The land-ice picture of ICESat-2

- A brief history of the ICESats
- ICESat -2 land-ice product overview
- ATL06: the solution to every problem*
- Mission status from the land-ice perspective

*some restrictions apply

ICESat

- ICESat operated from 2003-09
- It used a single-beam 1064-nm laser, pulsing 40 times per second
- Because the beam could not easily be aligned with the detector's field of view, the field of view had to be large, which led to substantial forward-scattering-driven elevation biases
- The laser lifetime proved unexpectedly short, so to prolong the mission, it was only turned on 60-90 days per year, repeating about 1/3 of its 91-day-repeat orbit
- Time-varying laser power led to time-varying elevation biases that have never been adequately calibrated
- Received power levels were low late in the mission, leading to lower precision.

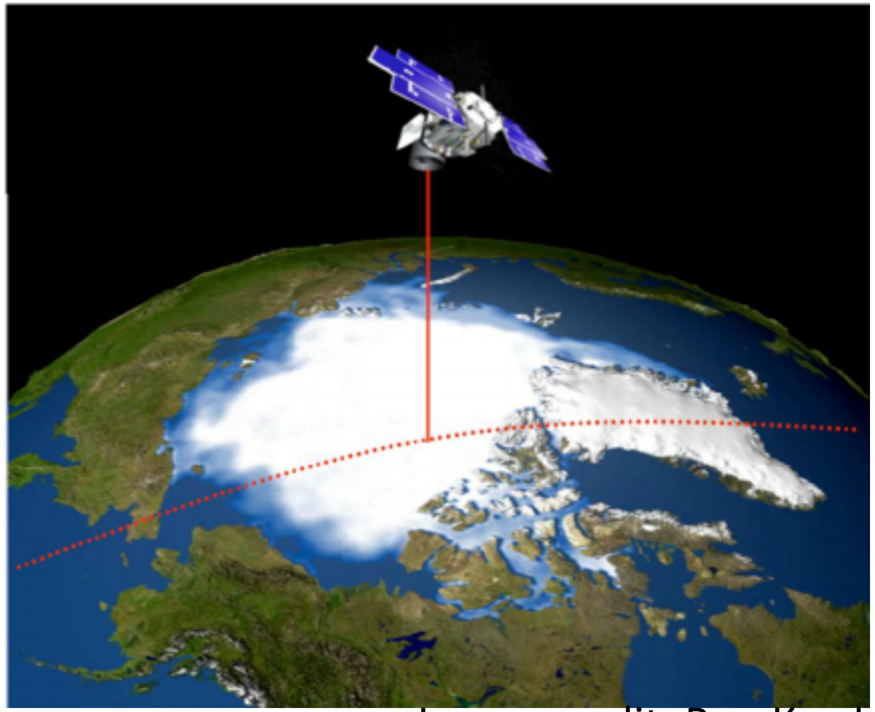
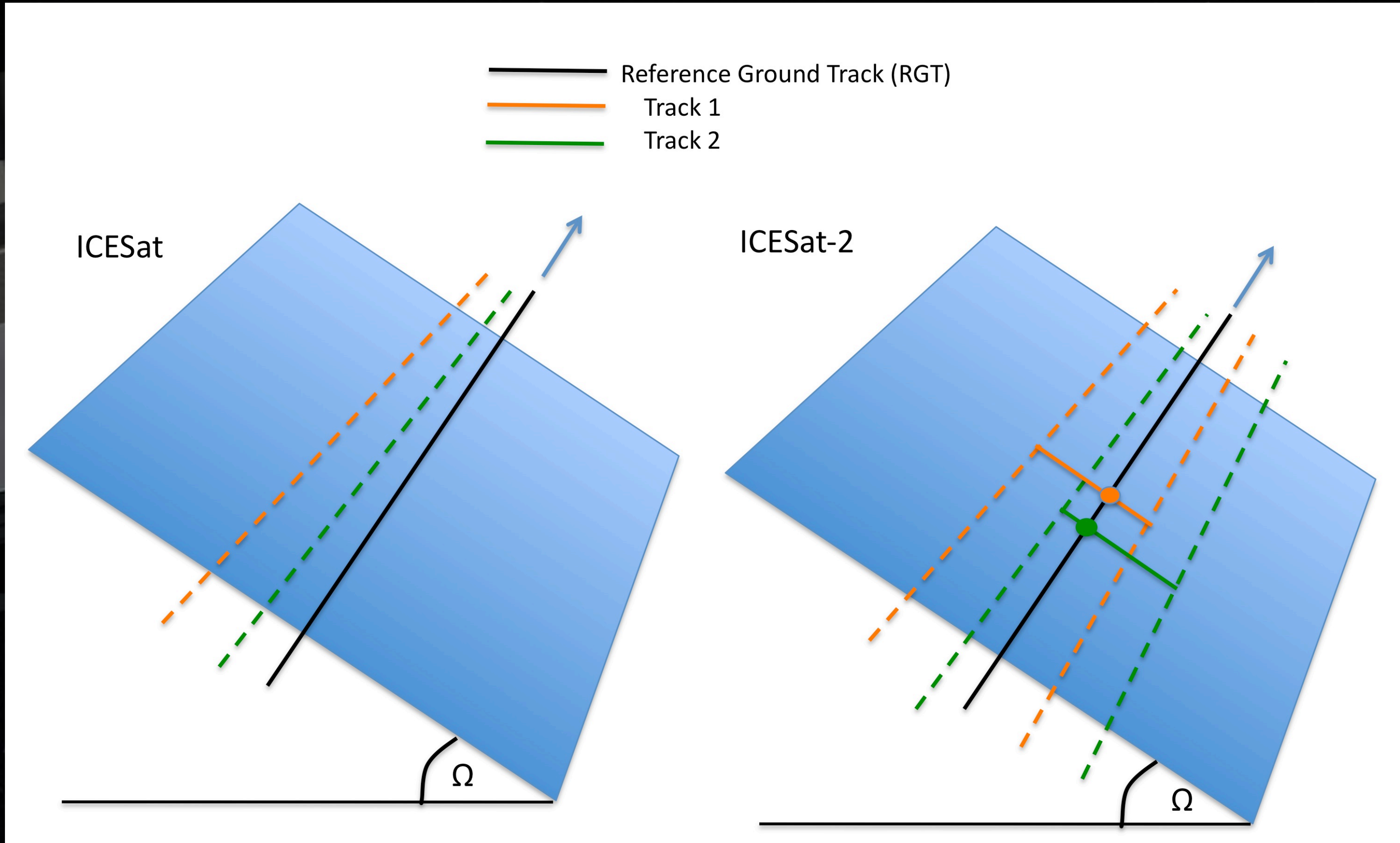


Image credit: Ron Kwok

Problems with ICESat-1 … and their solutions with ICESat-2

ICESat-1	ICESat-2
Short laser lifetime: Coarse temporal resolution	Continuous operation made possible by Low- per-pulse energy Better temporal sampling due to wide beam separation
Coarse spatial resolution	Six-beam configuration, basin-scale measurement
Cross-track slope / elevation change ambiguity	Beam pair repeat measurements
Time-varying instrumental biases	Monitoring using well-characterized targets
Transmit-pulse-power-driven instrumental biases	Adjustable transmit power to maintain consistent Tx/Rx behavior
Transmit-pulse-shape-driven instrumental biases	Monitoring of transmit-pulse shape Explicit treatment of pulse-shape effects in land-ice products
Forward-scattering (cloud/blowing snow) biases	Small receiver field of view / active beam steering Small grain-size dependence of green reflectance lets surface reflectance map cloud properties
Short mission duration (2003-09)	Data should be intercomparable with ICEsat-1 (2003-21?)

Ice sheets:
Cross-track slope recovery via pairs of beams

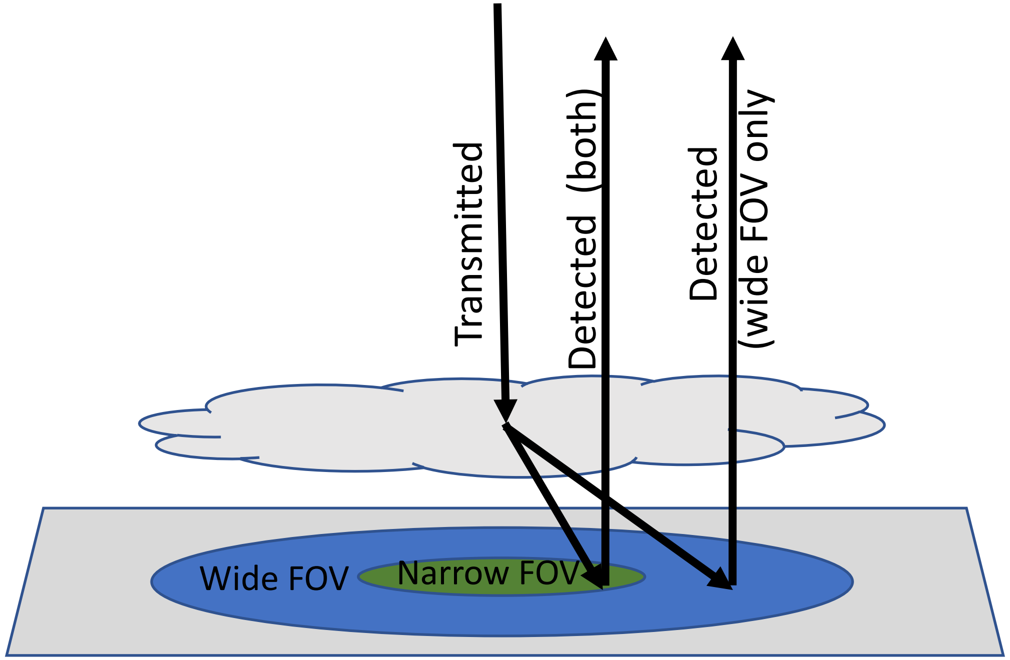


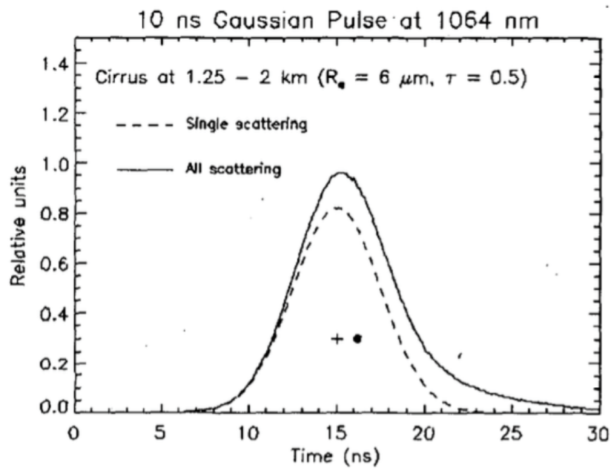
91-day repeat orbit
Pointing control requirement: 45 m
Pointing knowledge requirement: 6.5 m
Bias monitoring requirement: 0.2 cm/yr

Slide from Thorsten Markus/ May 2018 GSFC update

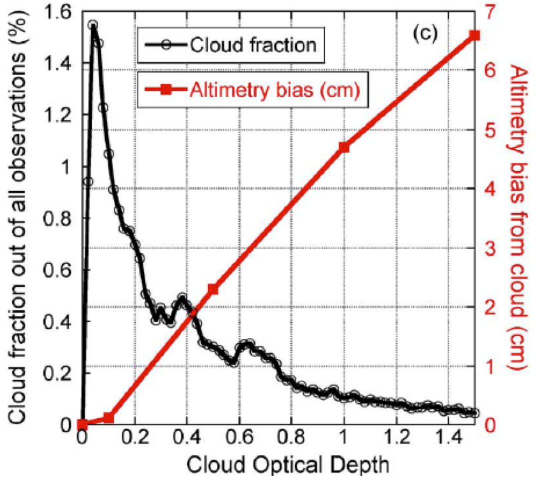
Cloud-scattering effects on surface returns

