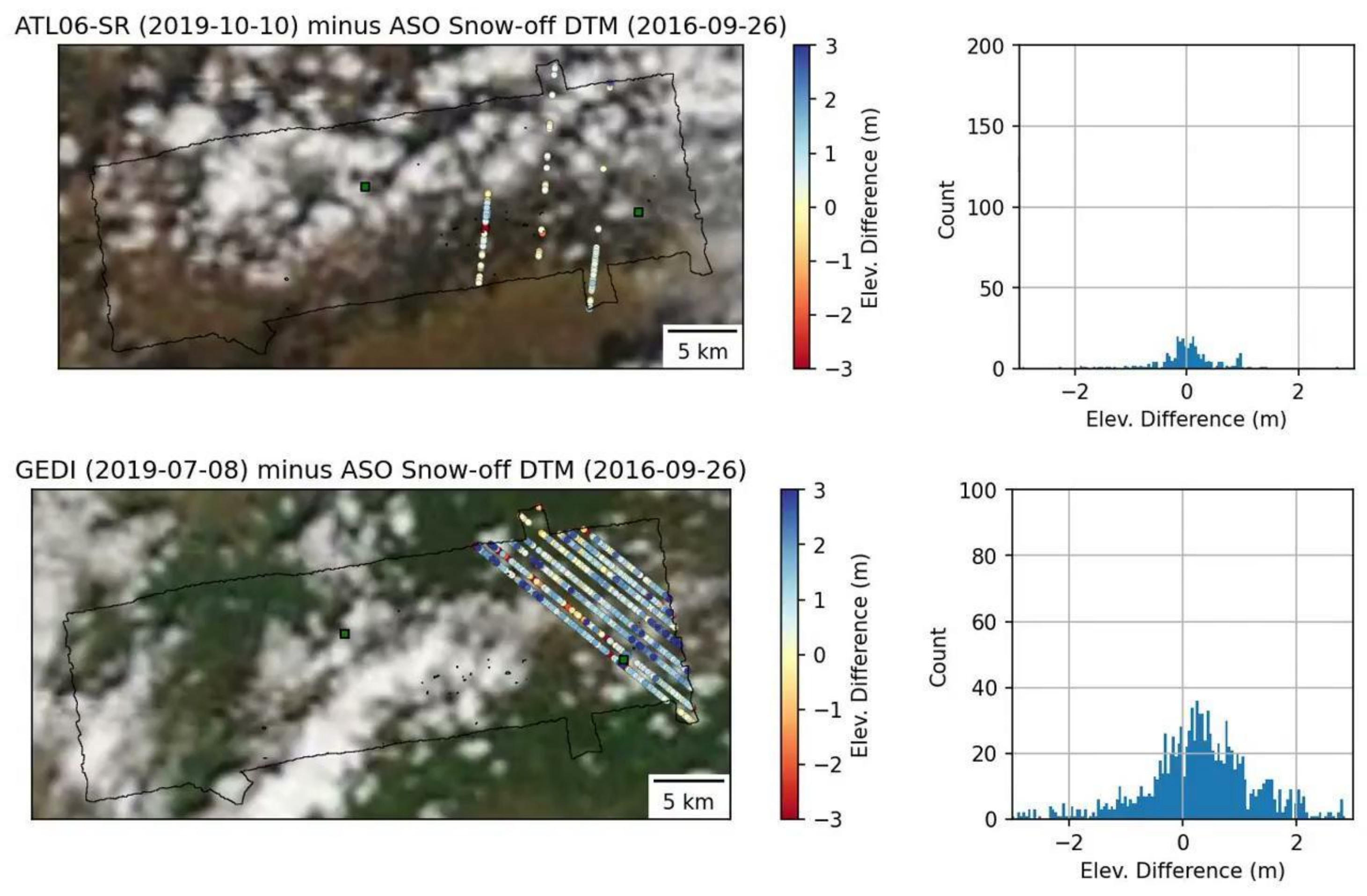
ATL08 (snow-on) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
3
2
1
0
−1
−2
−3
Count
n: 7725
med: 0.49
nmad: 0.90
spread: 2.27
175
150
125
100
75
50
25
0
−2
0
2
Elev. Difference (m)


ATL08 (snow-off) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
n: 5925
med: -0.07
nmad: 0.64
spread: 3.14
Count
Elev. Difference (m)
ATL08 (snow-on) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
n: 7725
med: 0.49
nmad: 0.90
spread: 2.27
Count
Elev. Difference (m)


ATL06-SR (snow-off) minus ASO Snow-off DTM (2016-09-26)
Snow-off ground returns Oct 2018 to July 2021
5 km
Elev. Difference (m)
n: 13904
med: 0.05
nmad: 0.35
spread: 0.88
Count
Elev. Difference (m)
ATL06-SR (snow-on) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
n: 24345
med: 0.63
nmad: 0.79
spread: 1.59
Count
Elev. Difference (m)


ATL06-SR (snow-off) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
n: 13904
med: 0.05
nmad: 0.35
spread: 0.88
Count
Elev. Difference (m)
ATL06-SR (snow-on) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
n: 24345
med: 0.63
nmad: 0.79
spread: 1.59
Count
Elev. Difference (m)

Daily aggregation of altimetry retrievals (with corresponding MODIS basemap)



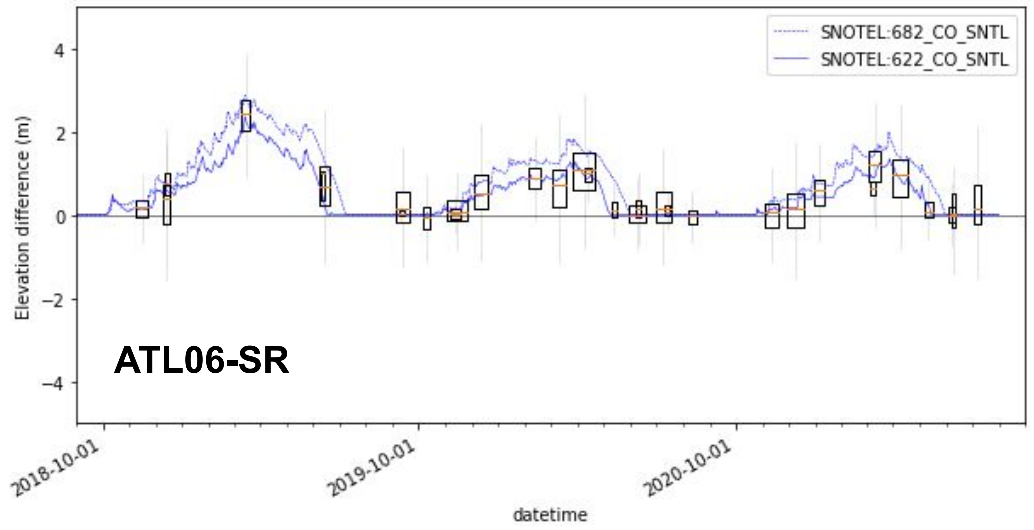
Aggregation

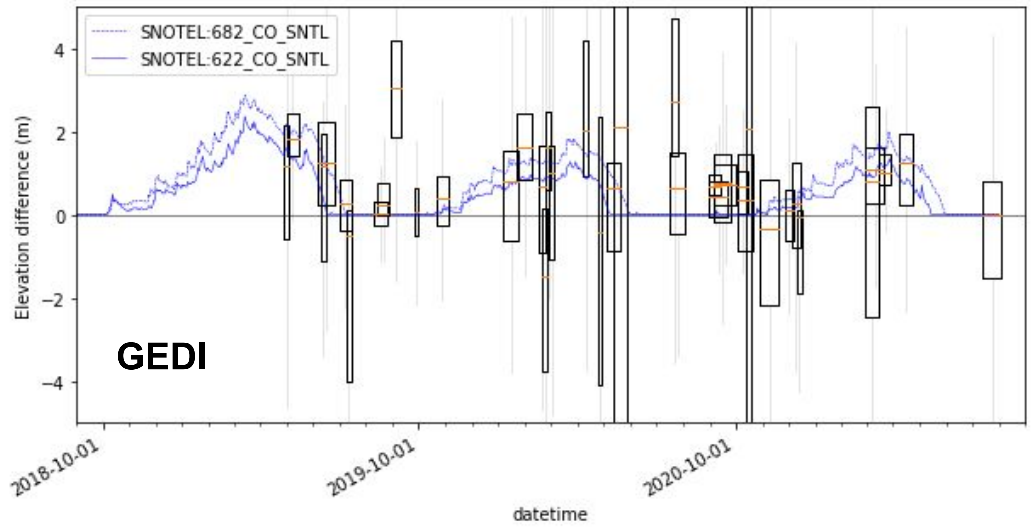
Spatial aggregation of altimetry by date

