

Monitoring Sentinel-3 SRAL Performance over Land Ice

S. K. Rose[1] S. B. Simonsen[1] J. Aublanc[2] and the S3-MPC Team

9th Sentinel-3 Validation Team Meeting
31 March 2026

[1]DTU Space, Denmark [2]Collecte Localisation Satellites, France

Monitoring Sentinel-3 SRAL Performance over Land Ice

Scope

- Mission focus: Sentinel-3 SRAL performance over Greenland and Antarctica.
- Study approach: both icesheet-wide diagnostics and regional reference sites.
- Time focus: recent product baselines, with emphasis on 2025 behavior.

What is assessed

- Un-correlated errors from ascending/descending and cross-over differences.
- Correlated elevation anomalies relative to Arctic DEM / REMA DEM.
- Signal behavior from Sigma0 statistics and seasonal sensitivity patterns.

For the MPC

Goal: quantify where current processing performs well, where it degrades, and which issues should be prioritized for monitoring and product evolution.

Additional

- Ideas for S3C Tandem Phase (Land ice)
- Ideas for S3C Tandem Phase (Sea ice)
- Recommendations to the Quality Working Group

Current Performance Challenges

Data Quality

- Duplication/Splitting of files
- Corrupt files
- Product handling:
  - Files are rerocessed
  - Info in Sentiwiki Product Notice
- S3B GNSS issue (Dec 2025-Jan 2026)
  - No significant elevation impact for LI

Current Performance Challenges

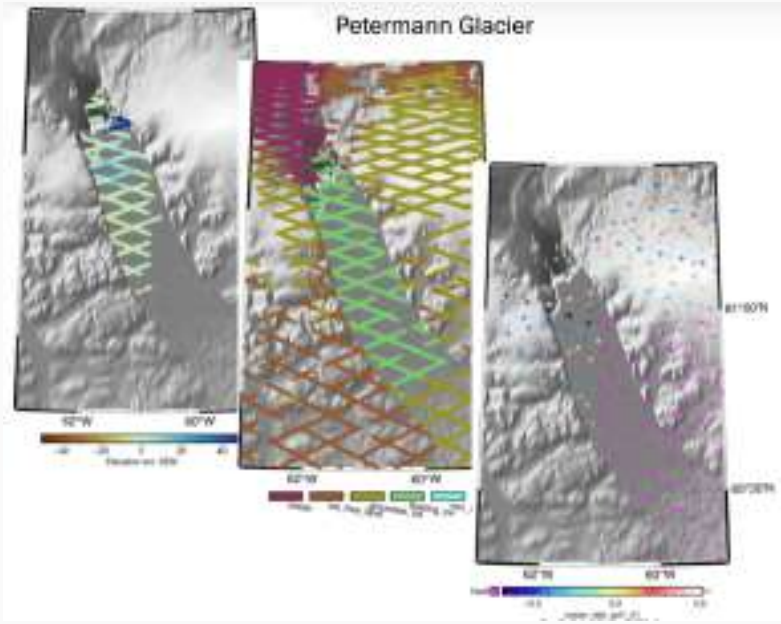
Data Quality

- Duplication/Splitting of files
- Corrupt files
- Product handling:
  - Files are rerocessed
  - Info in Sentiwiki Product Notice
- S3B GNSS issue (Dec 2025-Jan 2026)
  - No significant elevation impact for LI

Ice shelves/Ocean tide corr.

- PB 3.29 (2024) BedMachine applied
- Ocean tide coverage over ice shelves:
  - $\sim$ 60% over Greenland
  - $\sim$ 99% over Antarctica

  Challenge: tide model not available
- PB 3.32 Ice shelf GL not defined
- PB 3.35 Ice shelf retured, but NaN



Current Performance Challenges

Data Quality

- Duplication/Splitting of files
- Corrupt files
- Product handling:
  - Files are rerocessed
  - Info in Sentiwiki Product Notice
- S3B GNSS issue (Dec 2025-Jan 2026)
  - No significant elevation impact for LI

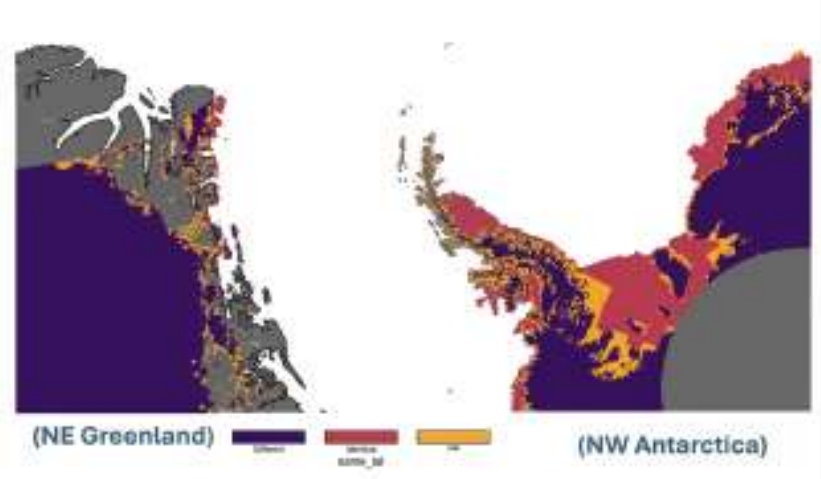
Ice shelves/Ocean tide corr.

- PB 3.29 (2024) BedMachine applied
- Ocean tide coverage over ice shelves:
  - $\sim$ 60% over Greenland
  - $\sim$ 99% over Antarctica

  Challenge: tide model not available
- PB 3.32 Ice shelf GL not defined
- PB 3.35 Ice shelf retured, but NaN

Tracking Issues

- Before PB 3.32:
  - Identical Nadir and POCA locations in the margins
- PB 3.32:
  - Slope model not defined here!
  - Elevation: empty data, gaps
- Before PB 3.35 (Current):
  - Empty data gaps filled.
  - More obs, valid obs, fewer NaNs
  - Still identical Nadir and POCA



Current Performance Challenges

Data Quality

- Duplication/Splitting of files
- Corrupt files
- Product handling:
  - Files are rerocessed
  - Info in Sentiwiki Product Notice
- S3B GNSS issue (Dec 2025-Jan 2026)
  - No significant elevation impact for LI

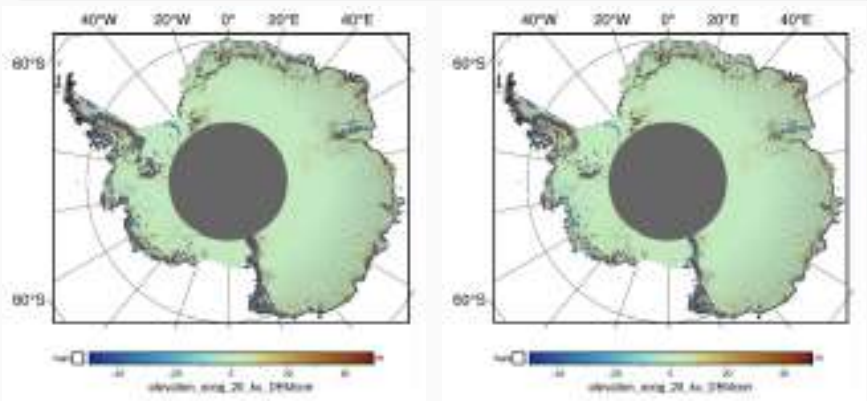
Ice shelves/Ocean tide corr.