- Cloud particles scatter light mostly in the forward direction
- Scattered photons that are detected by the satellite have taken longer paths / are delayed
- Wider optical fields of view allow detection of more scattered photons
  - Narrower FOVs reduce forward-scattering biases
- Mean centroid delay scales with:
  - Receiver FOV
  - Cloud optical depth
- Clouds can be detected by:
  - LIDAR returns (nighttime only)
  - Reduction in apparent surface reflectance (day or night)





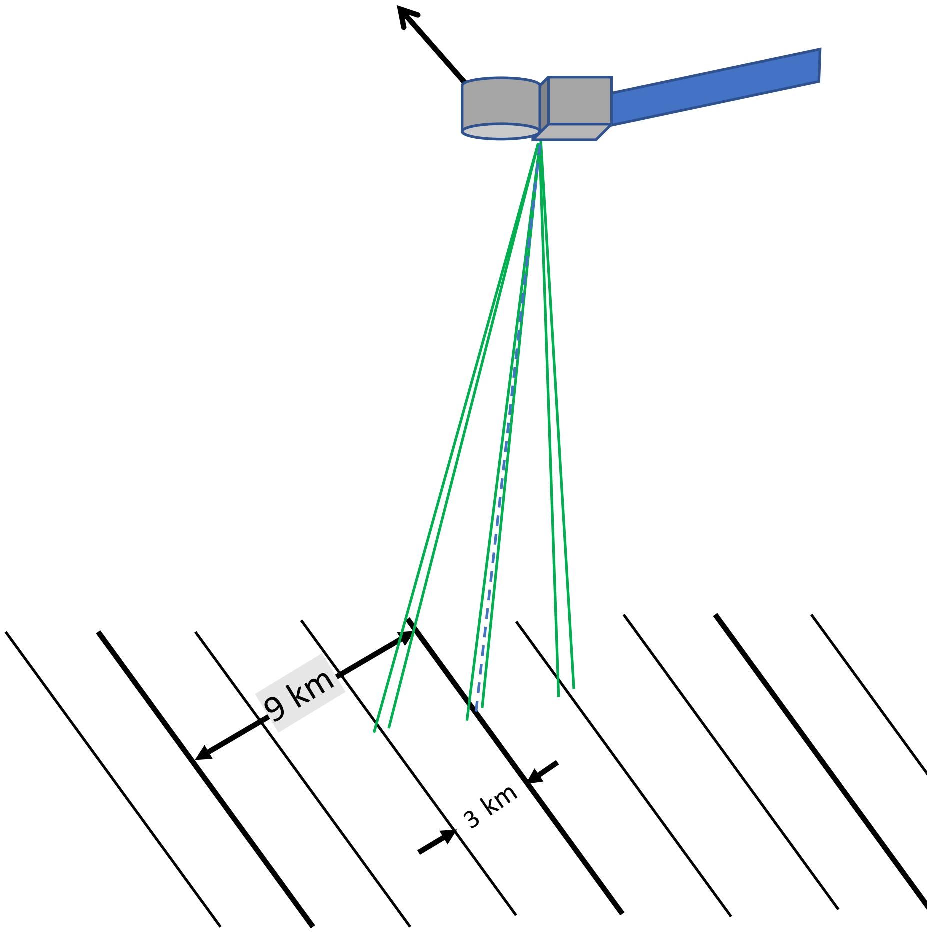
Spinhirne et al, 2000

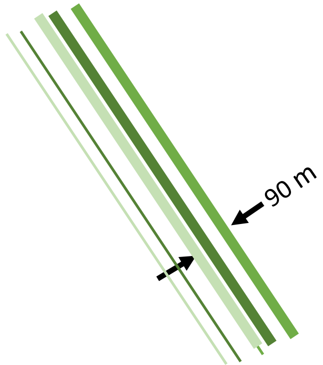


Yang et al, 2013

ICESat-2 repeat scheme

- ICESat-2’s ground track design is meant to measure exact repeats over glaciers with the maximum spatial and temporal resolution
- 91-day repeat orbit gives measurements per season for each ground track
- Nadir tracks are spaced every ~9 km at 72^o
- Beam pairs extend 3 km on either side of the nadir track
- Gaps between adjacent beam pairs < 3km
- Each beam pair measures surface slope, allows correction for cross-track slopes



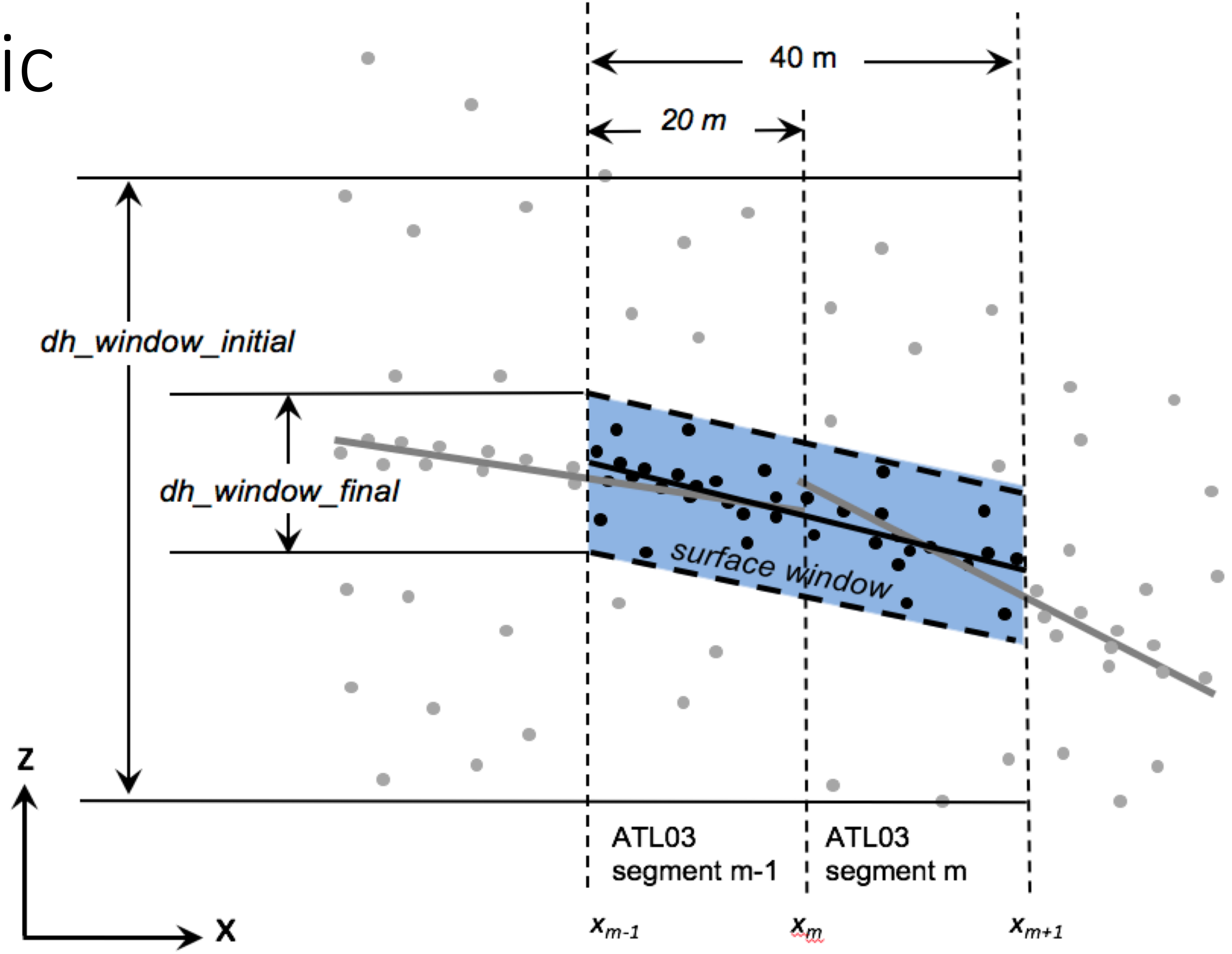


ICESat -2 data products

Product	What?	Resolution / posting	Volume Points / 10x10 km box
ATL03	Geolocated photon-returns	0.7 m / 0.7 m	>6,000,000 / yr
ATL06	Surface-height estimates for along-track segments	40 m / 20 m	32,000 / yr
ATL11	Surface height corrected to reference tracks	120 m / 60 m @ 4/yr	2,600 reference points 10,400 data points
ATL14	DEM	125 m -3 km / 125 m @1/yr	6400
ATL15	dh/dt maps	500 m – 3 km m, 500 m @4/yr	1600/yr

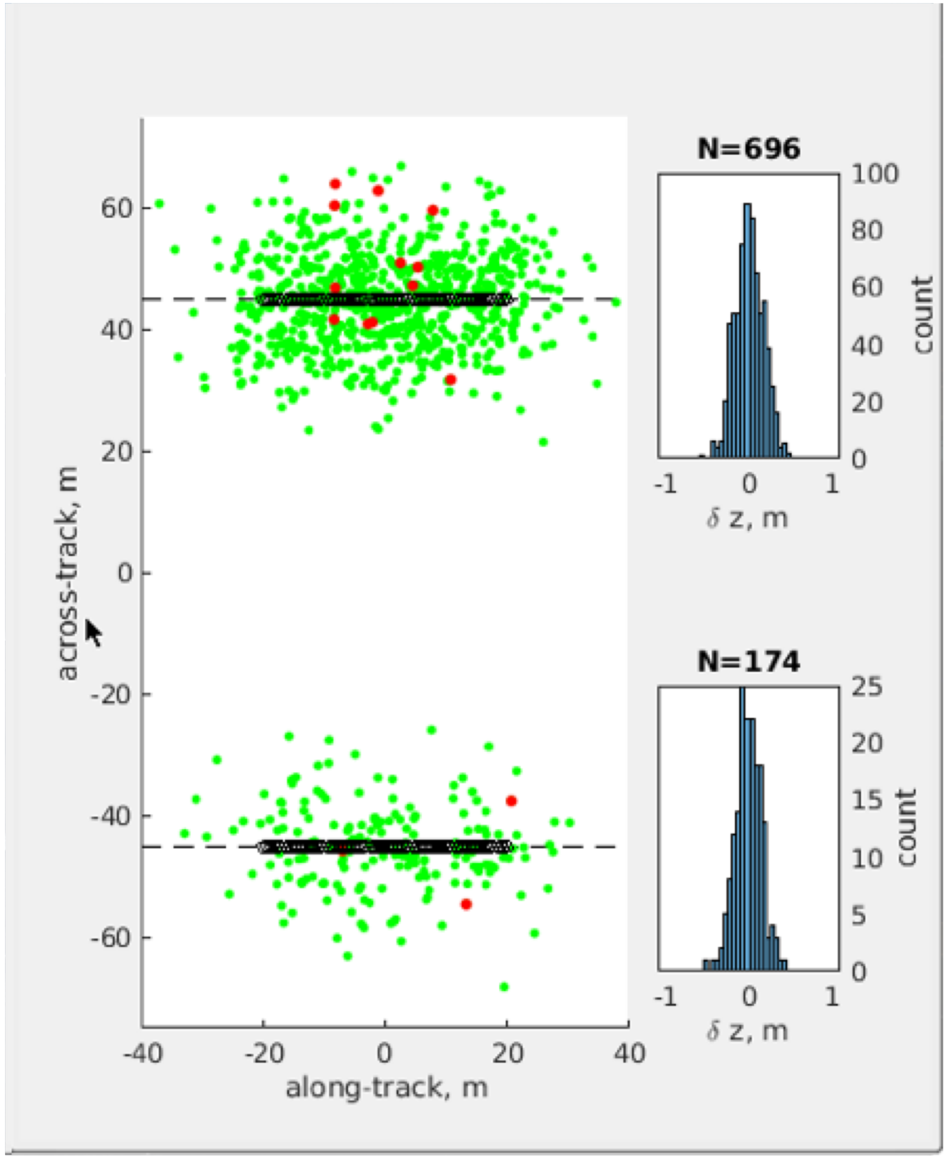
ATL06 schematic

- ATL06 is the lowest-level land-ice-height product
- It reports the elevation of 40-meter sloping segments of data, posted every 20 m along track
- An iterative fitting strategy tries to select a narrow band of photons that includes the surface
- Parameters describing the shape of the surface window help describe how well this process worked