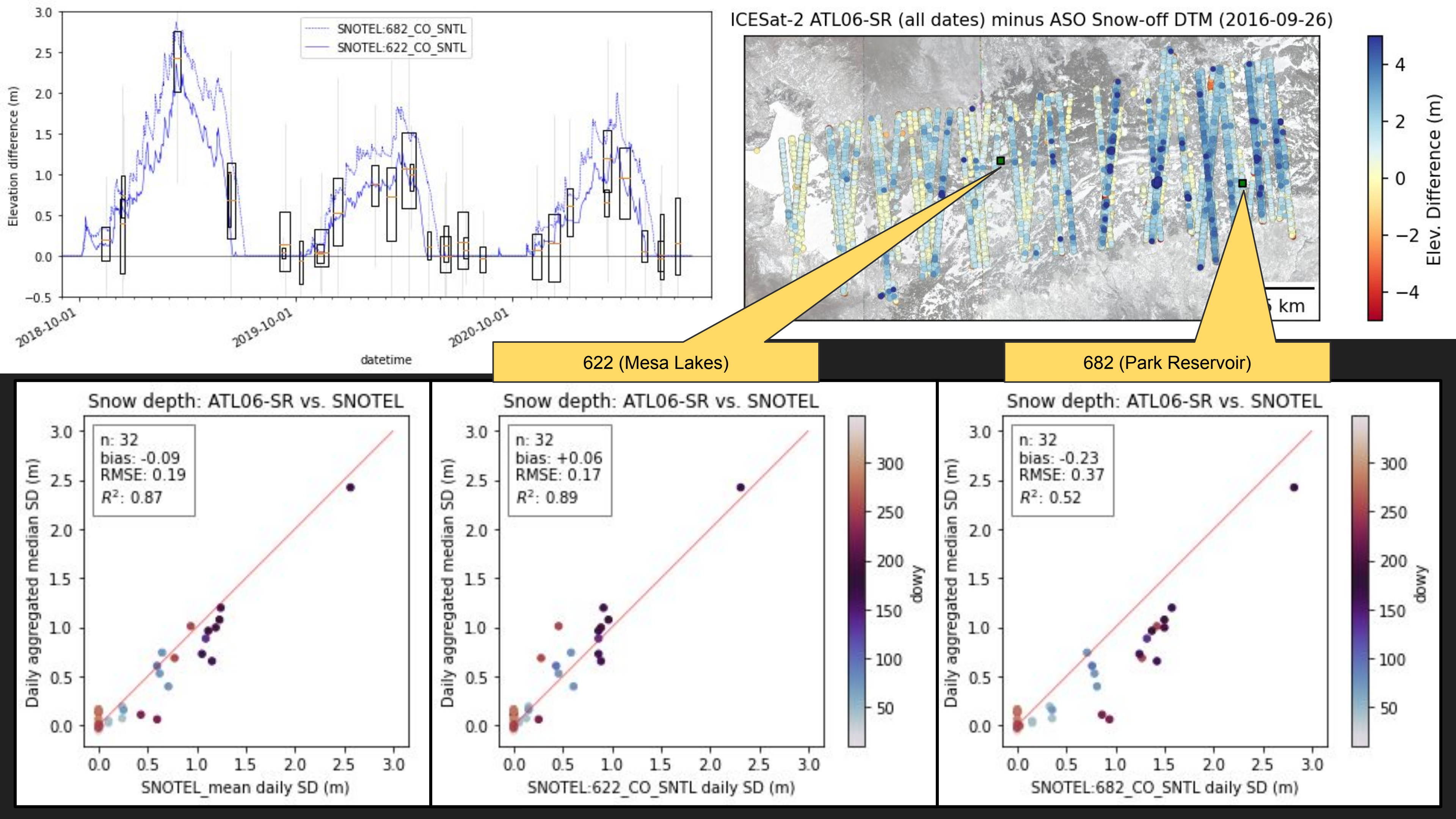
Bar width scales with sample size (wider is better)

Median of difference values (orange) is snow depth estimate for that day (elevation above snow-free reference DTM)

Evaluate resulting time series against daily SNOTEL snow depth







SNOTEL:682_CO_SNTL
SNOTEL:622_CO_SNTL
Elevation difference (m)
datetime
2018-10-01
2019-10-01
2020-10-01
ICESat-2 ATL06-SR (all dates) minus ASO Snow-off DTM (2016-09-26)
Elev. Difference (m)
622 (Mesa Lakes)
682 (Park Reservoir)
Snow depth: ATL06-SR vs. SNOTEL
n: 32
bias: -0.09
RMSE: 0.19
R^2: 0.87
Daily aggregated median SD (m)
SNOTEL_mean daily SD (m)
Snow depth: ATL06-SR vs. SNOTEL
n: 32
bias: +0.06
RMSE: 0.17
R^2: 0.89
SNOTEL:622_CO_SNTL daily SD (m)
dowy
Snow depth: ATL06-SR vs. SNOTEL
n: 32
bias: -0.23
RMSE: 0.37
R^2: 0.52
SNOTEL:682_CO_SNTL daily SD (m)
dowy

OK, but why does this work?

Good retrievals for a range of surface slopes and vegetation parameters at Grand Mesa

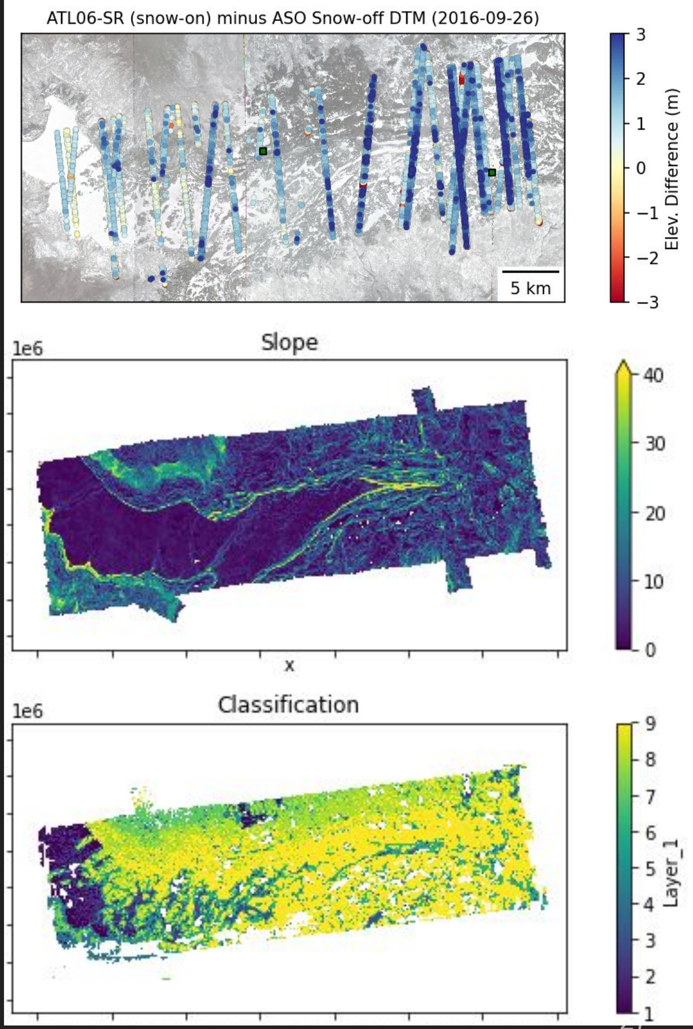
Need more analysis of...

Site-specific parameters:

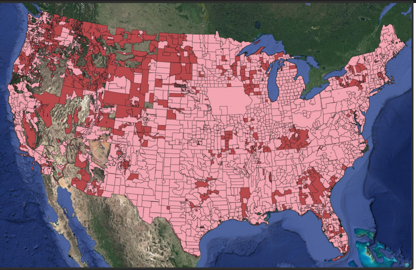
- Surface slope/roughness
- Vegetation density/type

Processing parameters:

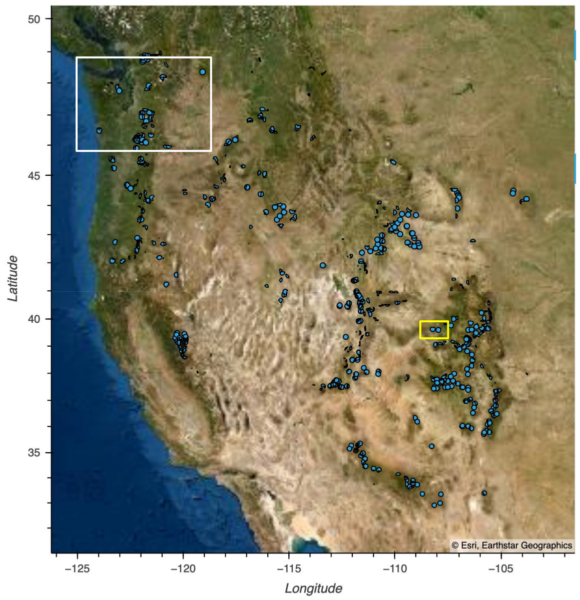
- Number/distribution of ground photons for fit
- Segment length for fit
- Aggregation (area/distance thresholds, sample size)