- PB 3.29 (2024) BedMachine applied
- Ocean tide coverage over ice shelves:
  - $\sim$ 60% over Greenland
  - $\sim$ 99% over Antarctica

  Challenge: tide model not available
- PB 3.32 Ice shelf GL not defined
- PB 3.35 Ice shelf retured, but NaN

Tracking Issues

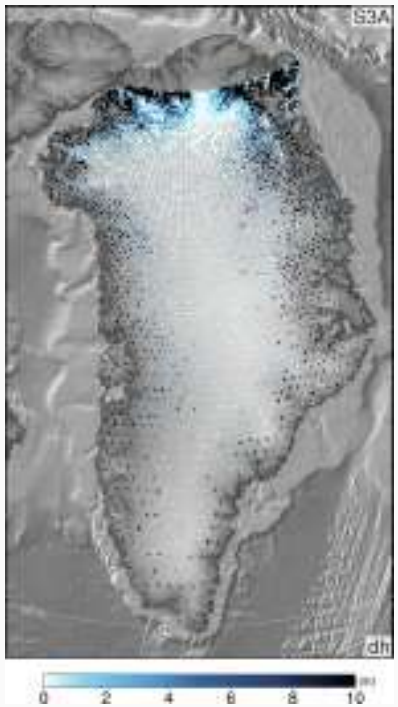
- Before PB 3.32:
  - Identical Nadir and POCA locations in the margins
- PB 3.32:
  - Slope model not defined here!
  - Elevation: empty data, gaps
- Before PB 3.35 (Current):
  - Empty data gaps filled.
  - More obs, valid obs, fewer NaNs
  - Still identical Nadir and POCA

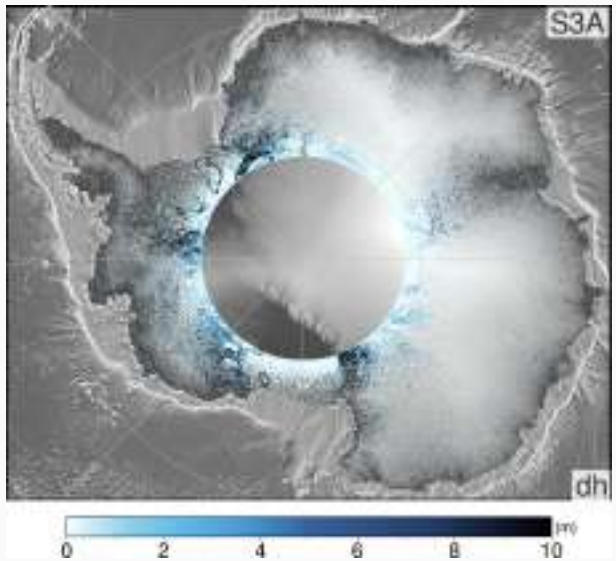


Total elevation biases - Un-correlated errors

Measurement precision

- Ascending/descending elevation differences
- Absolute differences for icesheet wide analysis
- Relative difference for study sites
- **Conclusion**:
  - Good performance in flat terrain
  - Struggles at the margins
  - Marginal zone median $|dh|$:
    GL: 5.9 ± 4.5 m
    AA: 3.6 ± 2.3 m
  - Consider AMPLI



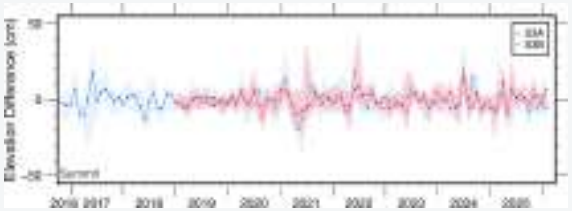


Region	**Sat**	**|dh|** cm	**Fraction** **|dh| < 1** m	**|dh| < 1** m cm
Greenland	S3A	54.7 ± 51.0	58.4%	15.1 ± 11.3
Greenland	S3B	54.2 ± 50.3	58.6%	15.8 ± 11.6
Antarctica	S3A	24.6 ± 20.4	75.2%	14.8 ± 10.6
Antarctica	S3B	23.9 ± 19.7	75.9%	14.7 ± 10.5

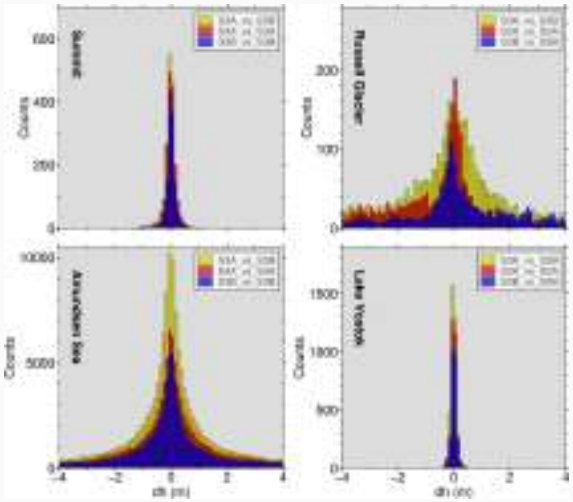
Rose et al. (2025) (In Review)

Elevation biases for Study sites

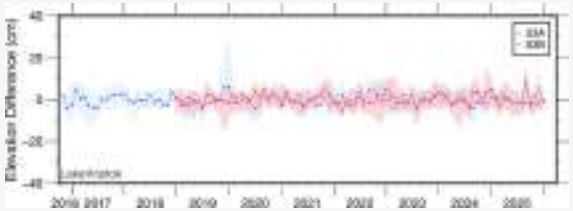
Summit



	Count	Mean	Median	STD	STD_error	IQR	MAD
S3A	1420	-0.681	-0.892	16.4	0.436	17.4	12.8
S3B	1420	449.000	-0.786	12000.0	319.000	15.3	11.4
S3A_S3B	1930	-335.000	-2.010	10300.0	235.000	15.9	11.7
S3A_I2	4260	-4.260	-5.780	18.1	0.278	20.6	15.2
S3B_I2	4480	208.000	-5.100	8300.0	124.000	20.5	14.9
S3A_C2	2020	-17.800	-18.100	33.3	0.740	19.6	14.3
S3B_C2	1990	296.000	-17.700	10200.0	228.000	18.7	13.9