ATL06: land-ice height

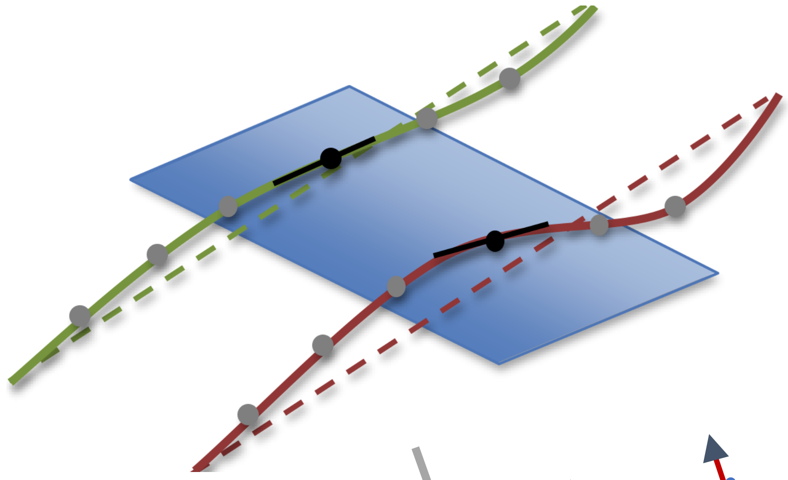
- Product goals:
    - Measure the surface at glaciologically meaningful scales
    - Provide statistically robust elevation estimates
    - Provide statistics to distinguish high-quality returns from low
    - Provide cross-track slope information to correct for fine-scale topography
- Measurement structure:
    - Photon heights from ATL03 are fit with 40-meter along-track segments
    - Segments are coordinated between beam pairs and between repeats
    - Vertical bounds around the segments help reject background noise
    - Statistics of the residuals to the segments allow error estimates and bias corrections

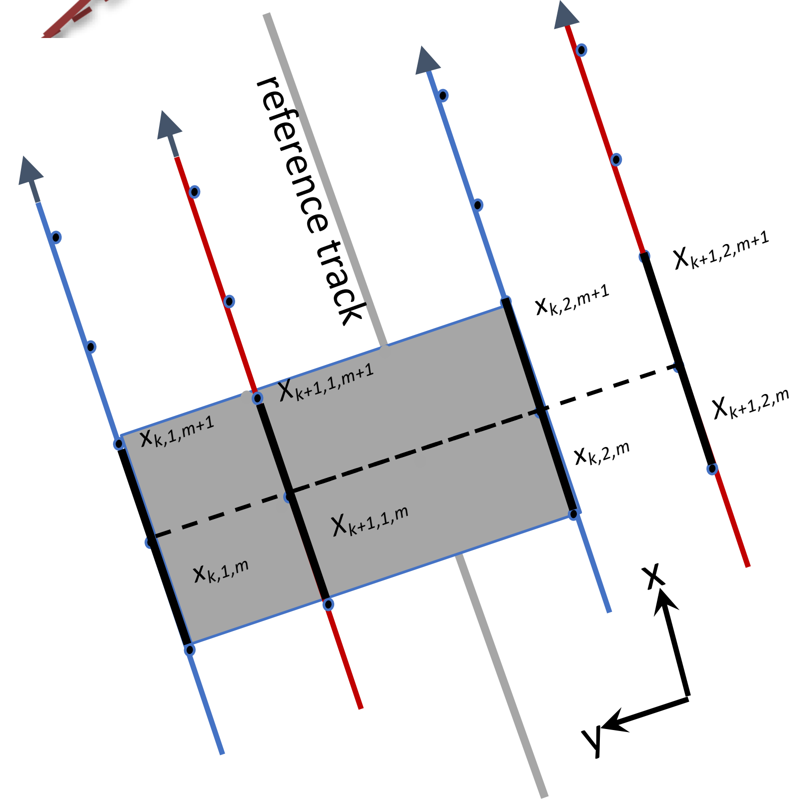


Frame 1: 50-meter airplane with crevasses in the background,
Frame 2: photons returned from one pulse
Frame 3: photons returned from 57 pulses

Along-track segments

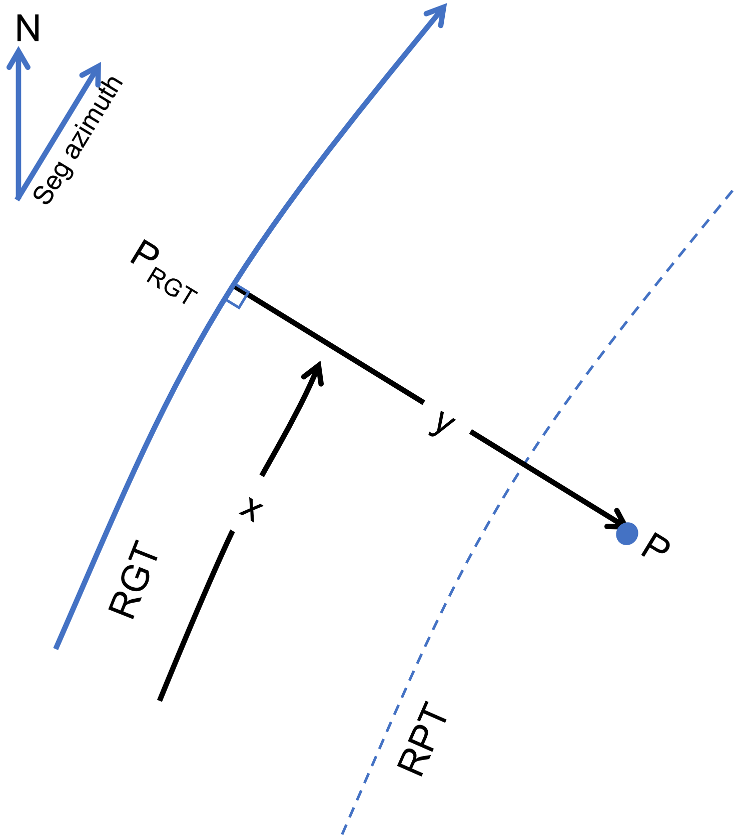
- Segments are centered on points spaced every 20 m along the reference ground tracks
- Segment numbers coordinate data between beams in a pair, and between repeats
- Along-track coordinate systems measure along-track and across-track positions for photons
  - ATL06 fits segments in the along-track direction
  - Beam-to-beam height differences define the across-track slope
  - ATL11 makes use of slope information in calculating height changes.





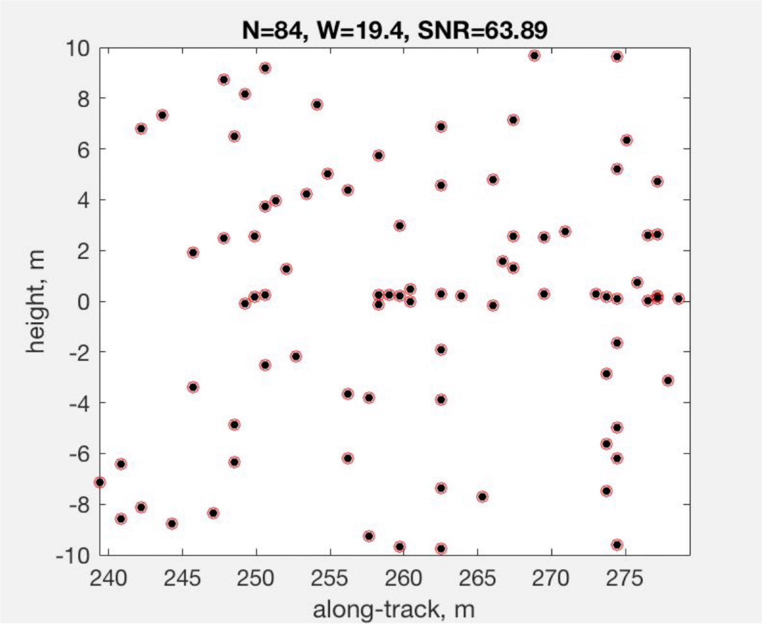
Along and across-track coordinates

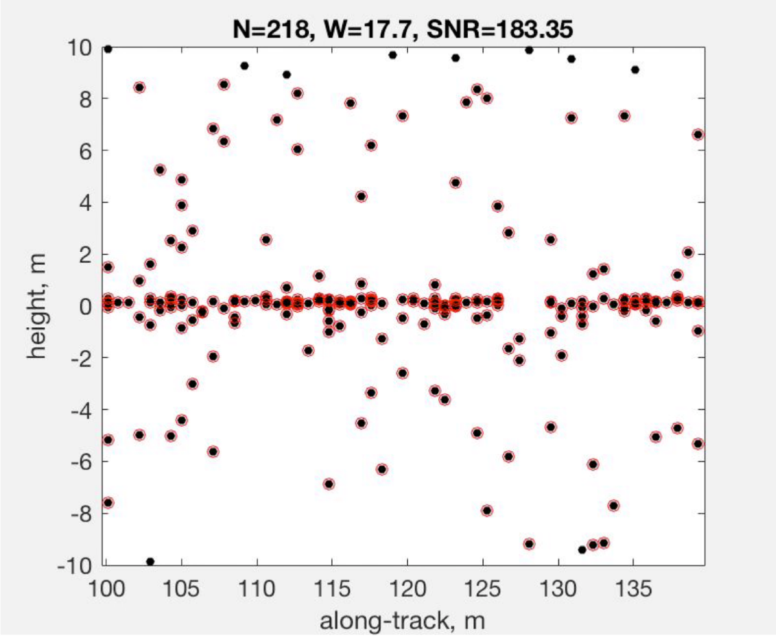
- Along-track coordinates (x_rgt) are measured parallel to each reference ground track, starting at the equator, heading North:
  - 0: First equator crossing
  - ~ 6500 km: Southern Greenland, heading north
  - ~10,000 km : Polehole North
  - ~13,000 km : Southern Greenland, heading south
  - ~27,000 km: Northern Antarctica, heading south
  - ~30,000 km : Southern polehole
  - ~33,000 km: Northern Antarctica heading north
- Across-track coordinates (y_rgt) are measured perpendicular to the RGT, to the left:
  - Gt1x: +3000 m
  - Gt2x : ~0 m
  - Gt3x : -3000 m



ATL06 algorithm overview

- Select photons
  - Horizontal selection uses 40-meter pre-defined along-track segments
  - Vertical selection uses ATL03 photon classification, with coarse vertical histograms as a backup
- Fit selected photons with a line segment
  - Iteratively narrow the vertical window to reject noise
- Calculate corrections and error estimates using histograms of line-segment residuals
  - Median-based height estimate
  - First-photon-bias correction
  - Transmit-pulse-shape correction
- Provide statistics for evaluating the success/failure of the fit





Animation: iterative fitting of a weak-beam segment through moderate clouds

Parameters that help define segment quality:

- Misfit statistics
  - h_robust_spread : estimate spread of the surface heights, taking into account the window size and background rate
  - rms_residual: the RMS misfit of photons in the window
- Window convergence
  - w_surface_window_final: the width (top-to-bottom) if the returned window
  - dh_fit_dx : the along-track slope of the refined window
- Signal level
  - r_eff: effective reflectance
  - SNR: signal-to-noise level
  - SNR_significance: the chance of the ATL06 algorithm finding
- Estimated errors:
  - h_li sigma: error estimate for h_li
- Combined quality flag (see table)
  - Passes all tests -> atl06_quality_flag=0
  - Fails one or more tests -> atl06_quality_flag=1