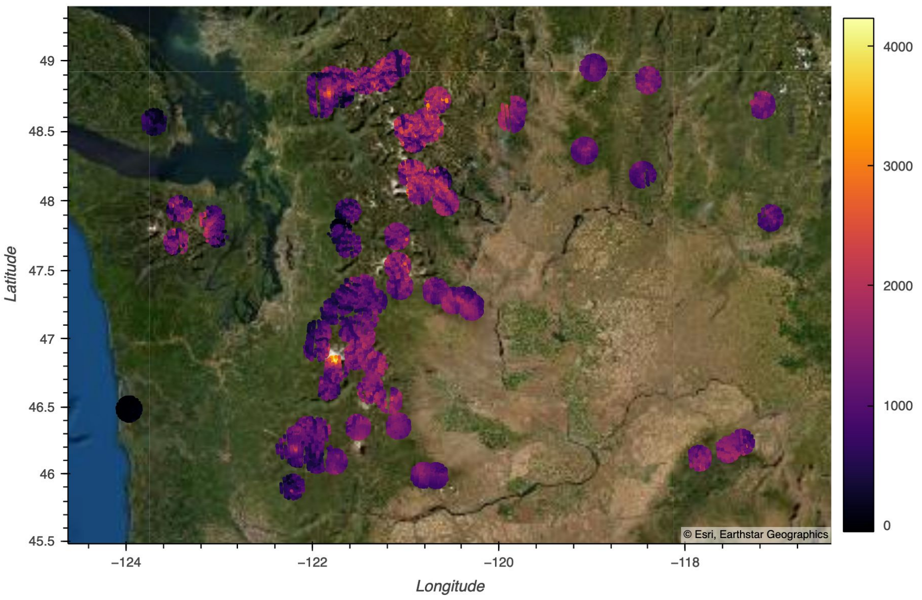
Further validation and scaling: SlideRule, 3DEP, SNOTEL



3DEP lidar DTMs: available on S3 (pink); collected, but not yet available (red)

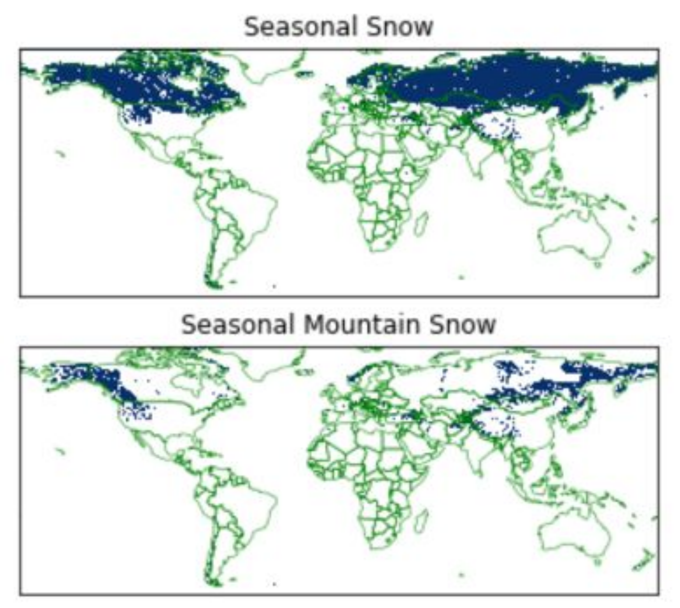


Available 3DEP within 10-km buffer of SNOTEL (blue)

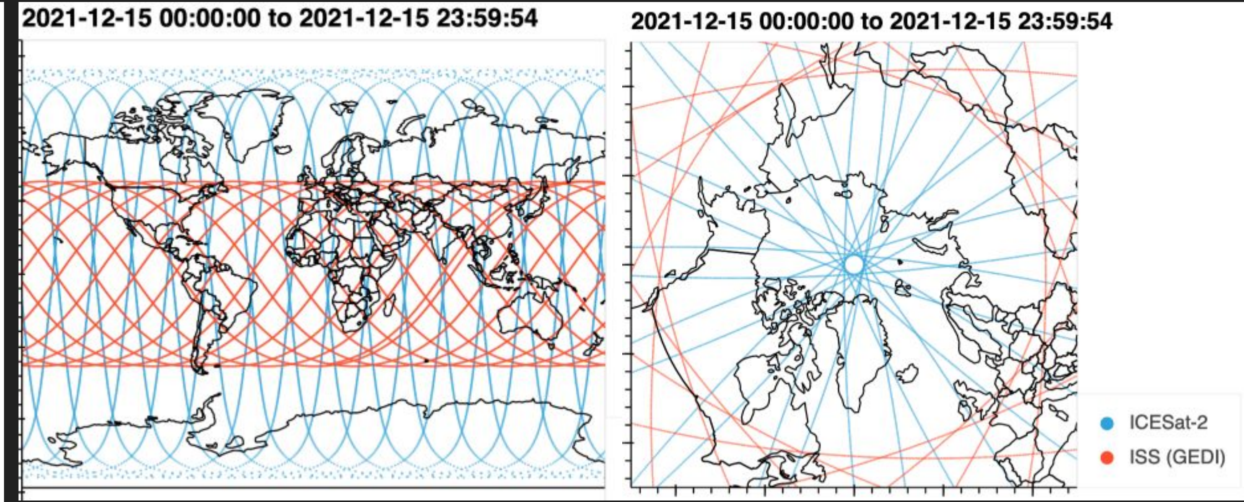


SlideRule ATL06-SR (ground) for 84 SNOTEL sites in WA state: ~5 minutes for inefficient loop

Consider a range of snow sites, reference DEMs, processing options - where does this work?
Scale to extract seasonal snow depth for watersheds, regions



MODIS snow masks from Wrzesien et al. (2019)



Ground tracks for ICESat-2 (blue) and GEDI (red) over 24 hours

GEDI - higher density for mid latitudes
ICESat-2 - higher density for high latitudes

Conclusions

Satellite laser altimetry can be used to measure seasonal snow depth over time

ICESat-2 ATL08 ground returns are better than GEDI ground returns

Shorter ATL06-SR segments (40 m) fit to ground photons are better than standard ATL08 segments (100 m) for mountain snow

Need aggregation and robust statistics (not individual shots)

Good agreement with SNOTEL records over 3 years (RMSE 0.19 m)

Scalable processing to evaluate key parameters for a range of sites

Potential for regional to global snow depth retrievals

Want to do a Postdoc at UW Seattle?

Satellite altimetry for snow

Satellite VHR optical stereo (WorldView, SkySat) processing/analysis

Machine learning and data fusion

Terrain Analysis and Cryosphere Observation Lab

University of Washington, Civil and Environmental Engineering

Scratch

Plugs

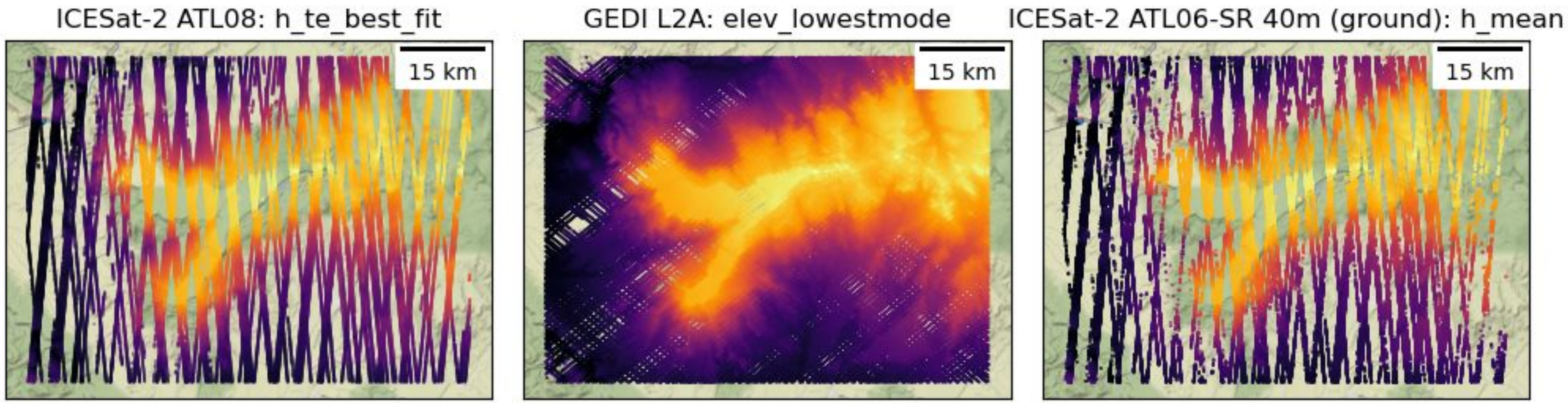
Michelle Hu (Monday AM) - WV Stereo DEM optimization