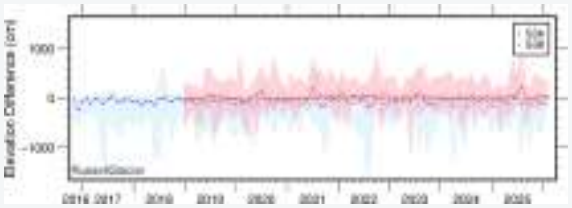


Lake Vostok



	Count	Mean	Median	STD	STD_error	IQR	MAD
S3A	2500	-0.2110	-0.468	9.57	0.191	10.2	7.53
S3B	2710	-0.0918	-0.129	9.67	0.186	10.6	7.90
S3A_S3B	4990	-1.0900	-1.170	10.20	0.145	11.5	8.54
S3A_I2	14100	1.5000	0.729	12.60	0.106	17.0	12.50
S3B_I2	13900	3.2400	2.510	13.20	0.112	17.4	12.90
S3A_C2	4670	-25.1000	-25.200	20.60	0.301	11.4	8.49
S3B_C2	4810	-24.1000	-24.200	20.80	0.300	11.6	8.66

Russell Glacier

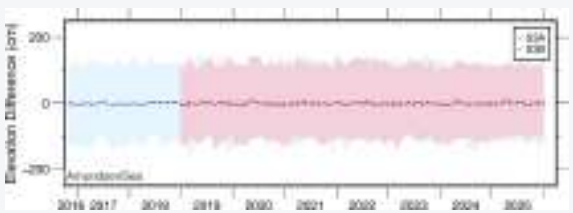


	Count	Mean	Median	STD	STD_error	IQR	MAD
S3A	3490	-263.00	-48.40	1450.0	24.6	586.0	424.0
S3B	3380	342.00	8.45	6320.0	109.0	697.0	517.0
S3A_S3B	7640	104.00	-2.58	5320.0	60.9	636.0	472.0
S3A_I2	14300	-4.38	-90.90	3350.0	28.1	582.0	394.0
S3B_I2	13900	164.00	-82.10	4490.0	38.1	485.0	405.0
S3A_C2	8830	469.00	-35.80	7510.0	79.9	1230.0	745.0
S3B_C2	8090	259.00	-32.70	8150.0	90.6	1350.0	762.0

Summary

- Monthly cross-overs in cm
- All, but Russell show nice results
- Median dh $\sim$ 1 cm
- Here, Snow penetration: 1-5 cm
- Trend for Summit/Vostok 2.5 cm/yr
- SAR advantages over LRM

Amundsen Sea

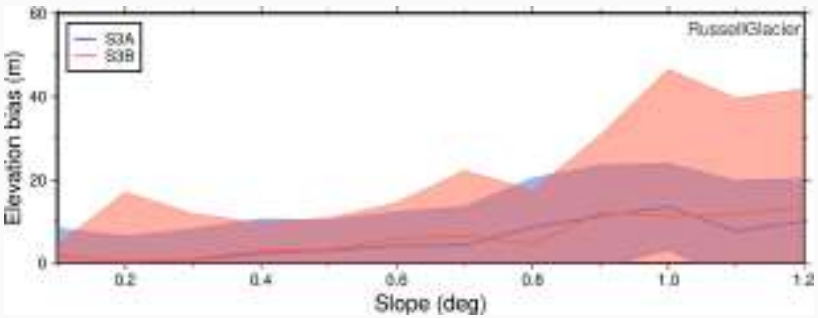


	Count	Mean	Median	STD	STD_error	IQR	MAD
S3A	97300	-3.9	-0.152	3150.0	10.1	238.0	176.0
S3B	105000	-97.7	-0.926	5630.0	17.4	228.0	169.0
S3A_S3B	210000	35.2	-1.260	5060.0	11.0	226.0	167.0
S3A_I2	97900	232.0	-62.000	5540.0	17.7	210.0	114.0
S3B_I2	93000	93.6	-63.600	4930.0	16.2	221.0	117.0
S3A_C2	151000	198.0	-70.700	6720.0	17.3	397.0	208.0
S3B_C2	143000	63.6	-70.000	6240.0	16.5	419.0	207.0

*Results are in cm

Absolute Elevation Biases wrt Slopes

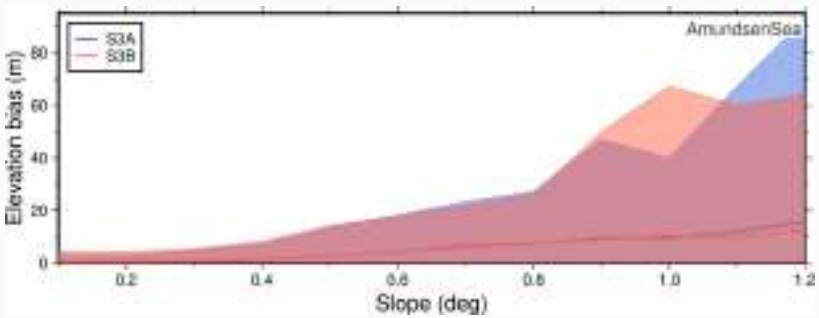
Russell Glacier



		S3A			S3B		
	Degree	Count	Median [m]	MAD [m]	Count	Median [m]	MAD [m]
Low	$< 0.3°$	1409	0.96	6.1	682	0.44	14.6
Moderate	$0.3 - 1°$	2380	4.44	8.9	2141	4.1	10.7
Steep	$> 1°$	702	14.6	63.2	597	13.6	41.1
All	-	4765	3.7	36.4	3503	4.24	22.0

- Max slope: $\sim 4°$
- Cumulative bins (steps $0.2°$):
  - S3A: Better than 2 m $\Rightarrow < 0.6°$
  - S3B: Better than 2 m $\Rightarrow < 0.8°$

Amundsen Sea

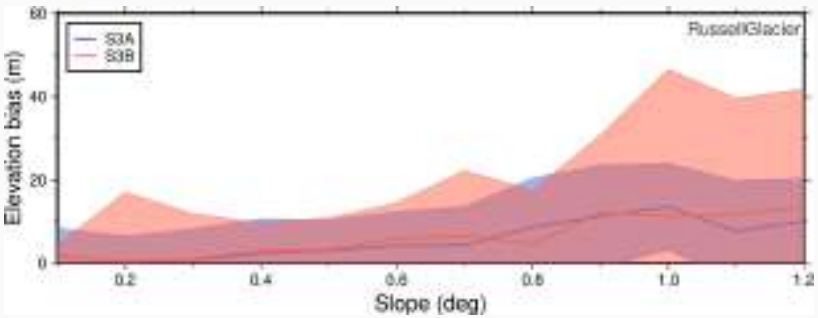


		S3A			S3B		
	Degree	Count	Median [m]	MAD [m]	Count	Median [m]	MAD [m]
Low	$< 0.3°$	67292	0.51	2.6	49395	0.43	4.1
Moderate	$0.3 - 1°$	55092	2.8	12.8	42801	2.63	12.7
Steep	$> 1°$	10084	14.6	79.1	7619	16.7	101.0
All	-	133005	1.2	15.4	100269	1.1	18.2