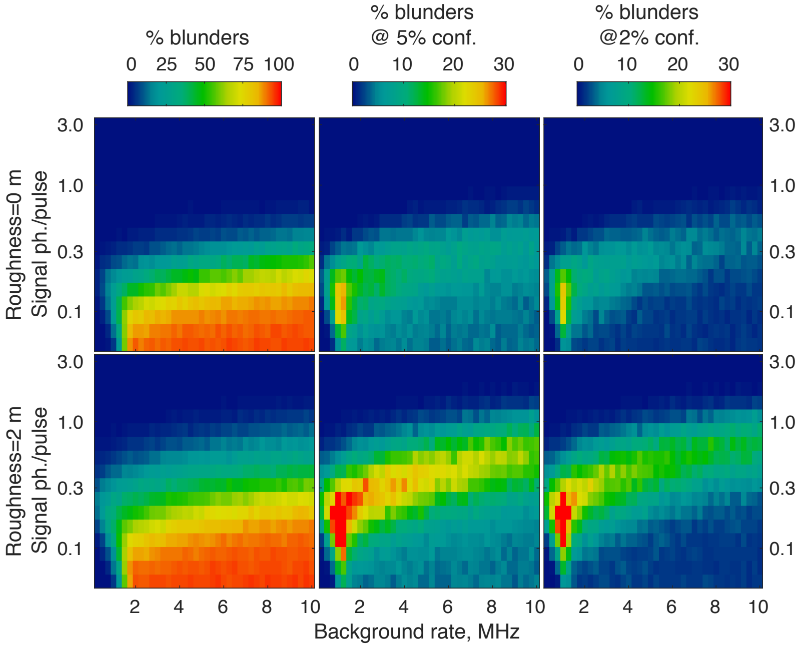
Parameter	Threshold	Description
Signal selection source	<= 1	Signal selection is based on PE flagged in ATL03.
h_li_sigma	< 1 m	Errors in surface height are moderate or better
snr_significance	< 0.02	Surface detection blunders are unlikely
Photon density **= n_fit_photons/ w_surface_window**	>1 /m for weak beams, >4/m for strong beams	Indicates how well the window converged. Large windows and weak signals indicate poor convergence

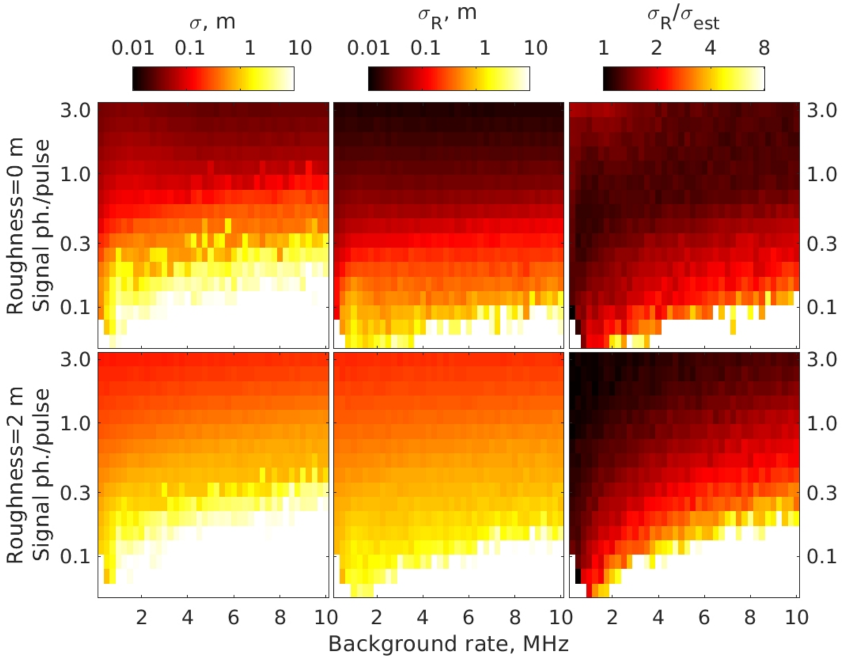
Do ATL06 signal finding and data filtering work?

- The fitting algorithm was run on synthetic data to test height recovery as a function of
  - Signal level (0.03 ph/pulse – 3 ph/pulse
  - Background photon rate (0-12 MHz)
  - Surface roughness (0 and 2 m)

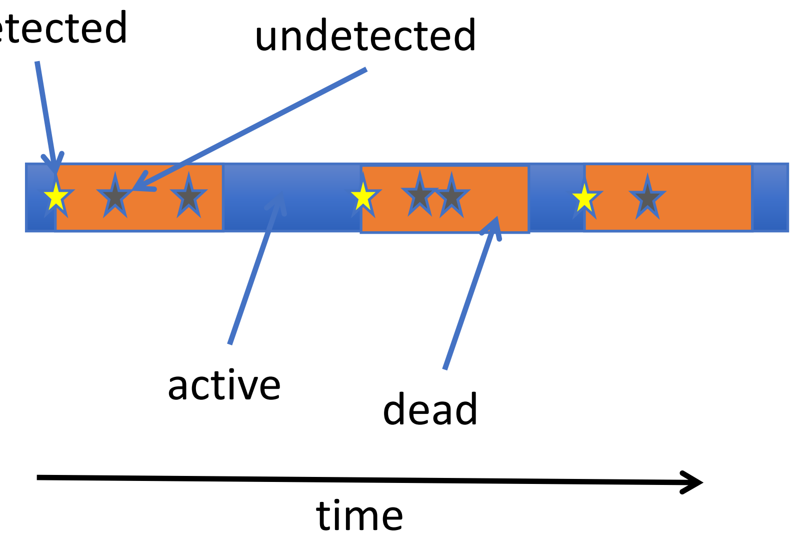
- Fitting started with a 40-m initial window of photons, ATL06 had to select the best window within these photons.
  - Blunder filters were applied based on SNR_significance (the probability of a segment with the observed SNR for pure-noise inputs)

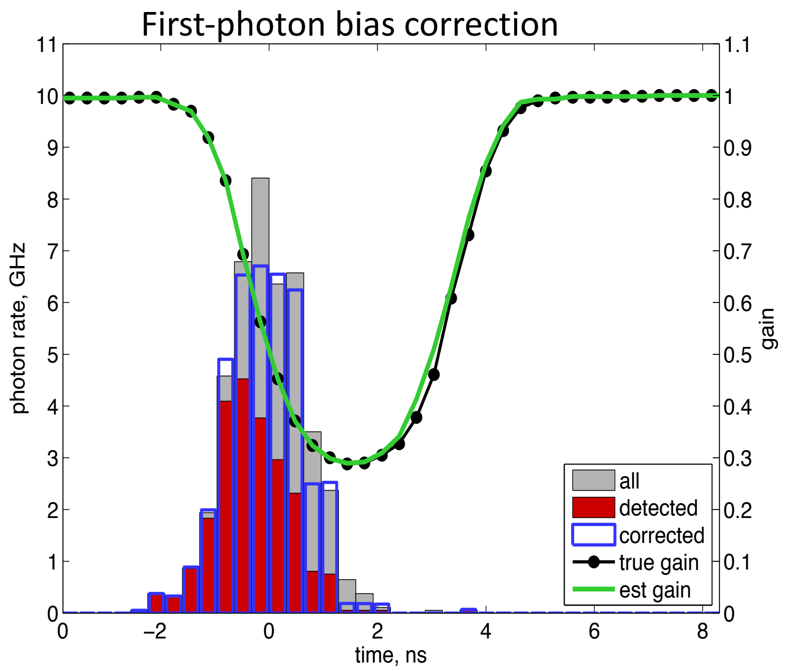
- Results were evaluated by:
  - Counting the failed fits (% blunders remaining)
  - Calculating the RMS and robust spread of the estimated surface heights

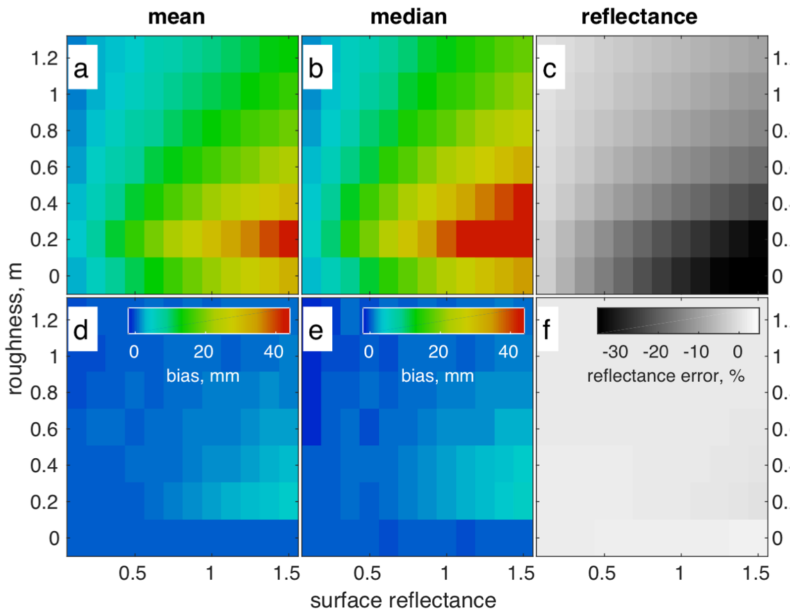




Biases corrections 1: first-photon bias

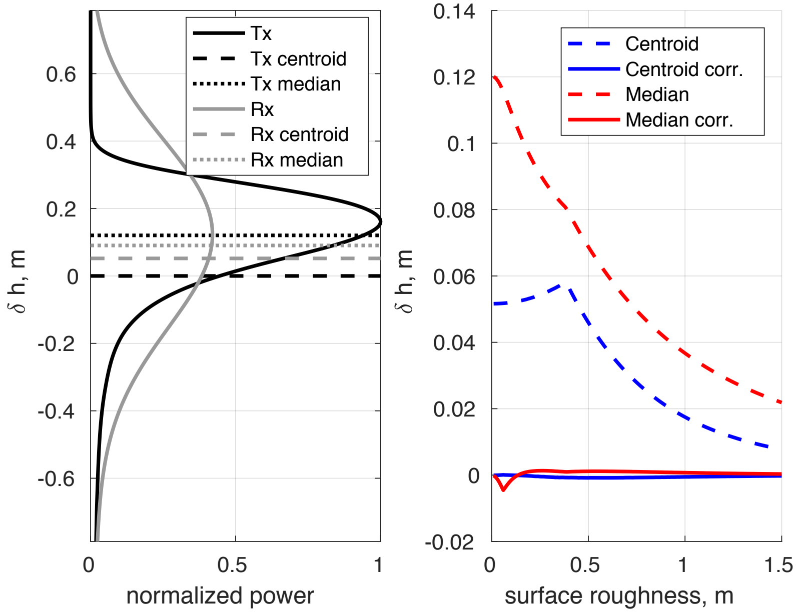




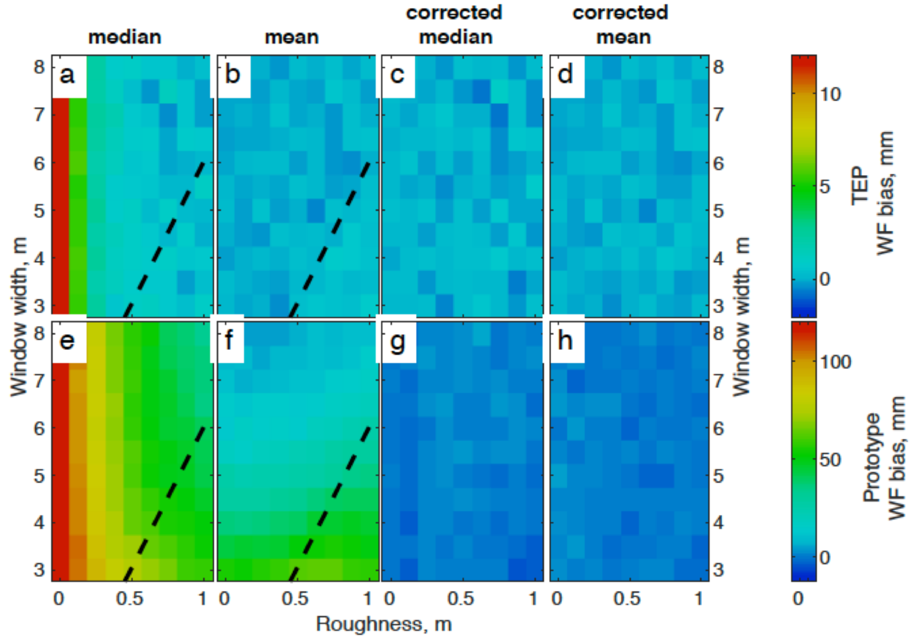


- Bias due to limited counting rates of ATLAS detectors
  - Detectors can only record 1 photon every ~3 ns
  - Recording only the first photons gives
    - surface heights that are biased high (up to a few cm)
    - Reflectance estimates that are biased low (up to 20-30%)
  - Using multiple detector pixels per pulse limits the effect of this bias
  - Correction based on the histogram of received photons reduces biases to <1mm (height) or 2-3% (reflectance)