ICESat-2 Town Hall (Monday PM)
https://agu.confex.com/agu/fm21/meetingapp.cgi/Session/119379

Yiyu Ni (Monday PM)
https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/926180

Open Source Session (Fri PM)

Altimetry Data Processing (ground returns)



NSIDC/EarthData and icepyx: ATL08 v004

LPDAAC: GEDI L2A v2

SlideRule: ATL06-SR, 40 m segment (ground class)

GEDI and ATL08 filtered with recommended quality flags

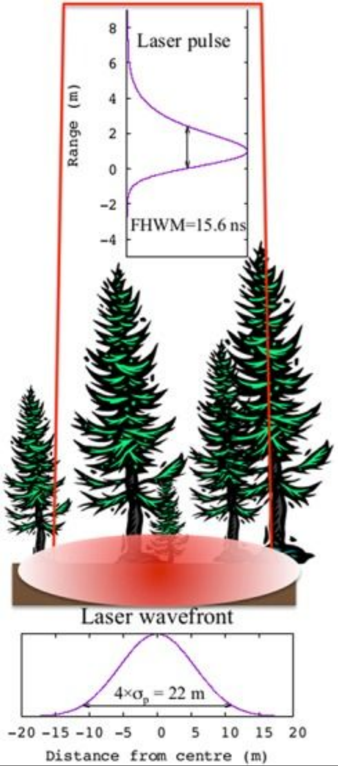
Follow-on Questions

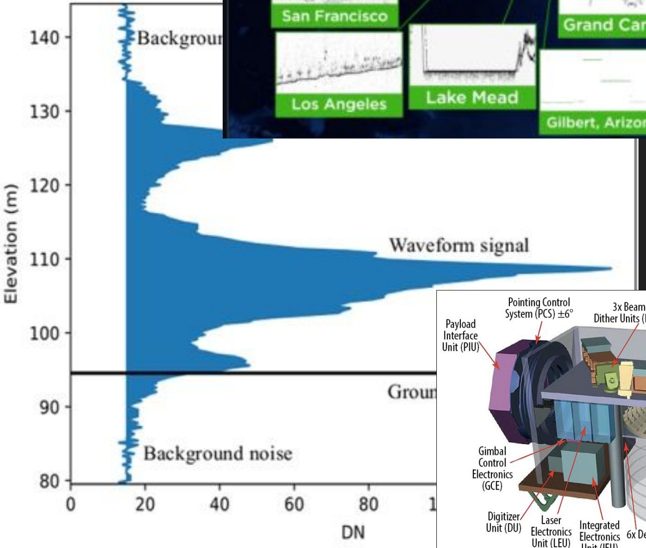
Is this result representative, or specific to Grand Mesa (flat, high, open)?

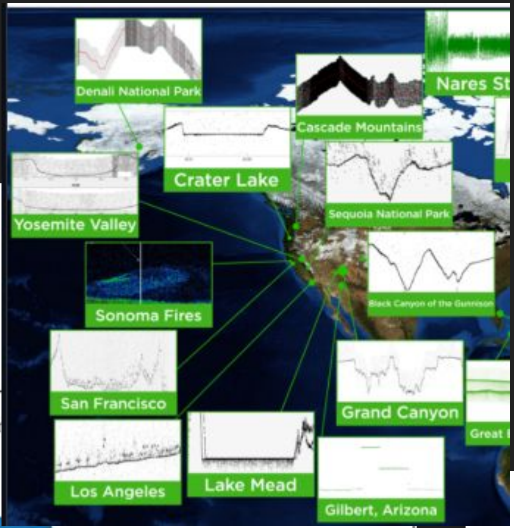
Where does this technique break down and why?

What if no lidar reference is available? Can we use snow-off VHR stereo DEMs (EarthDEM, ArcticDEM), Global DEMs (Copernicus 30 m)?

Can altimetry-only crossovers provide enough coverage at higher latitudes?







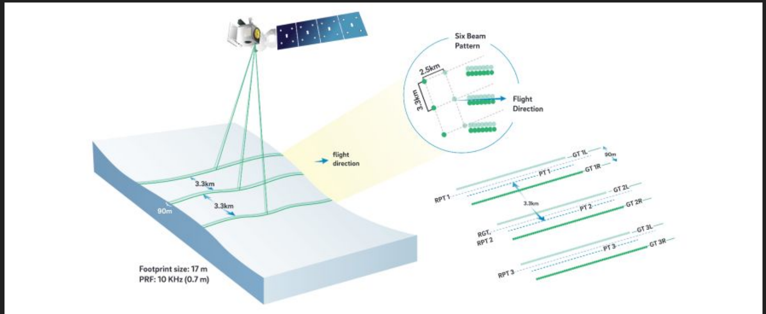
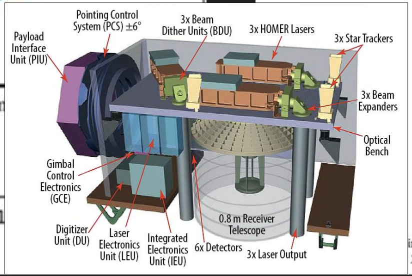
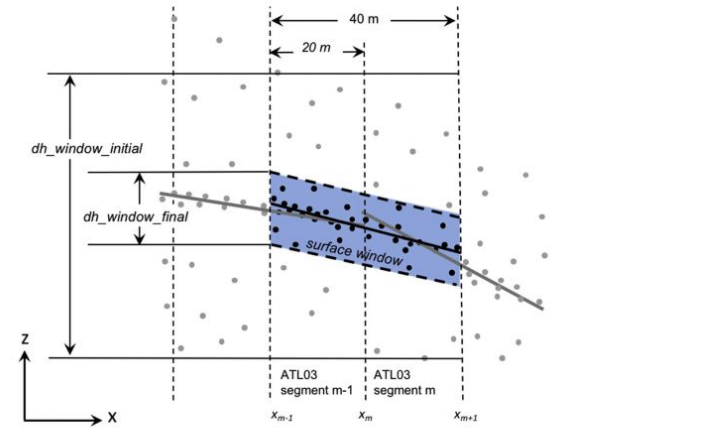


Fig. 1. Schematic of the ATLAS six-beam pattern. The central RPT (Reference Pair Tracks) follows the RGT (Reference Ground Track, which matches the nadir track of the predicted orbit). GTNX (where N is the beam pair number (1–3) and X is L (left) or R (right)) are the ground tracks generated by successive ATLAS spots (green circles). ATLAS is shown here in the forward direction, with the weak beams on the left side of the beam pair. The weak and strong beams are pitched relative to each other such that the weak beams lead the strong beams by ~2.5 km. When ATLAS is oriented in the backward orientation, the relative positions of weak and strong beams change; the strong beams are on the left side of the GT pairs and lead the weak beams. Measured Pair Tracks (PTs) are defined by line that bisects the pairs of GTs, and deviate slightly from the RPTs because of inaccuracies in repeat-track pointing. The separation of GTs within each pair is greatly exaggerated compared to the separation between RPTs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)





ing: Along-track segments fit to photon heights (gray circles) as a function of along-track distance (x) for segment *m* (black line) and 1 and *m-1* (gray lines). Photons selected by the ATL06 photon-refinement algorithm for reference point *m* are shown in black.