- Max slope: $\sim 16°$
- Cumulative bins (steps $0.2°$):
  - S3A: Better than 1 m $\Rightarrow < 1°$
  - S3B: Better than 1 m $\Rightarrow < 1°$

Absolute Elevation Biases wrt Slopes

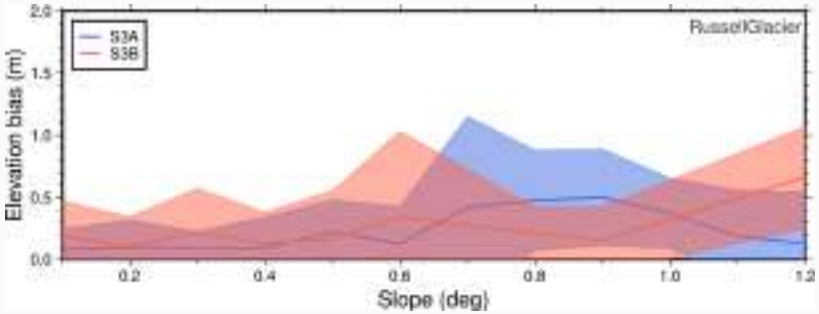
Russell Glacier



		S3A			S3B		
	Degree	Count	Median [m]	MAD [m]	Count	Median [m]	MAD [m]
Low	$< 0.3°$	1409	0.96	6.1	682	0.44	14.6
Moderate	$0.3 - 1°$	2380	4.44	8.9	2141	4.1	10.7
Steep	$> 1°$	702	14.6	63.2	597	13.6	41.1
All	-	4765	3.7	36.4	3503	4.24	22.0

- Max slope: $\sim 4°$
- Cumulative bins (steps $0.2°$):
  - S3A: Better than 2 m $\Rightarrow < 0.6°$
  - S3B: Better than 2 m $\Rightarrow < 0.8°$

Russel Glacier (AMPLI)

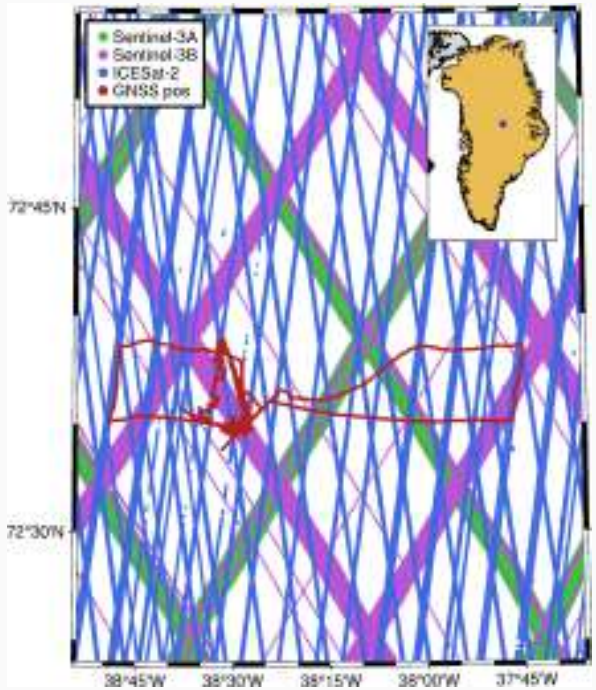


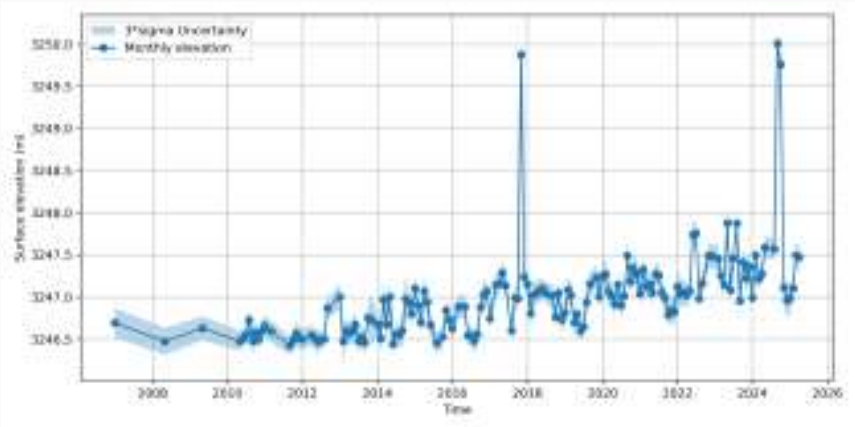
		S3A			S3B		
	Degree	Count	Median [m]	MAD [m]	Count	Median [m]	MAD [m]
Low	$< 0.3°$	608	0.096	0.177	282	0.131	0.273
Moderate	$0.3 - 1°$	709	0.135	0.305	300	0.187	0.377
Steep	$> 1°$	50	0.235	0.476	18	0.466	0.598
All	–	1367	0.116	0.263	600	0.158	0.342

- Quality flag filters out many observations
- Outperforms L2 over Russell Glacier
- Too few observations (S3B $> > 1°$)

GNSS Surface elevation at Summit

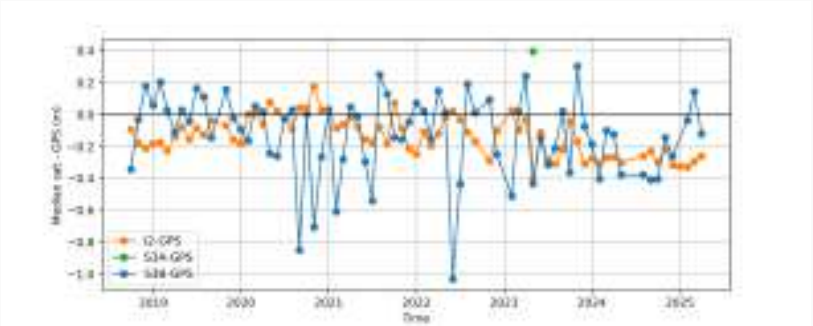
- ICESat/ICESat-2 Traverse: Monthly GPS Surface Elevation Data at Summit Station, (Hawley et al., 2026)
- Removing GPS outliers: median absolute deviation (MAD) filtering
- Sentinel-3A/B: Search radius of 1.5 km (within effective footprint)
- ICESat-2: Search radius of 65 m (Pickell et al., 2026)