Biases corrections 2: Transmit-pulse shape error

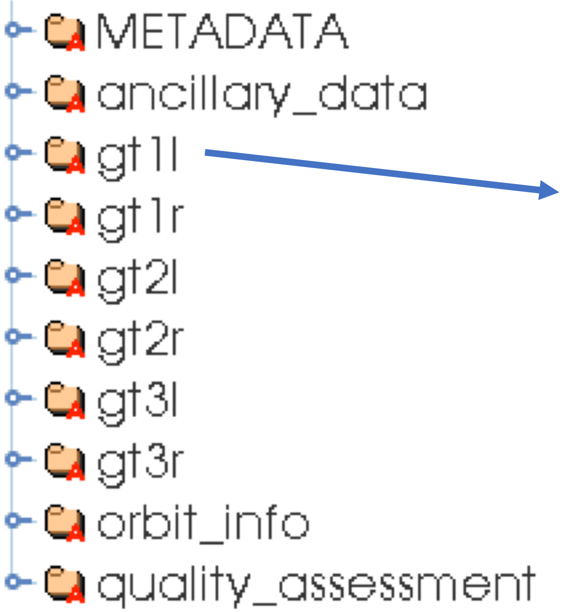


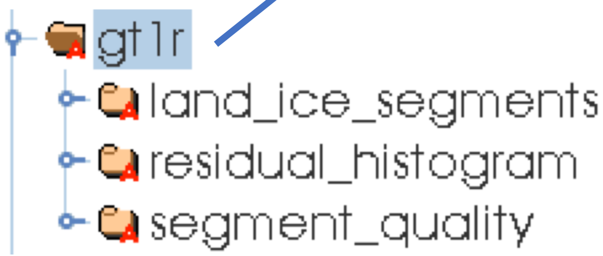
- Bias due to asymmetric transmit-pulse shape, and finite duration of the return window
  - Calculating heights based on a truncated version of the received pulse removes some energy from the late part of the return
  - Affects the mean and the median of returned photons differently
  - Magnitude of the bias depends on the surface roughness, the shape of the transmitted pulse, and the size of the converged surface window: ~1-2 cm for medians over smooth surfaces
  - Corrections reduce the bias to sub-milimeter levels



A look at the ATL06 product

- Product structure, using hdfview





Top level:
-grouped by beam:
Pairs 1-3
Left and right beams

Each beam contains:
-*land_ice_segments*:
Altimetry data for each segment
-*residual_histogram:*
pseudo—waveform data
-*segment_quality*:
segment-level diagnostic data

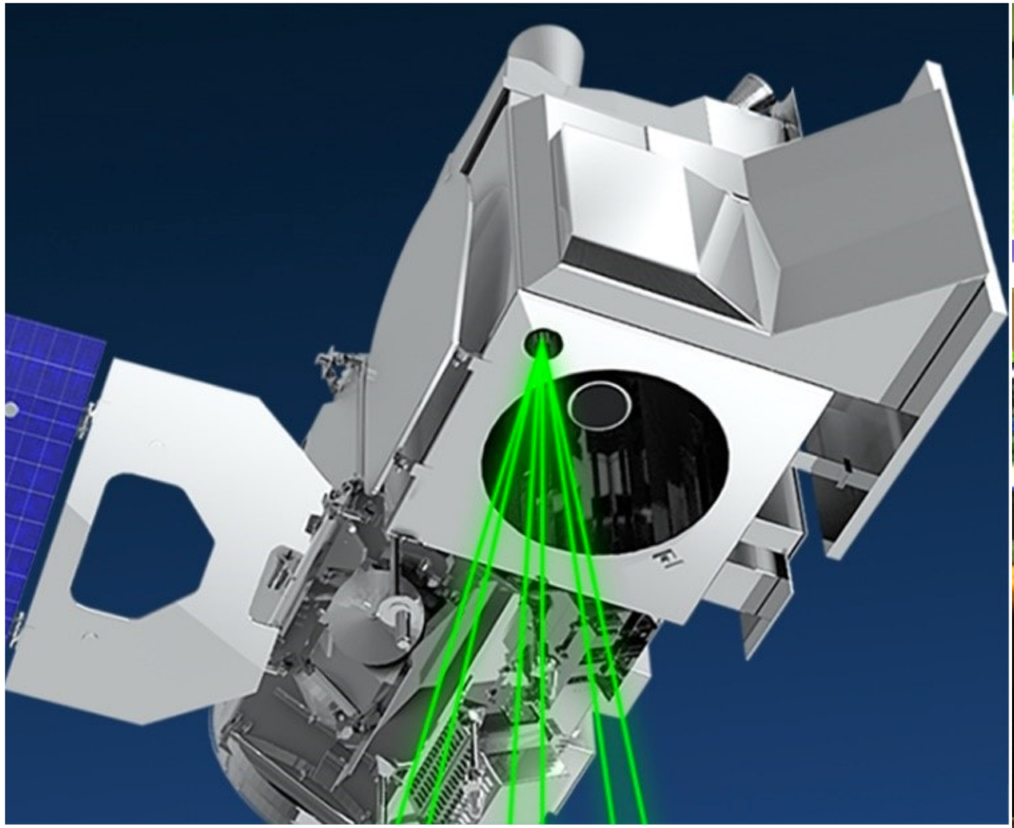
land_ice_segments contains:
-Main altimetry parameters:
latitude, longitude, elevation, time
-Subgroups (same resolution):
-DEM, fit_statistics, geophysical corrections, ground_track

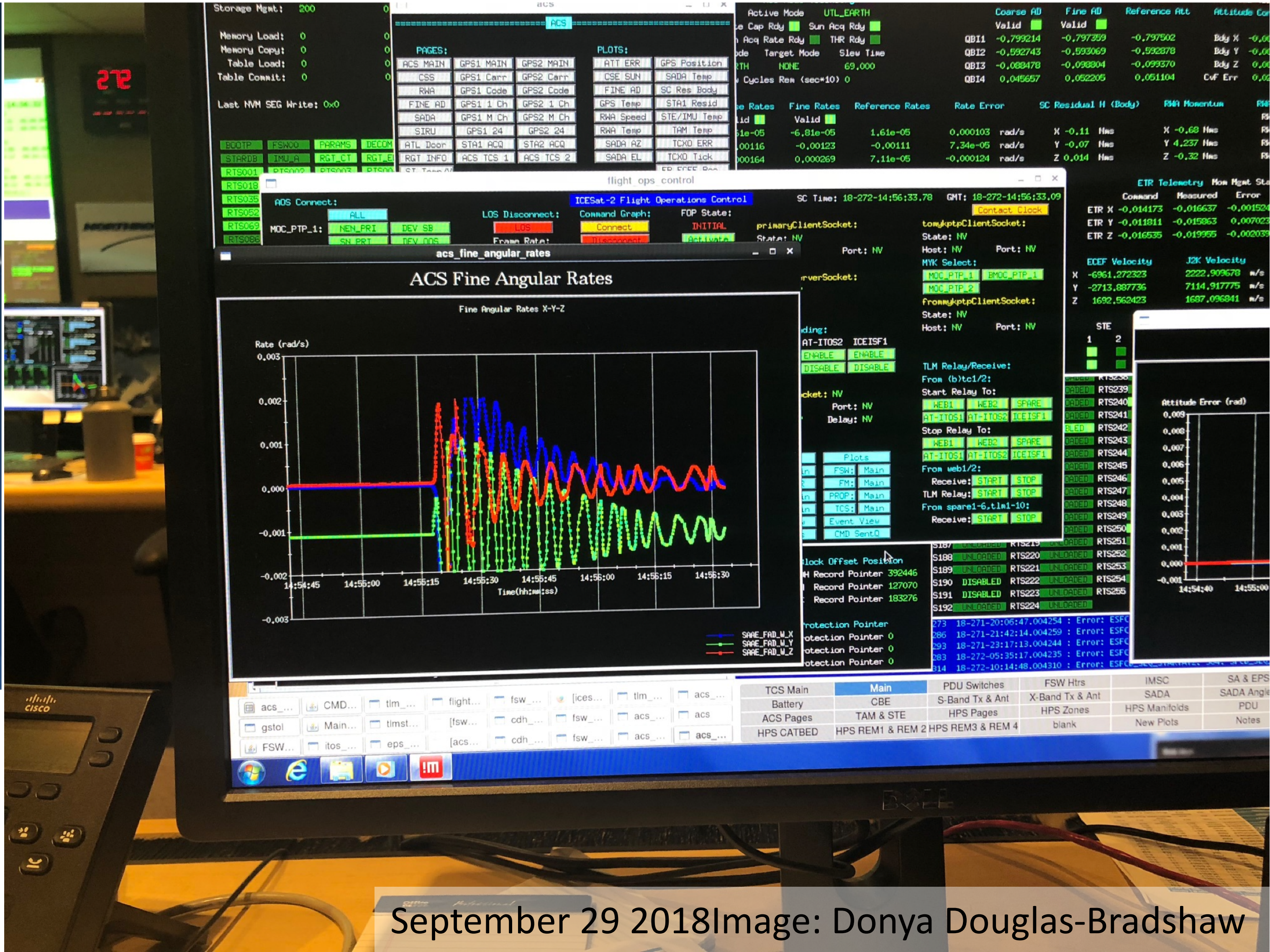
Mission status from a land-ice perspective.

So, how's it going?

- Great*
  - The door opened
  - We have photons
  - The fitting strategy works well
  - We have very accurate and precise results!
  - We have better than expected spatial resolution for the first two cycles*

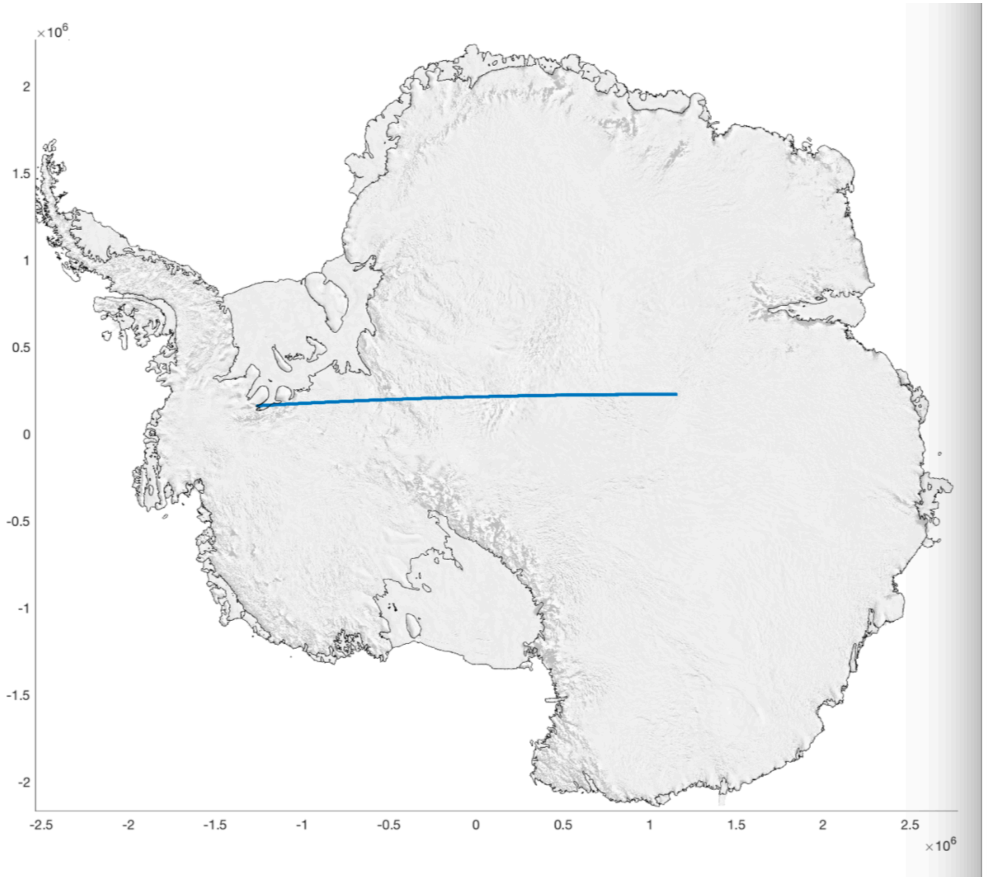
Great moments in ICESat-2 history 1: the door opened