Hancock et al (2019) doi:10.1029/2018EA000506

Smith et al. (2019) doi:10.1016/j.rse.2019.111352

ATL06

Land ice algorithm

40 m segment

Very good at finding the surface, but doesn’t expect canopy

Only available near glaciers and ice sheets

ATL08

DRAGAN photon classifier (ground,

100 m segments

Linear fits to ground and canopy photons

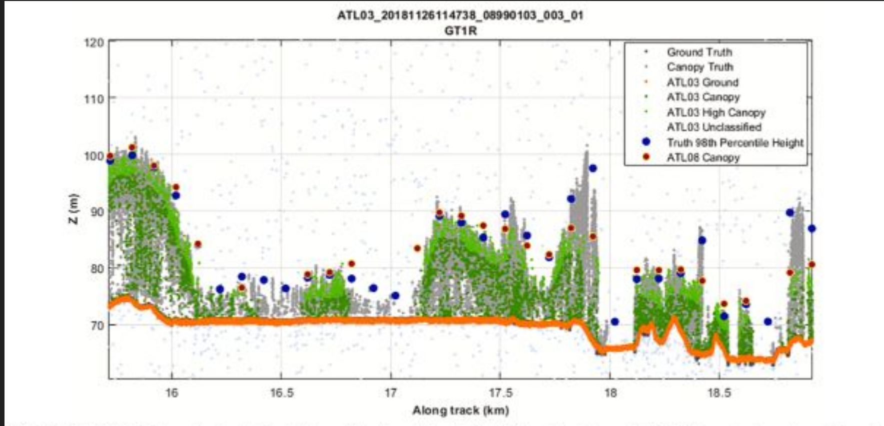
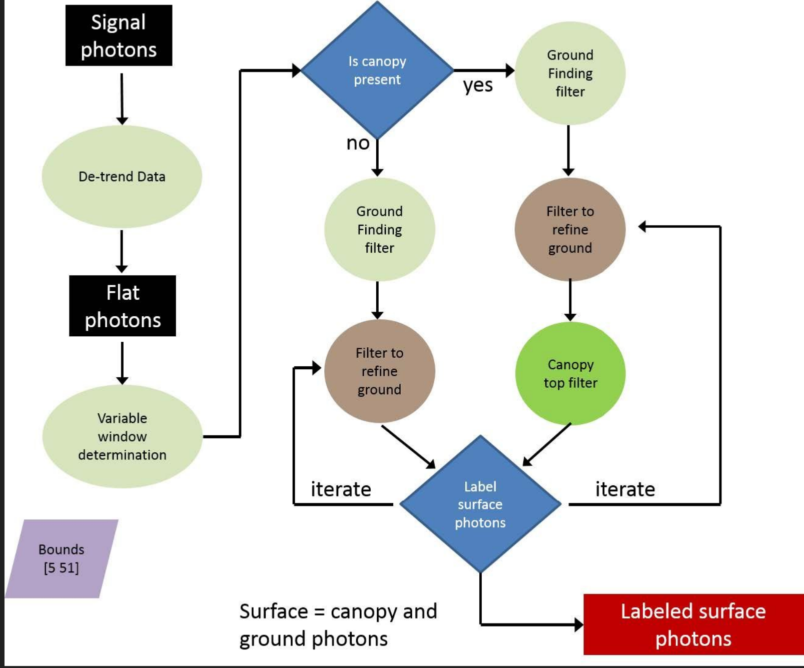


Fig. 5. Profile of ICESat-2 data products against the backdrop of the airborne lidar data. In this figure, the photons on the ATL03 data product are color coded based on their classification from the ATL08 algorithm. Green dots correspond to canopy (dark green) and top of canopy photons (light green) whereas the orange dots correspond to the identified ground photons. Airborne lidar data are shown in grey. For comparison, the ATL08 h_canopy value is represented with a larger red dot and the airborne lidar data for the same 100 m segment is shown with a large blue dot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



https://nsidc.org/data/ATL08/versions/3/print
Neunschwander and Pitts (2020)
https://www.sciencedirect.com/science/article/abs/pii/S0034425718305066

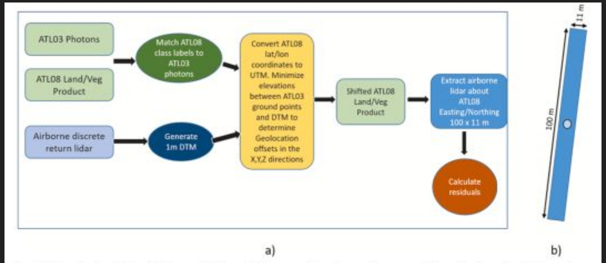
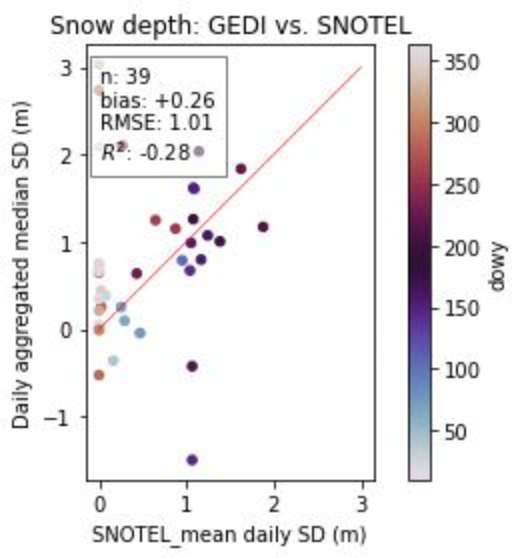
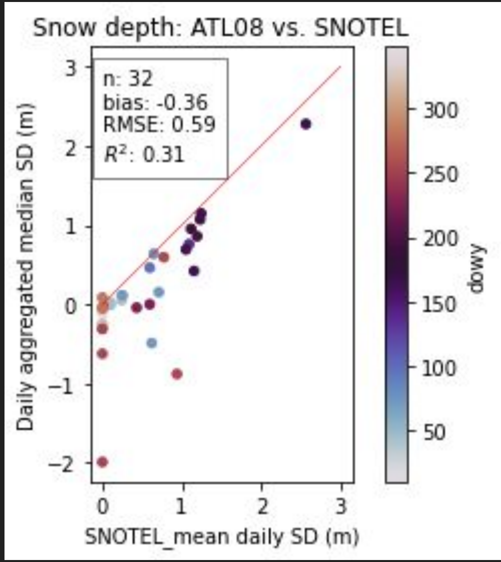
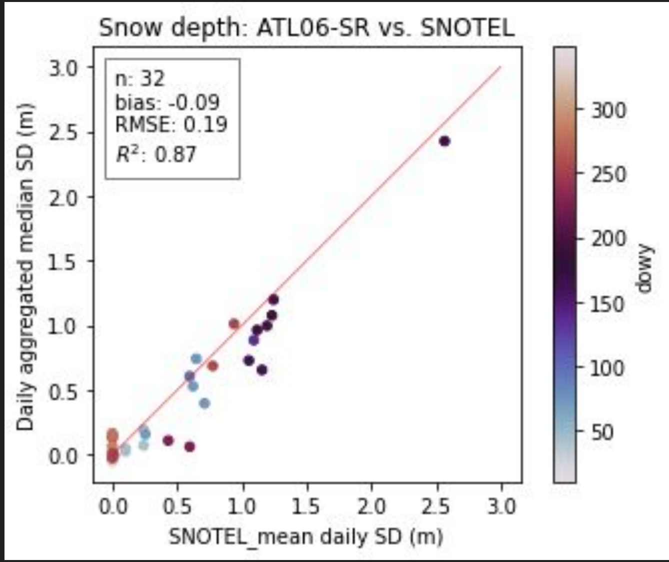


Fig. 4. a) Flowchart for ATL08 validation methodology and b) representation of box used to extract airborne data about the ATL08 coordinate.