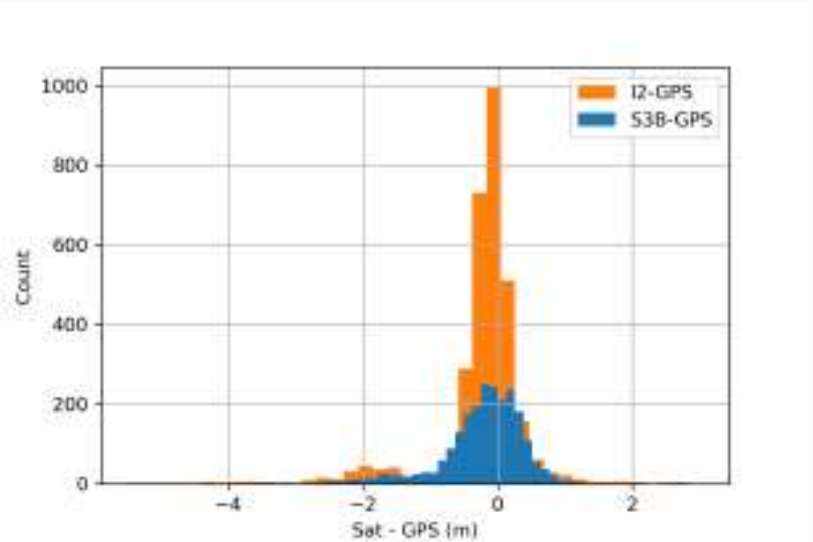




GNSS Surface elevation at Summit

- ICESat/ICESat-2 Traverse: Monthly GPS Surface Elevation Data at Summit Station, (Hawley et al., 2026)
- Removing GPS outliers: median absolute deviation (MAD) filtering
- Sentinel-3A/B: Search radius of 1.5 km (within effective footprint)
- ICESat-2: Search radius of 65 m (Pickell et al., 2026)

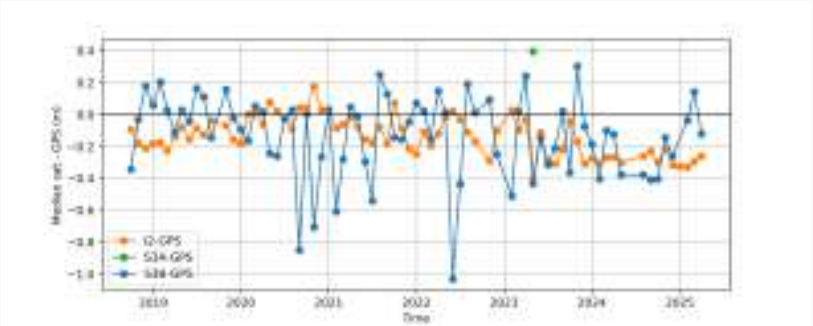


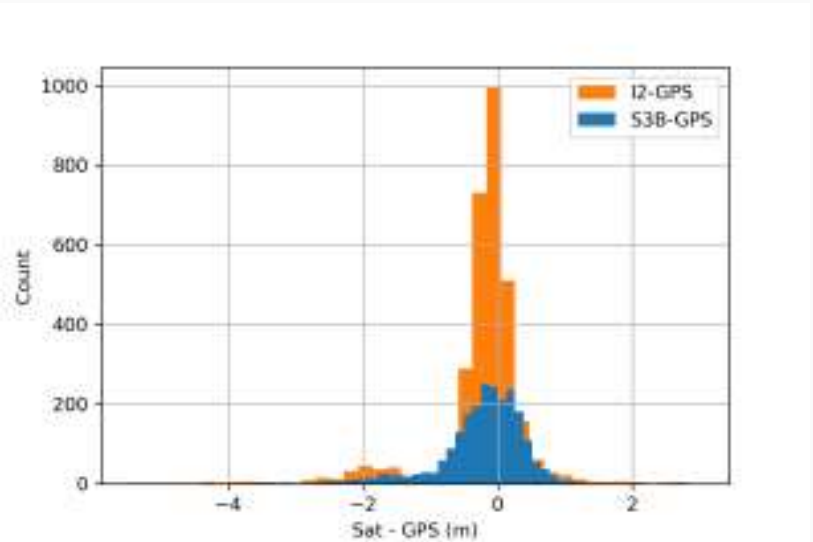


Mission residual wrt GPS	N	Mean (cm)	Median (cm)	STD (cm)	RMSE (cm)	NMAD (cm)
Sentinel-3B	2263	-23.7	-13.6	64.3	68.5	47.7
ICESat-2	3179	-23.7	-11.8	72.6	76.3	27.8

GNSS Surface elevation at Summit

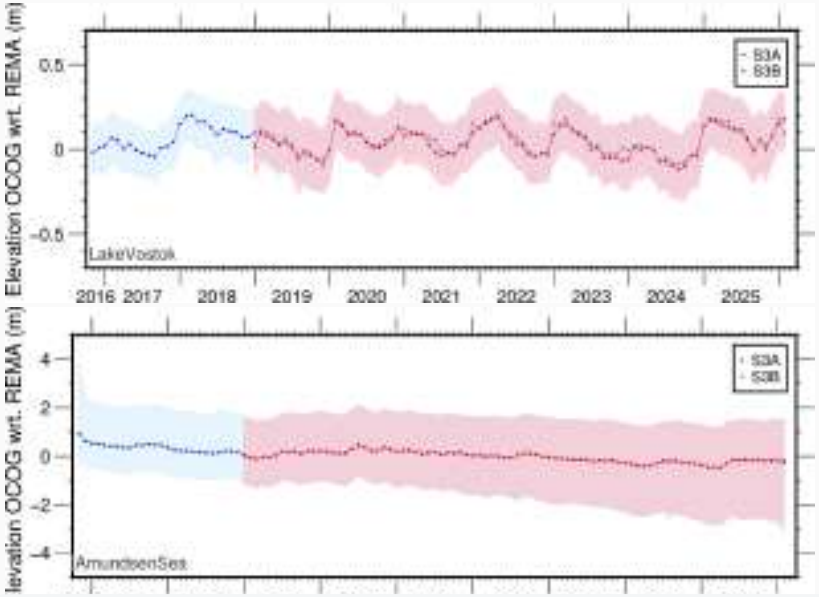
- ICESat/ICESat-2 Traverse: Monthly GPS Surface Elevation Data at Summit Station, (Hawley et al., 2026)
- Removing GPS outliers: median absolute deviation (MAD) filtering
- Sentinel-3A/B: Search radius of 1.5 km (within effective footprint)
- ICESat-2: Search radius of 65 m (Pickell et al., 2026)