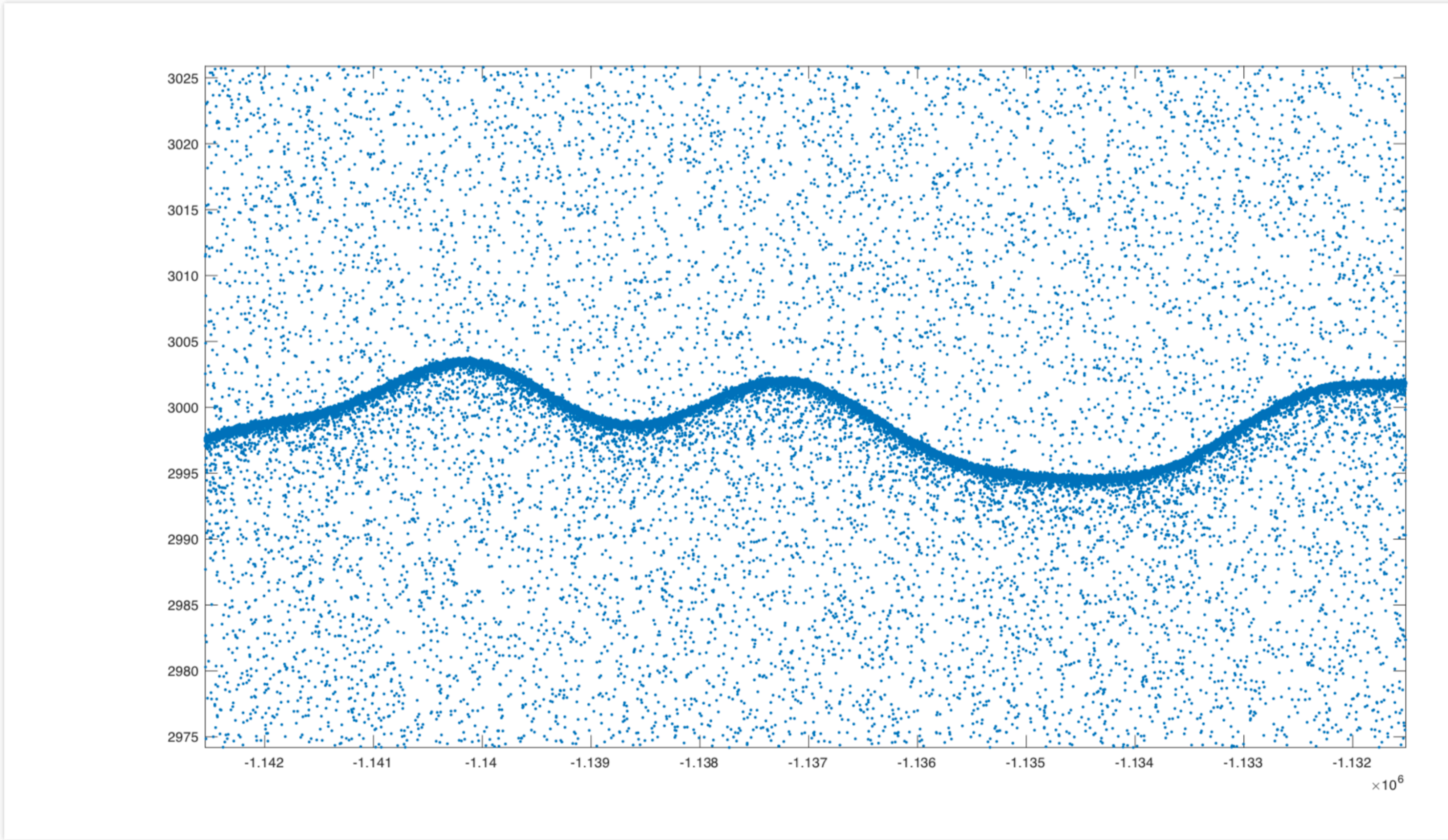




September 29 2018Image: Donya Douglas-Bradshaw

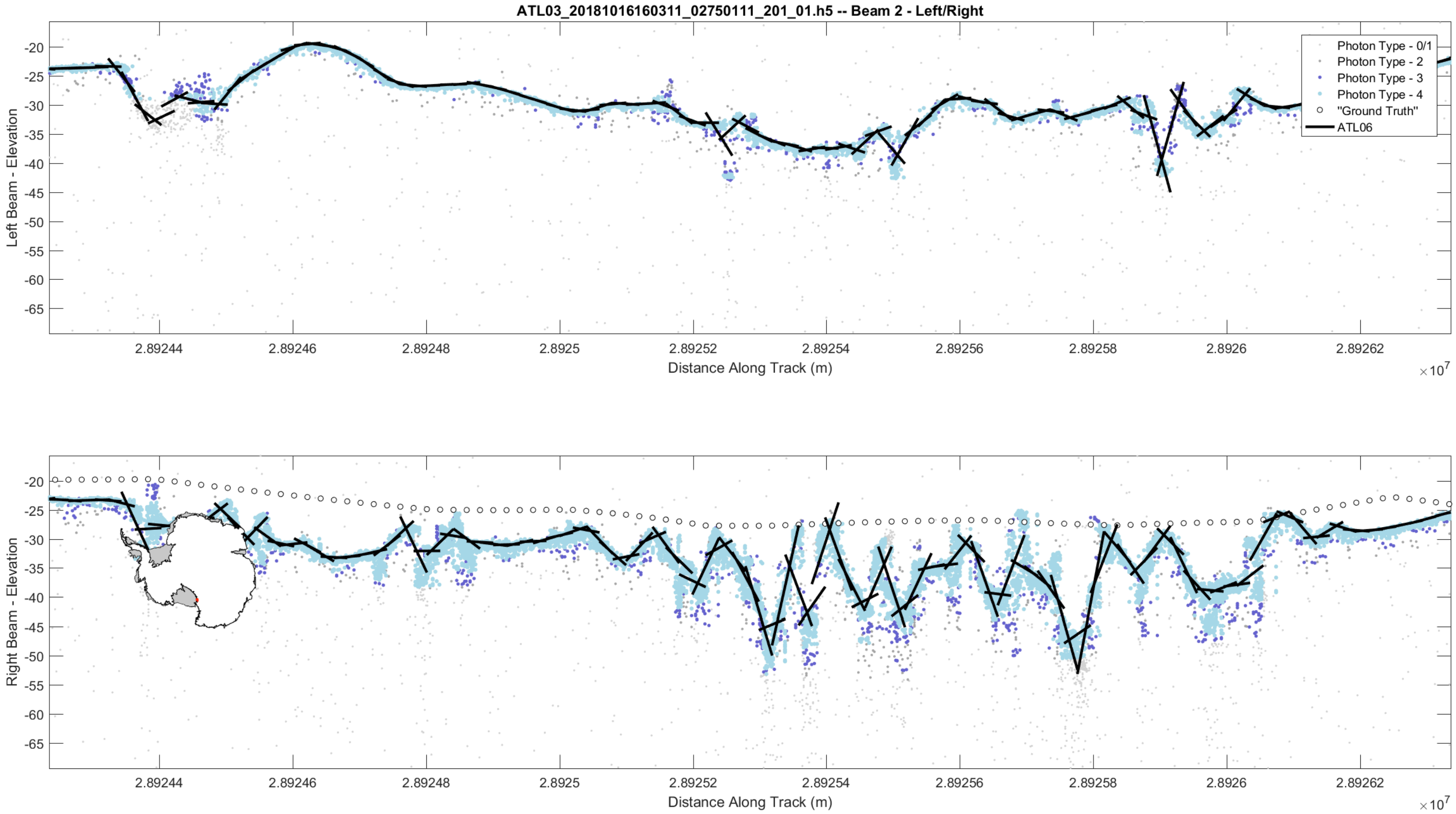
Great moments in ICESat-2 history 2: First data over Antarctica