Snow Depth: Altimetry vs. SNOTEL







ATL06-SR Snow Depth vs. SNOTEL

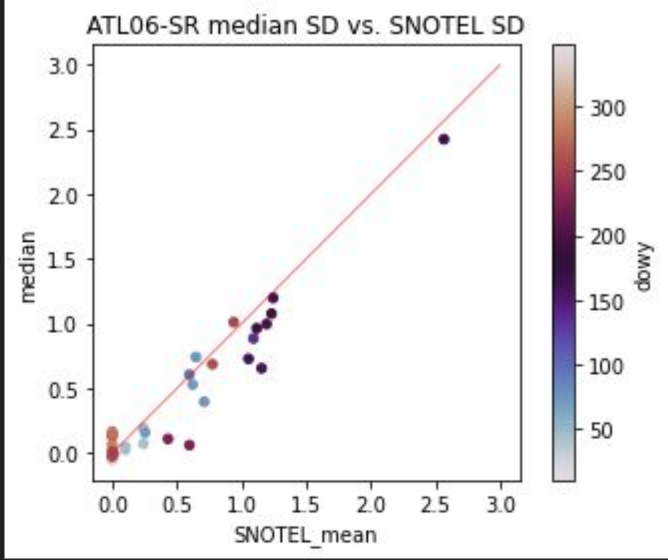
Bias -0.09 m

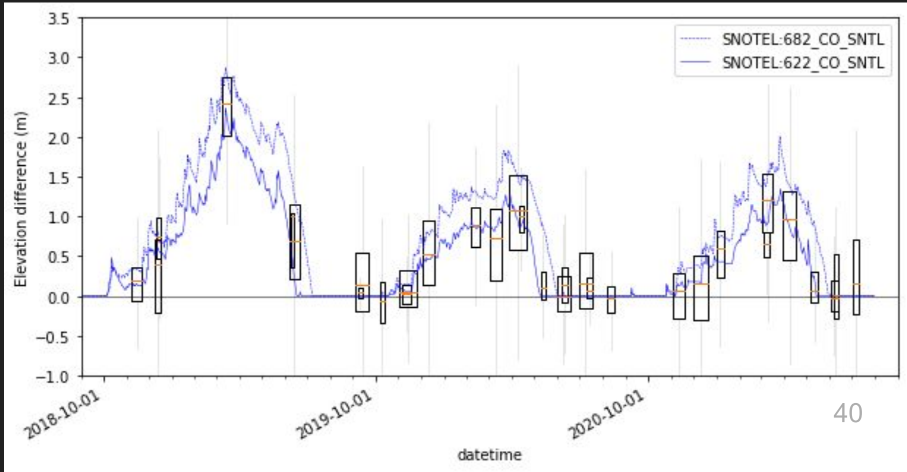
RMSE

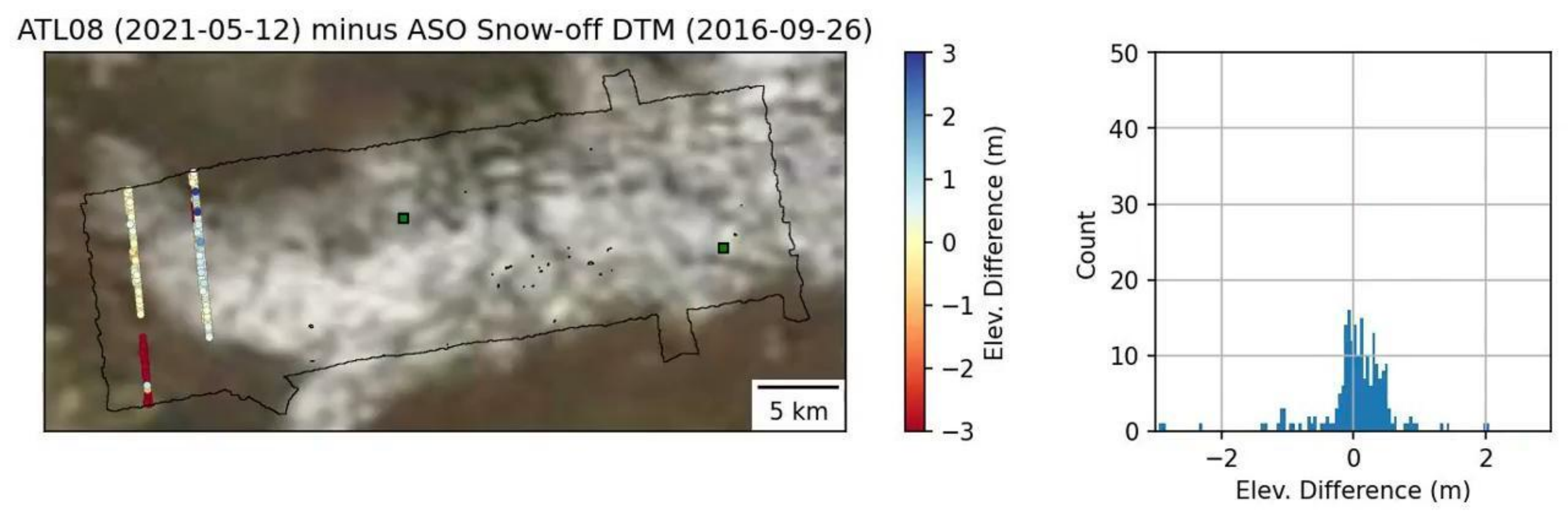
med - SNOTEL:682_CO_SNTL 0.37

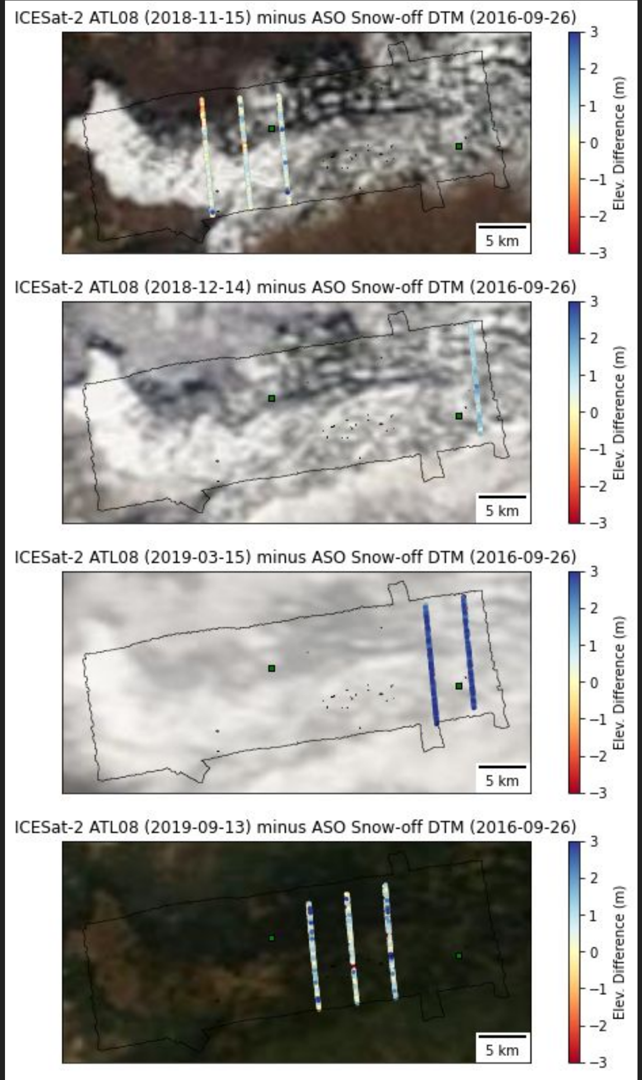
med - SNOTEL:622_CO_SNTL 0.17

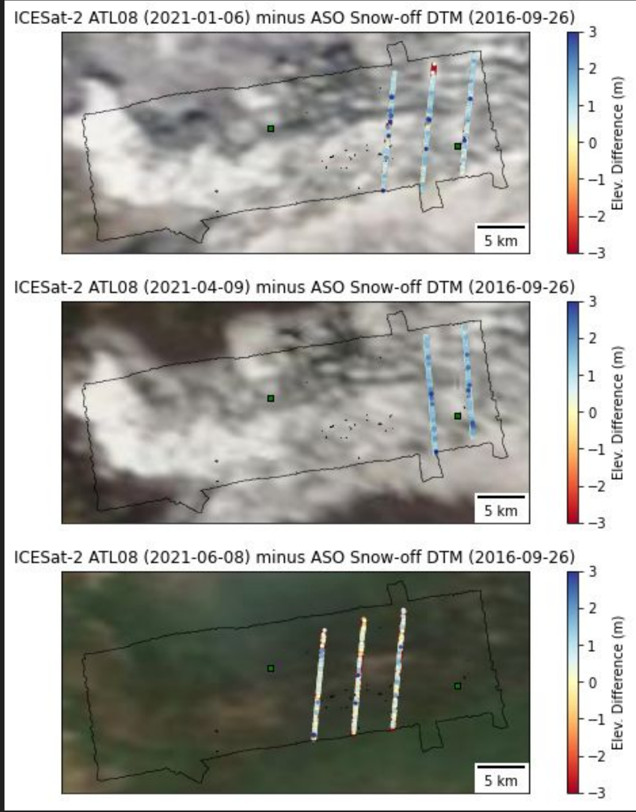
med - SNOTEL_mean 0.19

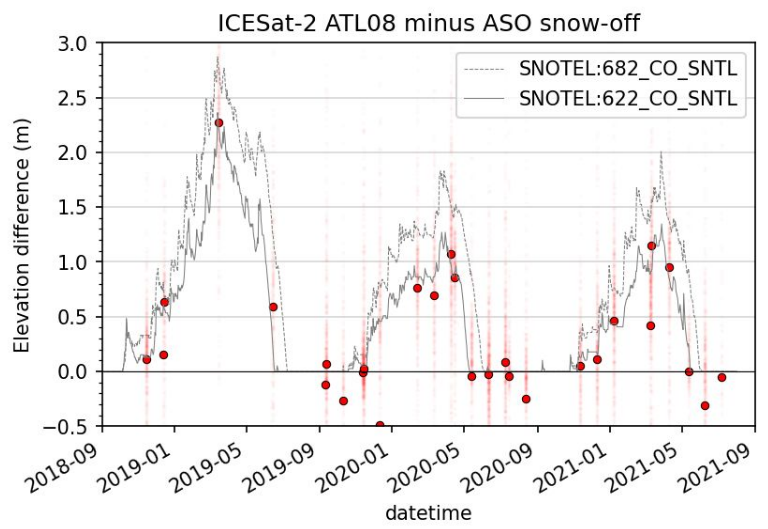


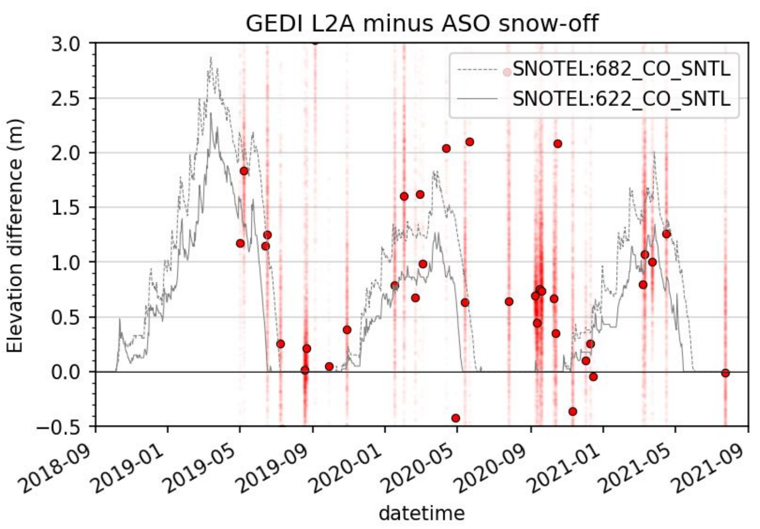


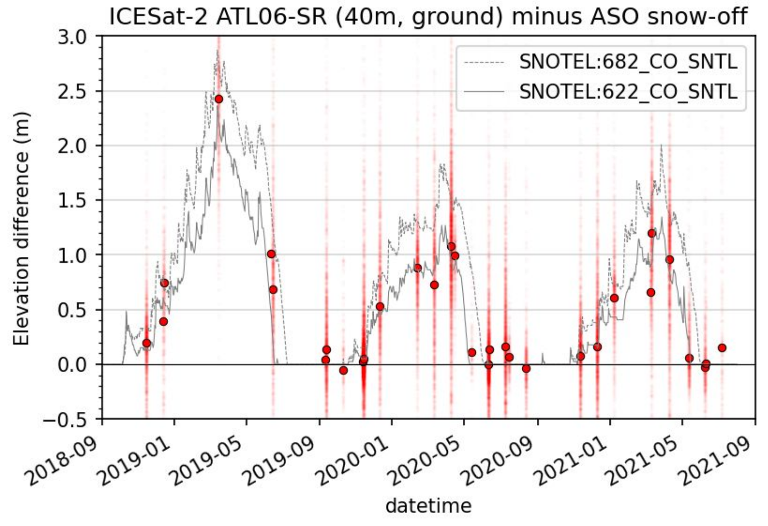

ATL08 (2021-05-12) minus ASO Snow-off DTM (2016-09-26)
5 km
Elev. Difference (m)
3
2
1
0
−1
−2
−3
Count
50
40
30
20
10
0
−2
0
2
Elev. Difference (m)

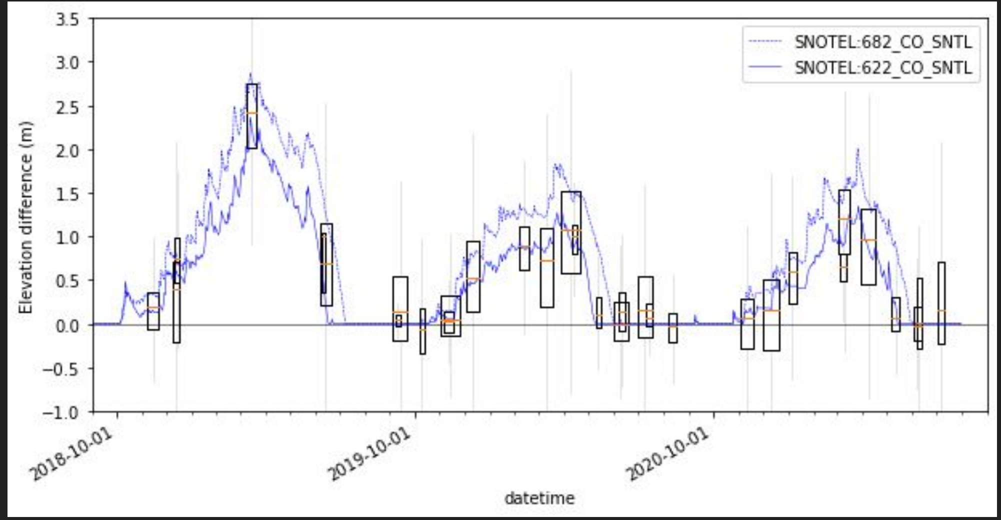

ICESat-2 ATL08 (2018-11-15) minus ASO Snow-off DTM (2016-09-26)
5 km
3
2
1
0
−1
−2
−3
Elev. Difference (m)
ICESat-2 ATL08 (2018-12-14) minus ASO Snow-off DTM (2016-09-26)
5 km
3
2
1
0
−1
−2
−3
Elev. Difference (m)
ICESat-2 ATL08 (2019-03-15) minus ASO Snow-off DTM (2016-09-26)
5 km
3
2
1
0
−1
−2
−3
Elev. Difference (m)
ICESat-2 ATL08 (2019-09-13) minus ASO Snow-off DTM (2016-09-26)
5 km
3
2
1
0
−1
−2
−3
Elev. Difference (m)