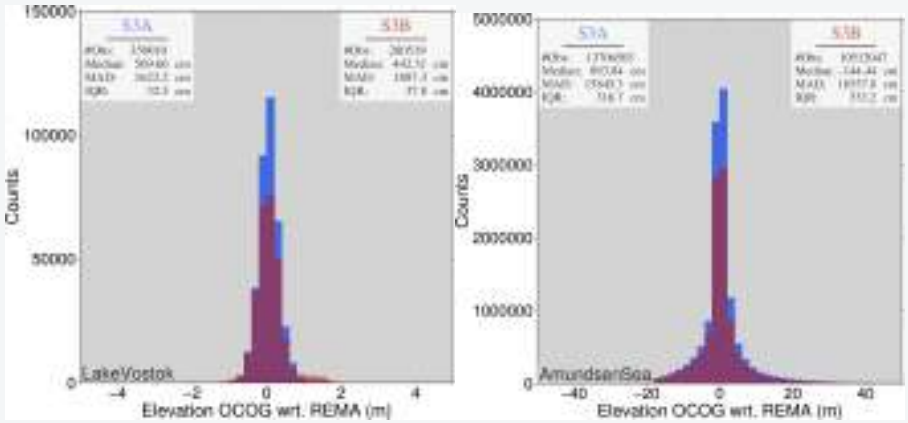


Mission residual wrt GPS	N	Mean (cm)	Median (cm)	STD (cm)	RMSE (cm)	NMAD (cm)
Sentinel-3B	2263	-23.7	-13.6	64.3	68.5	47.7
ICESat-2	3179	-23.7	-11.8	72.6	76.3	27.8

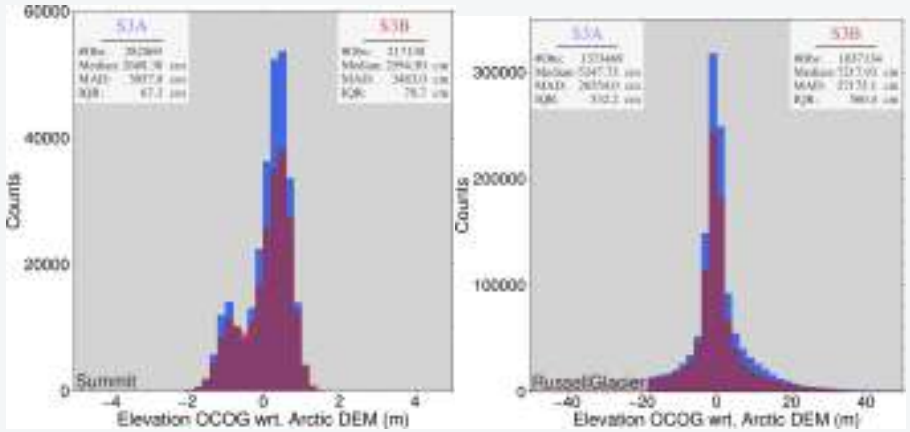
Elevation OCOG/ICE-1 wrt. DEM

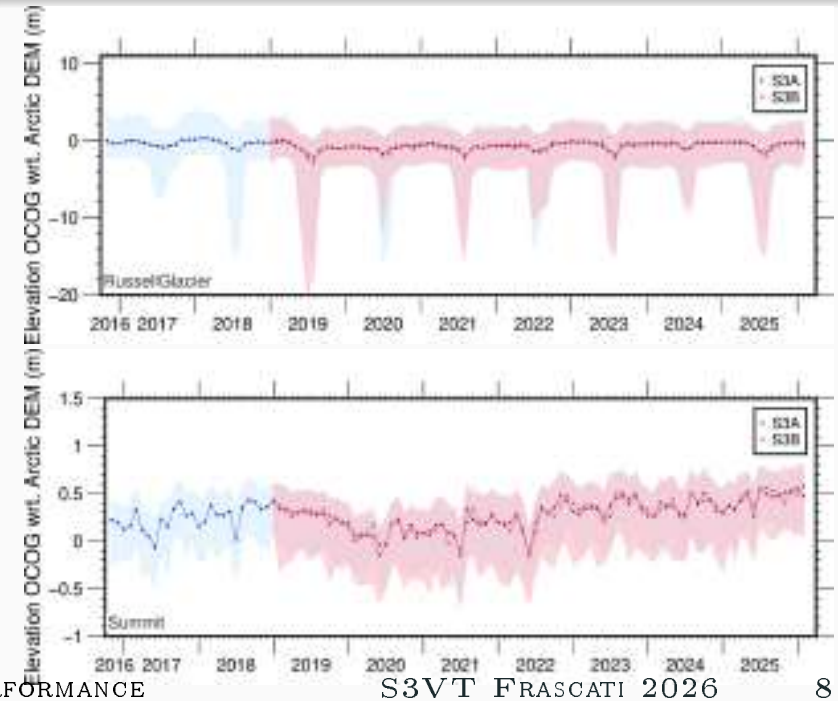


- S3A/S3B agrees very well
- S3A slightly higher anomaly
- Vostok good Amundsen okay performance

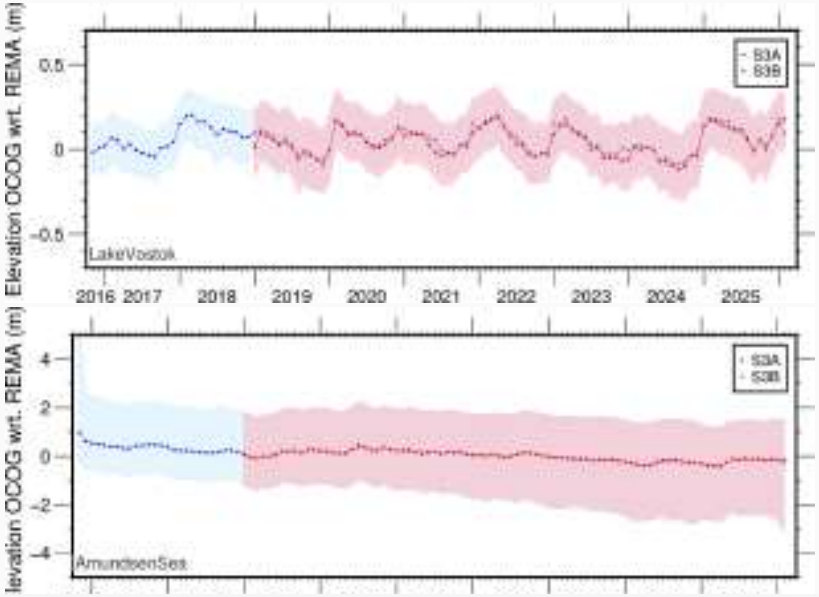


- Higher median over GL sites
- Two modes due to Arctic DEM
- Russell Glacier a challenging area