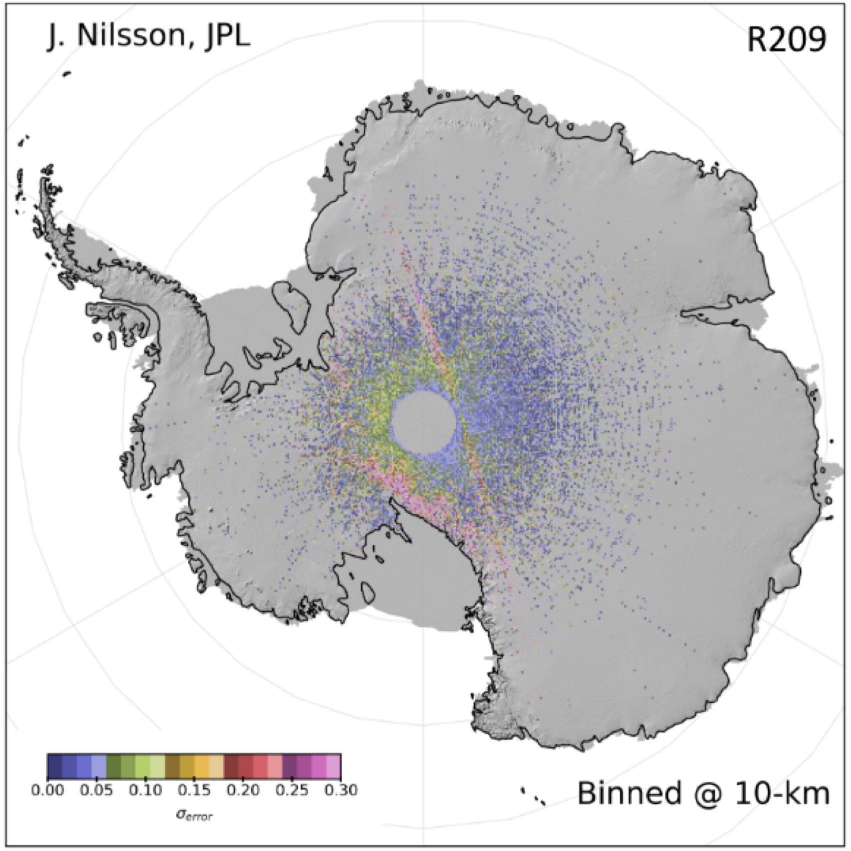


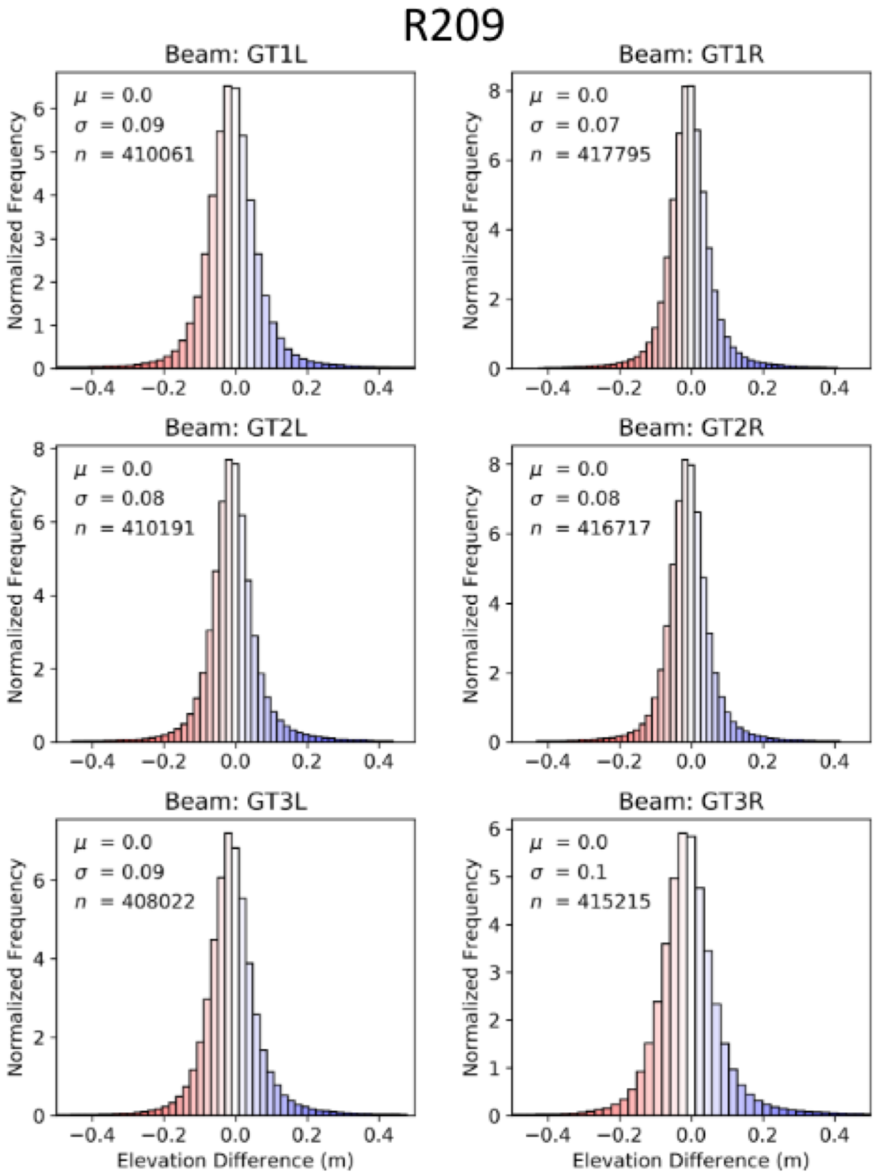
First data: posted 2018-10-03 by Susheel Adusumilli

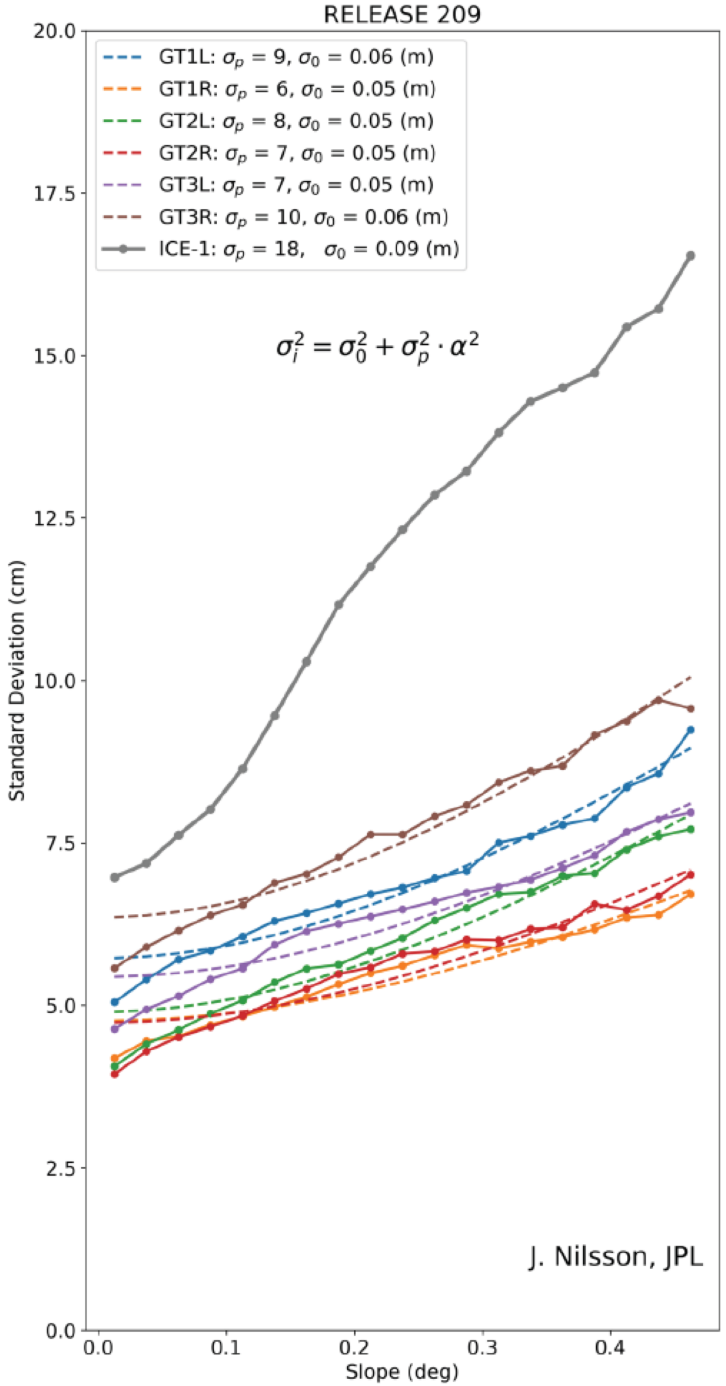
ATL03 and ATL03 over crevassed glacier surfaces



Self-consistency checks: Crossovers in Antarctica (Credit: Johan Nilson)