ICESat-2 ATL08 (2021-01-06) minus ASO Snow-off DTM (2016-09-26)
5 km
3
2
1
0
−1
−2
−3
Elev. Difference (m)
ICESat-2 ATL08 (2021-04-09) minus ASO Snow-off DTM (2016-09-26)
5 km
3
2
1
0
−1
−2
−3
Elev. Difference (m)
ICESat-2 ATL08 (2021-06-08) minus ASO Snow-off DTM (2016-09-26)
5 km
3
2
1
0
−1
−2
−3
Elev. Difference (m)

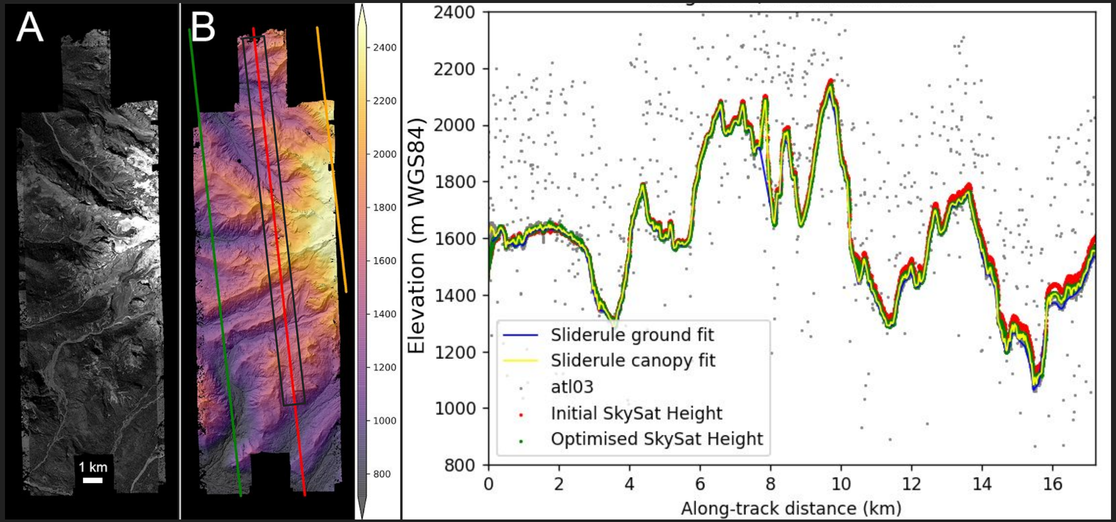

ICESat-2 ATL08 minus ASO snow-off
SNOTEL:682_CO_SNTL
SNOTEL:622_CO_SNTL
Elevation difference (m)
datetime
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
2018-09
2019-01
2019-05
2019-09
2020-01
2020-05
2020-09
2021-01
2021-05
2021-09


GEDI L2A minus ASO snow-off
SNOTEL:682_CO_SNTL
SNOTEL:622_CO_SNTL
Elevation difference (m)
datetime
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
2018-09
2019-01
2019-05
2019-09
2020-01
2020-05
2020-09
2021-01
2021-05
2021-09

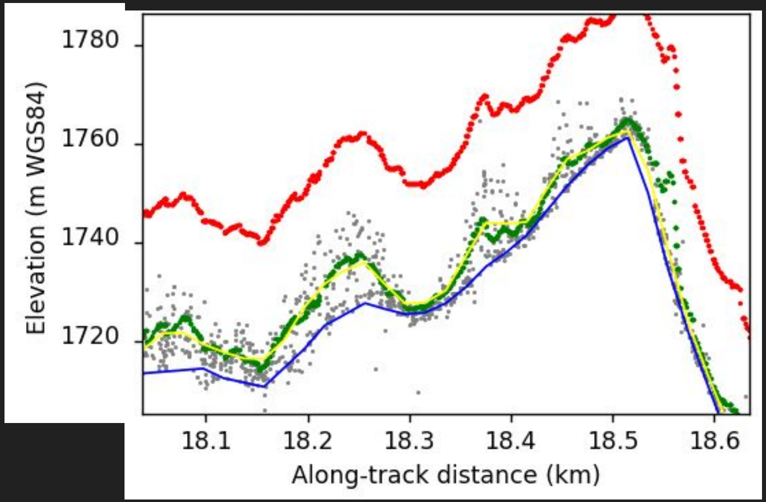

ICESat-2 ATL06-SR (40m, ground) minus ASO snow-off
SNOTEL:682_CO_SNTL
SNOTEL:622_CO_SNTL
Elevation difference (m)
datetime
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
2018-09
2019-01
2019-05
2019-09
2020-01
2020-05
2020-09
2021-01
2021-05
2021-09