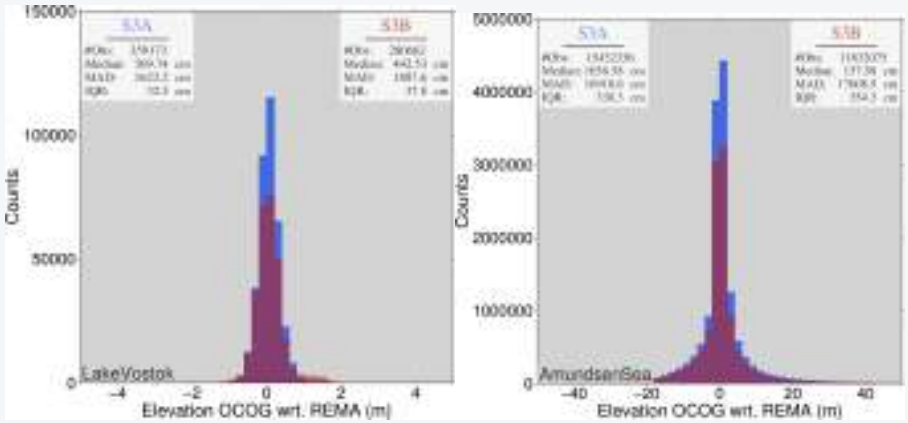




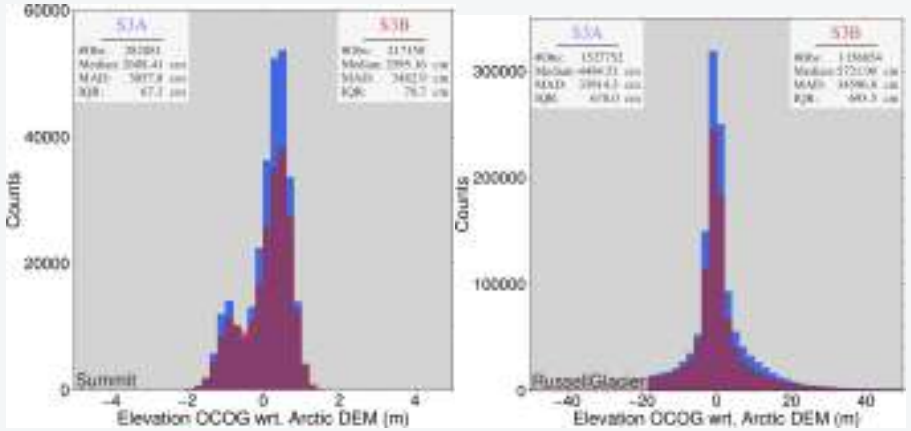
Elevation OCOG/ICE-1 wrt. DEM OLD PB

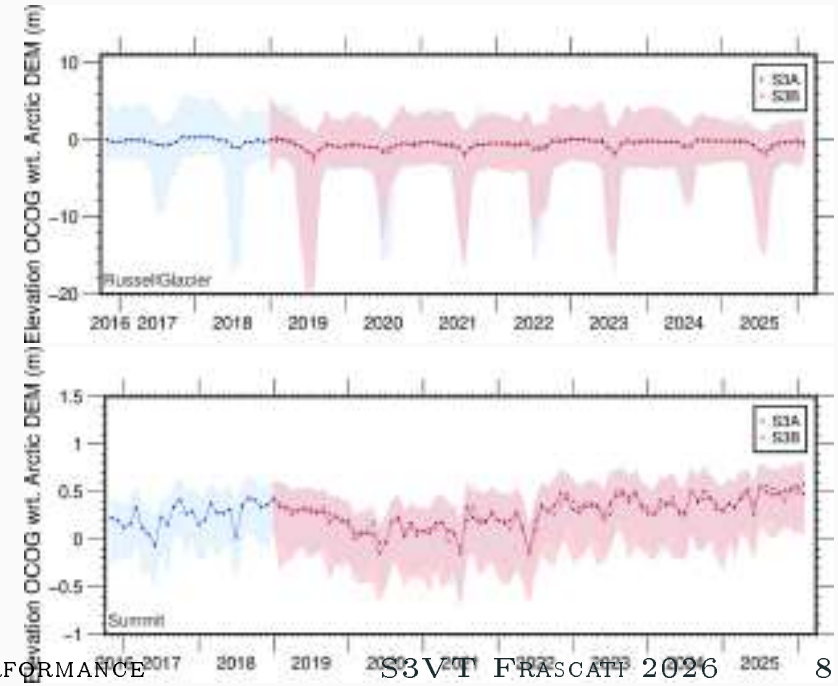


- S3A/S3B agrees very well
- S3A slightly higher anomaly
- Vostok good Amundsen okay performance

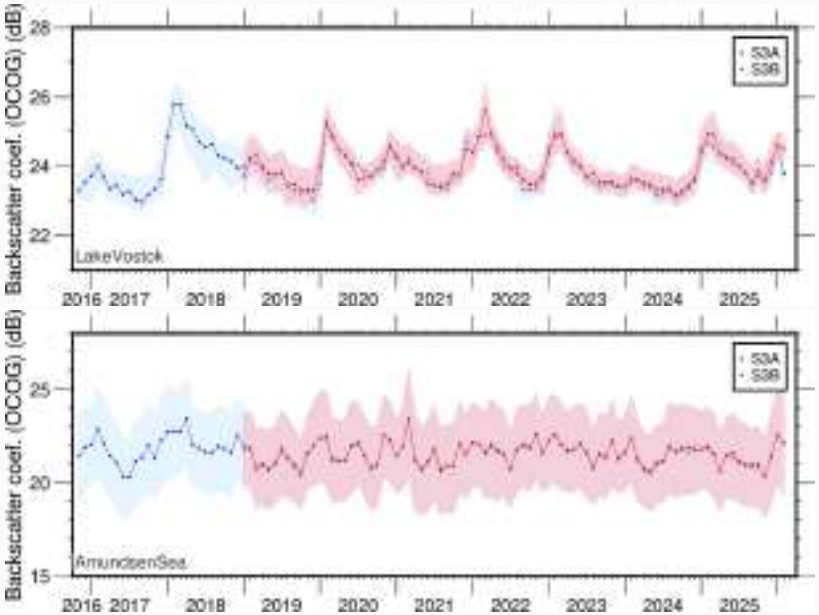


- Higher median over GL sites
- Two modes due to Arctic DEM
- Russell Glacier a challenging area