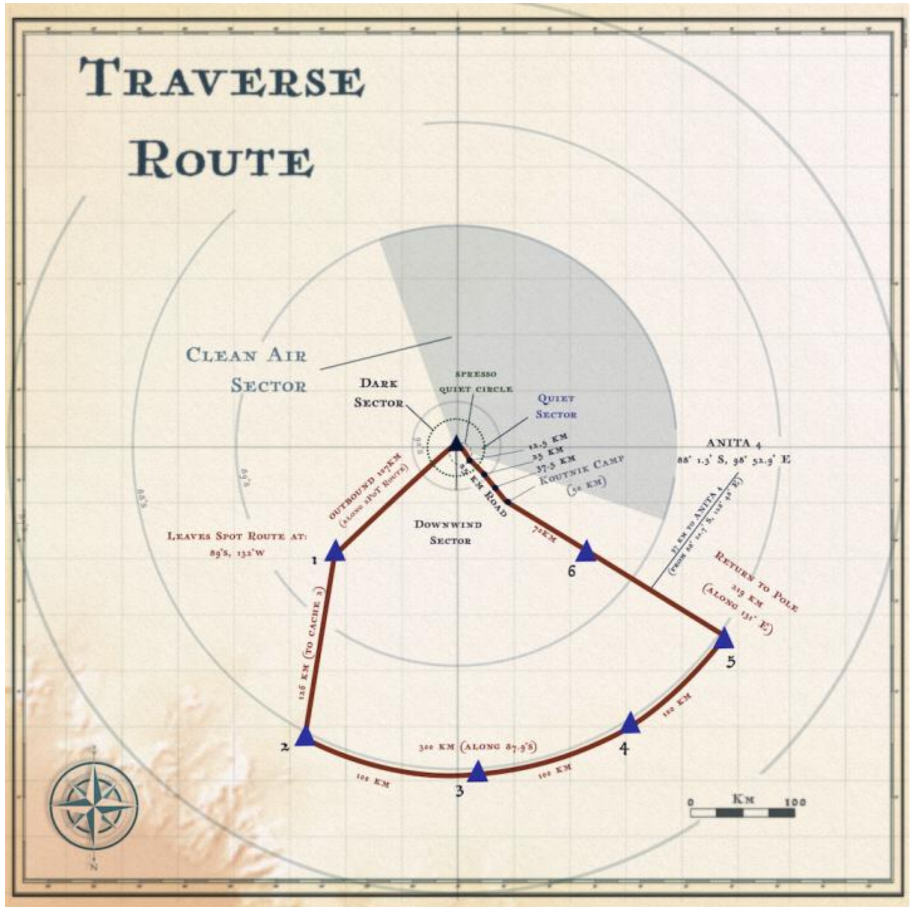




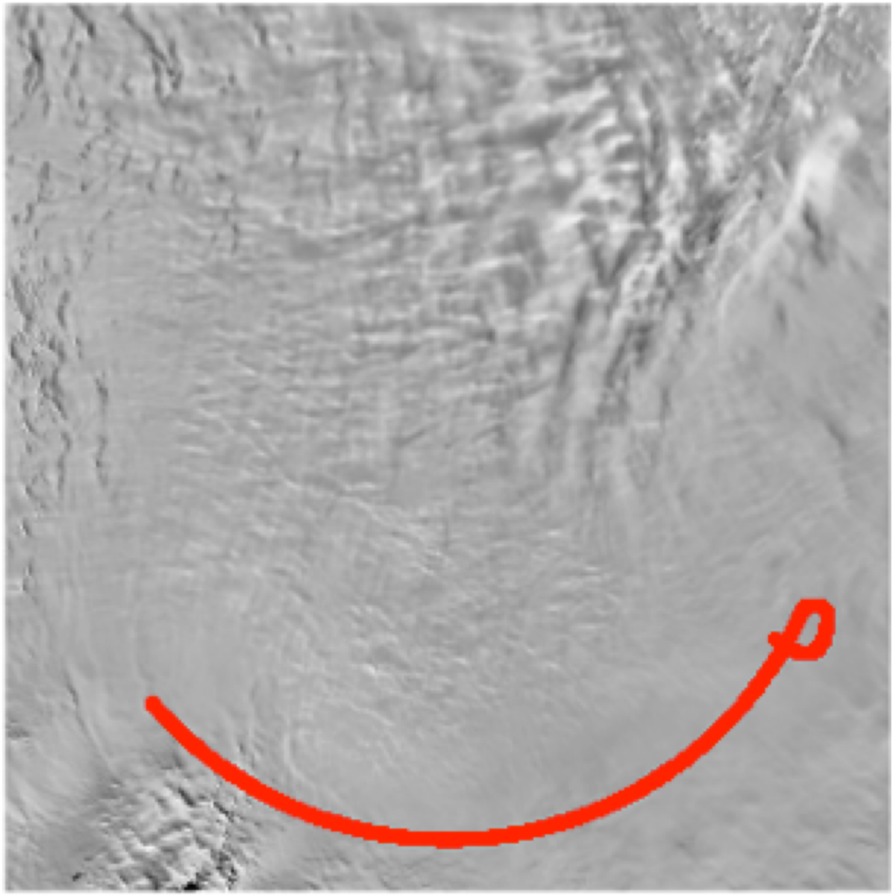


Per-segment ranging errors ~ 5cm
Geolocation errors ~6-10 m

Ground truth at 88 degrees S

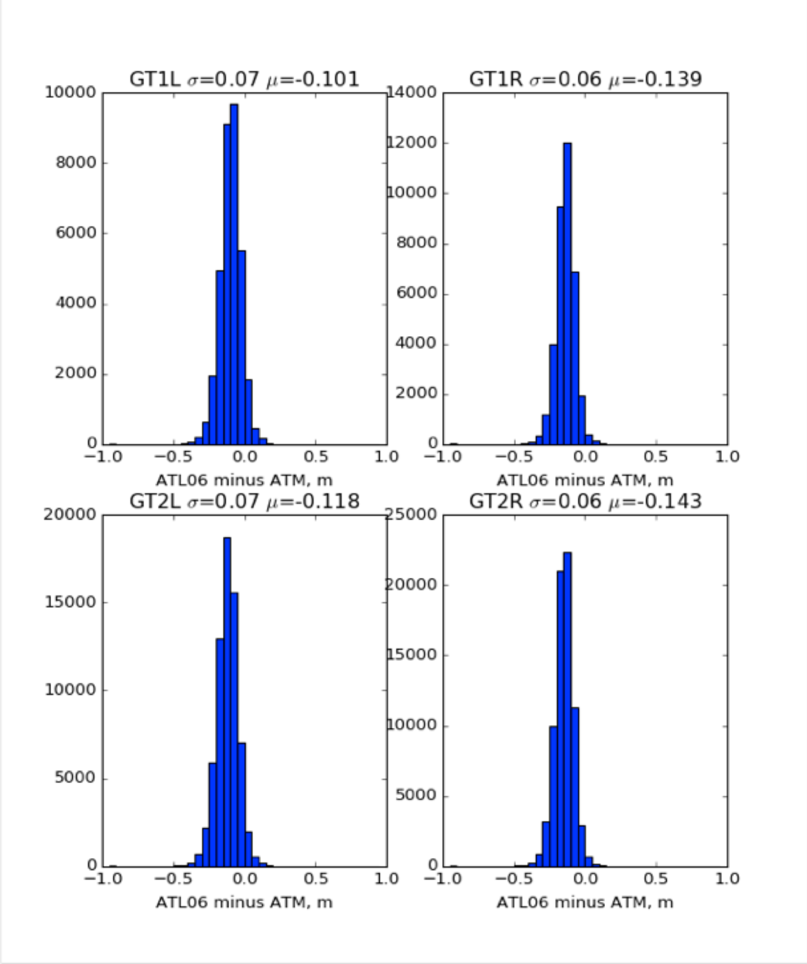


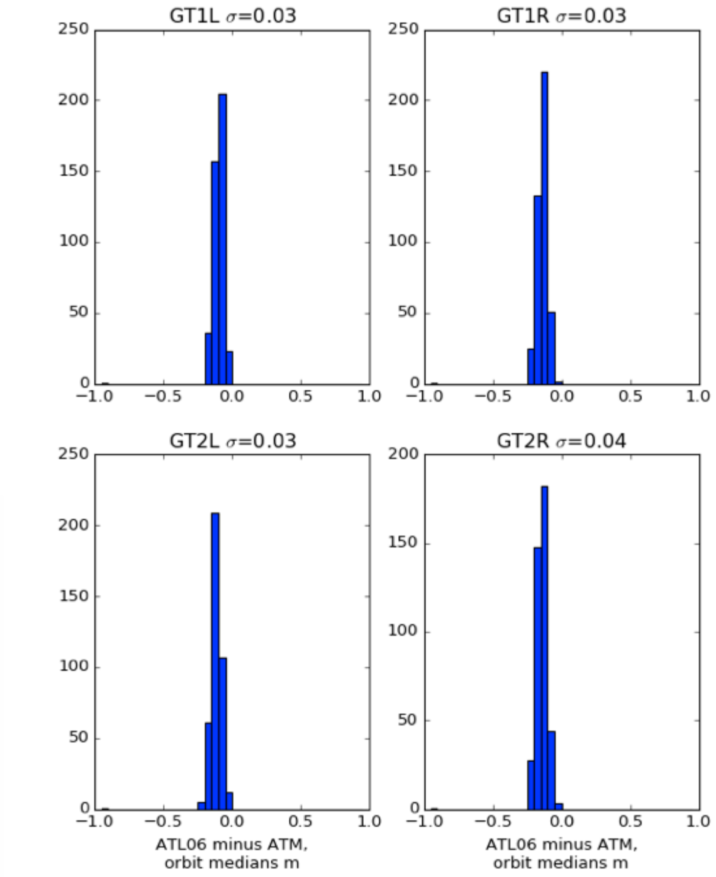
Ground traverse (image from NASA SVS)

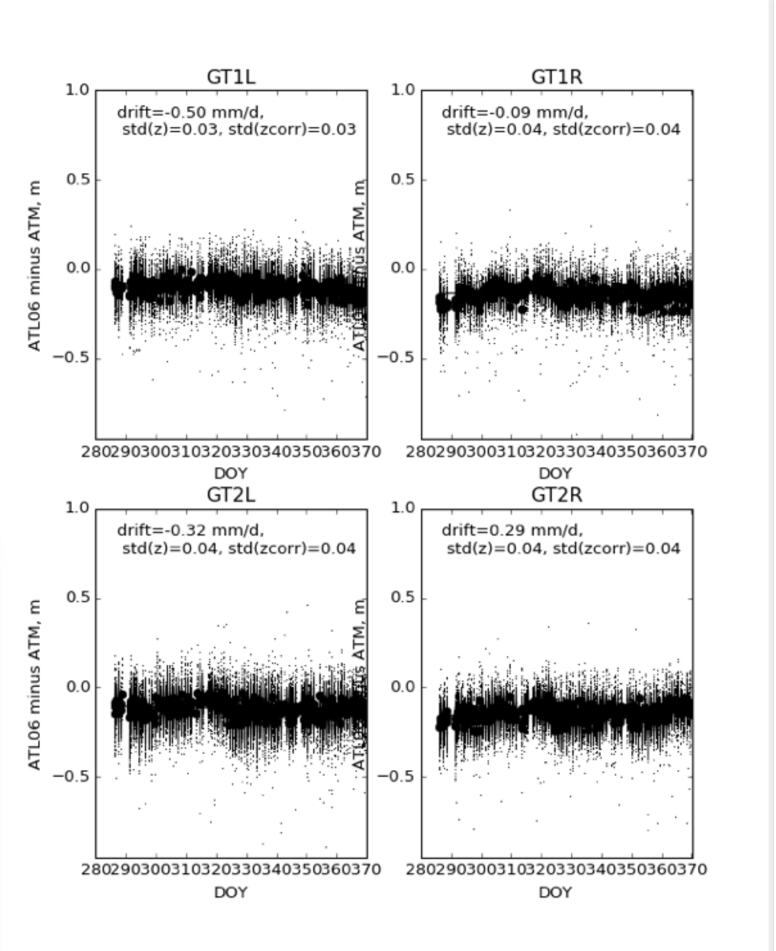


Airborne laser-altimetry data from ATM

ATL06 relative calibration from ATM airborne laser altimetry data







- Segment residuals:
  - Error per segment is 6-7 cm
- Orbit-median residuals:
  - Error per orbit (averaged over segments) is 3-4 cm
- Orbit-median trends
  - Drift in height biases is 0.3-0.5 mm/day

ICESat-2 absolute calibration from Polehole Traverse GPS

*ICESat-2 (**ATL03**, rel209, 14 Oct – 3 Feb) vs GPS data:*

Spot	Bias (std), cm	N
1	+1.2 (9.0)	127
2	+2.5 (7.1)	110
3	+3.0 (7.8)	201
4	+3.2 (8.4)	181
5	+5.7 (10.1)	262
6	+6.1 (9.1)	239
Aggregate	+3.8, SE=0.79	

*ICESat-2 (**ATL06**, rel001, 14 Oct – 1 Feb) vs GPS data*

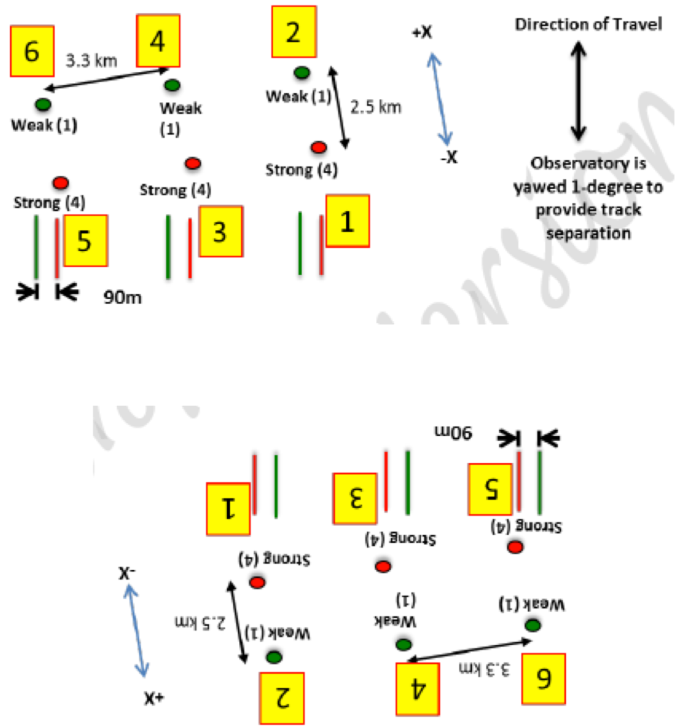
Spot	Bias (std), cm	N
1	-4.4 (9.8)	171
2	-1.3 (8.6)	177
3	+0.6 (9.6)	506
4	+0.7 (9.4)	490
5	+1.4 (9.0)	499
6	+1.6 (10.3)	479
Aggregate	+0.4 SE=0.68	

ATLAS Spot:

1) Launched in +x orientation (sc_orient == 1);
TEP spots are 2R and 3R.

2) Post yaw flip, -x orientation (sc_orient == 0);
TEP spots are 1L and 2L.

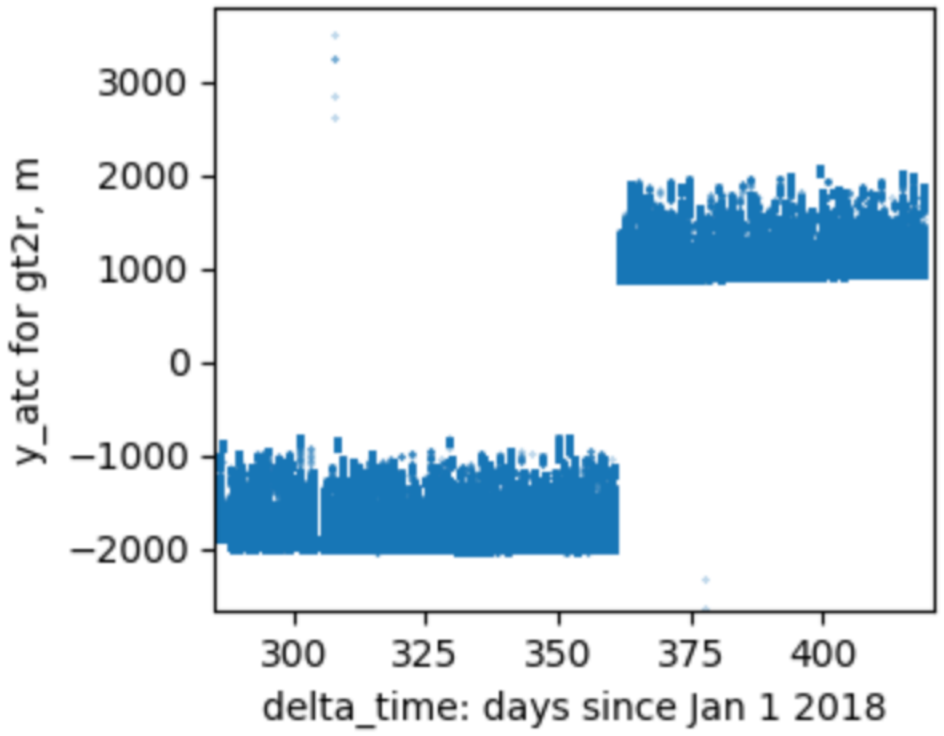
3) For mapping, TEP ATLAS Spots are 1 and 3.



Credit (data+figure) : Kelly Brunt

What about those asterisks?

- For the first two cycles of operations, there was a software problem with the star trackers. ICESat-2 pointed 1-2 km away from the RGT
- The problem was fixed in mid March, and the old data have been reprocessed with corrected pointing. Geolocation and vertical accuracy are better than required.
- …But: we only started making repeat-track measurements in March.
  - Mission cycle 3 is being measured on the RGTs.
  - The two previous cycles are offset significantly
  - We can start making repeat-track-difference calculations when cycle 3 is processed, late this summer.
- The first two cycles provide better-than-expected resolution for comparisons with ICESat-1 and IceBridge, and for DEM generation



Where to learn more:

- The ICESat-2 webpage (https://icesat-2.gsfc.nasa.gov):
  - Links to the Algorithm Theotretical Basis Documents:
  - KMLs of ground-track locations (under Tech Specs)
  - Animations

- The NSIDC landing page (https://nsidc.org/data/icesat-2):
  - Product format descriptions
  - Data file naming conventions
  - News on data releases
  - Known issue descriptions
  - Data(!)

Can we see ICESat-2 during the hackweek?

- Probably not: Passes over western Washington are at ~11:40 GMT, or ~4:40 AM PDT. Sunrise is ~5:10 AM
- If you want to try, the best place is probably on Highway 202 just outside Snoqualmie, WA, Thursday morning.