SNOTEL:682_CO_SNTL
SNOTEL:622_CO_SNTL
Elevation difference (m)
datetime
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
2018-10-01
2019-10-01
2020-10-01

Planet SkySat-C stereo and ICESat-2 altimetry



Bhushan et al. (2021)



Initial SkySat-C Stereo DEM (red)
ICESat-2 ATL08 canopy (yellow) and ground (blue)
Co-registered SkySat-C Stereo DEM (green)

Time offset of ~7 days between SkySat-C triplet stereo and ICESat-2

Stereo DEM provides dense canopy coverage between sparse altimetry

Geolocation uncertainty

Won't matter for sample

6.5 m geolocation error, not much useful

Error based on slope * geolocation error

Can improve with ref DEM - better than 30 m DEM used for ATL08 stats

temporal aspects of these parameters are better understood. For a preliminary quantification of the uncertainties, Equation 1.1 is valid to incorporate the instrument related factors.

$$\sigma_Z = \sqrt{\sigma^2_{Orbit} + \sigma^2_{trop} + \sigma^2_{forwardscattering} + \sigma^2_{pointing} + \sigma^2_{timing}} \quad \text{Eqn. 1.1}$$

Although σ_Z on the ATL03 product represents the best understanding of the uncertainty for each geolocated photon, it does not incorporate the uncertainty associated with local slope of the topography. The slope component to the geolocation uncertainty is a function of both the geolocation knowledge of the pointing (which is required to be less than 6.5 m) multiplied by the tangent of the surface slope. In a case of flat topography (<=1 degree slope), σ_Z<= 25 cm, whereas in the case of a 10 degree surface slope, σ_Z =119 cm. The uncertainty associated with the local slope will be combined with σ_Z to produce the term $\sigma_{Atlas_{Land}}$.

$$\sigma_{Atlas_{Land}} = \sqrt{\sigma^2_Z + \sigma^2_{topo}} \quad \text{Eqn. 1.2}$$

$$\sigma_{topo} = \quad \sigma_{topo} = \sqrt{\left(6.5tan(\theta_{surfaceslope})\right)^2} \quad \text{Eqn. 1.3}$$

Ultimately, the uncertainty that will be reported on the data product ATL08 will include the $\sigma_{Atlas_{Land}}$ term and the local rms values of heights computed within each data parameter segment. For example, calculations of terrain height will be made on photons classified as terrain photons (this process is described in the following sections). The uncertainty of the terrain height for a segment is described in Equation 1.4, where the root mean square term of $\sigma_{Atlas_{Land}}$ and rms of terrain heights are normalized by the number of terrain photons for that given segment.

$$\sigma_{ATL08_{segment}} = \sqrt{\sigma^2_{Atlas_{Land}} + \sigma^2_{Zrms_{segment\_class}}} \quad \text{Eqn. 1.4}$$

But we don’t have LiDAR everywhere

Snow-free VHR stereo DSMs - ArcticDEM and EarthDEM for open/sparse veg

Higher latitudes - better altimetry coverage

Global DEMs - Copernicus 30 m precision is excellent

Variables

Surface:

- Terrain slope, roughness, aspect relative to along-track direction
- Landcover type - open vs. vegetated (type and density)

Instrument:

- Altimeter shot diameter, spacing
- Altimeter beam strength (weak/strong)
- Altimeter wavelength: reflectance of snow, penetration

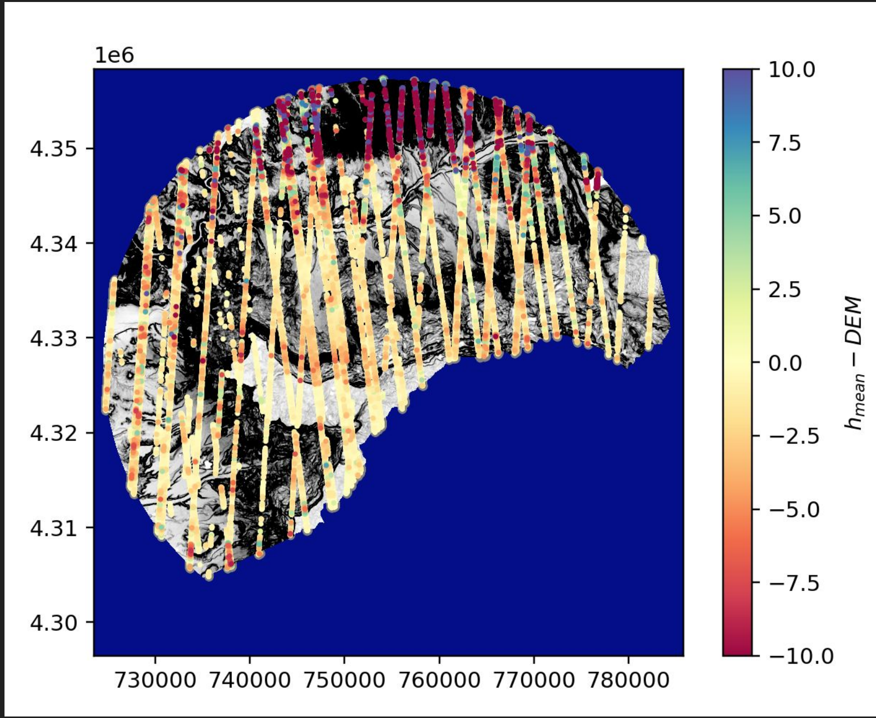
Processing (ATLAS):

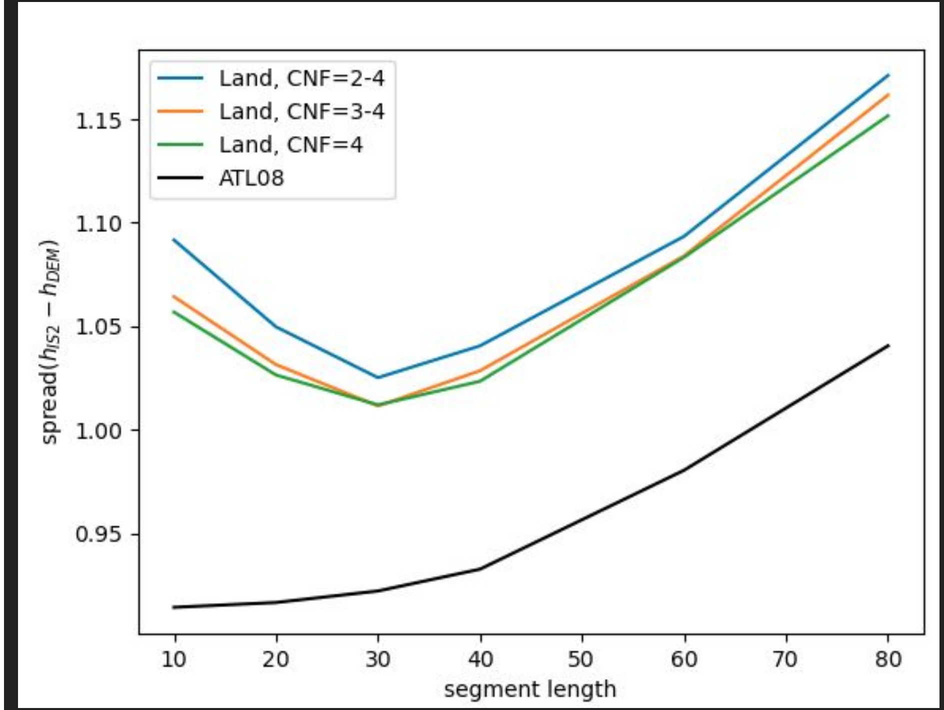
- Segment length
- Classification routine
- Fit thresholds: number of ground photons

Processing (snow):

- Sampling strategy (nearest neighbor, zonal stats for footprint)
- Aggregation area
- Snow depth correlation length scale
- Minimum sample count

Parameter choices and height-estimate precision





Over land surfaces, product precision depends on segment length, slope and roughness, and signal-selection parameters.

Can evaluate precision based on external LIDAR-based DEMs (here 3DEP)