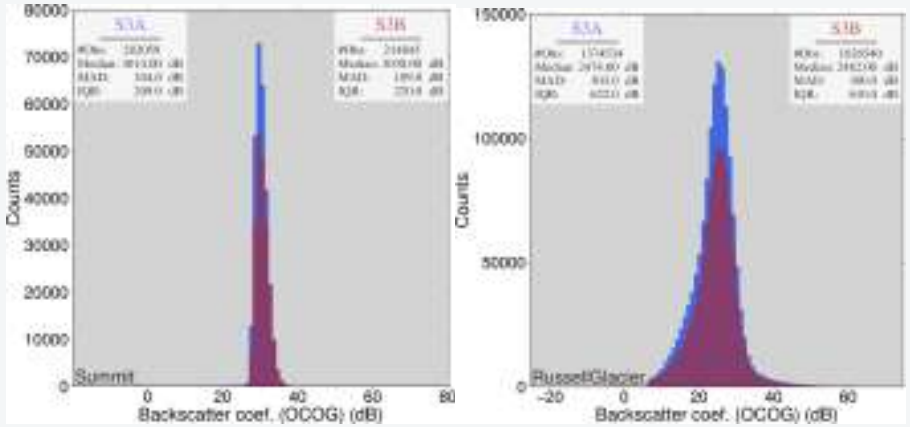




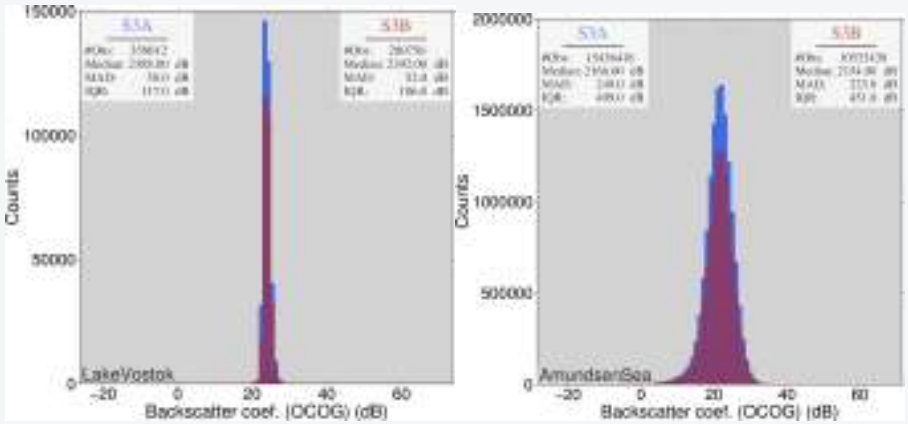
General performance Sig0 OCOG

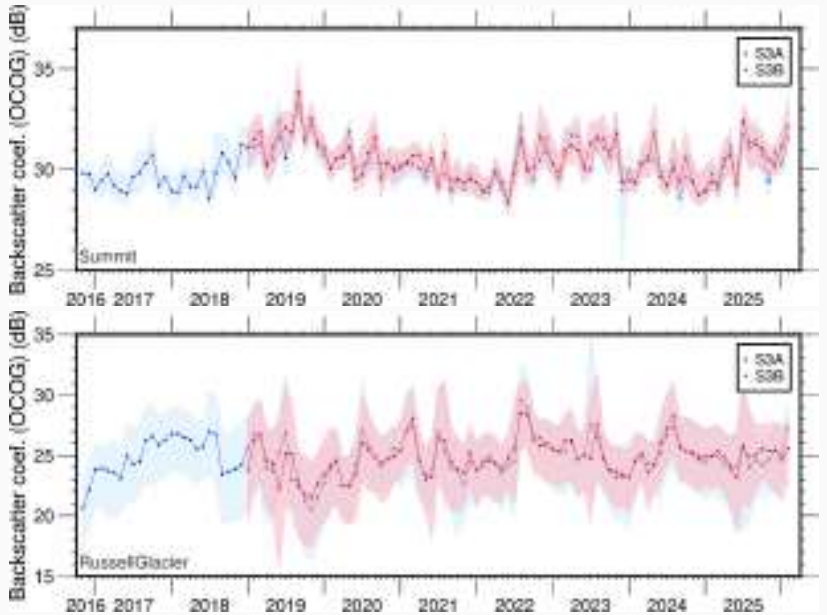


- S3A/S3B agrees very well
- Instrument stability
- Lake Vostok a good site for validation



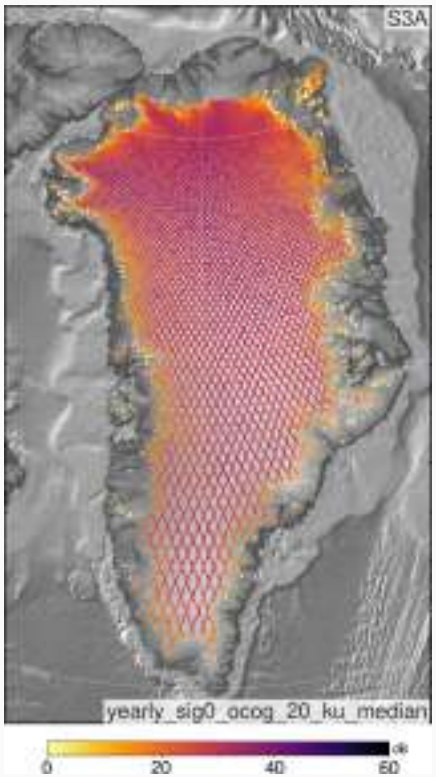
- No anomalous obs. or irregularities
- Natural fluctuations





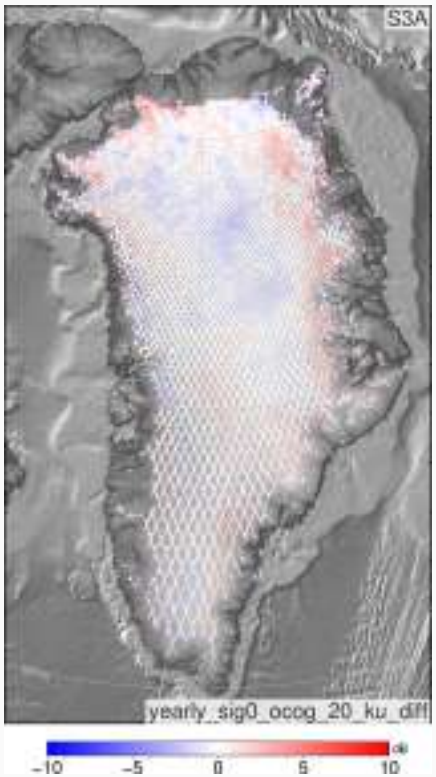
S3A Greenland: 2025 Annual Backscatter Assessment

2025 Median

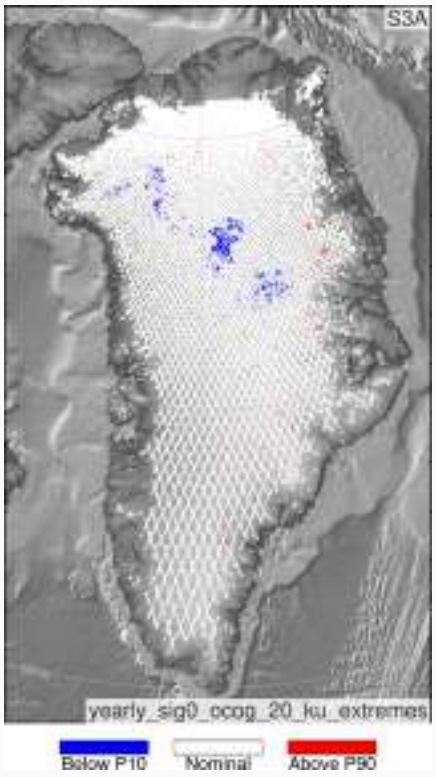


Counts

Diff to baseline



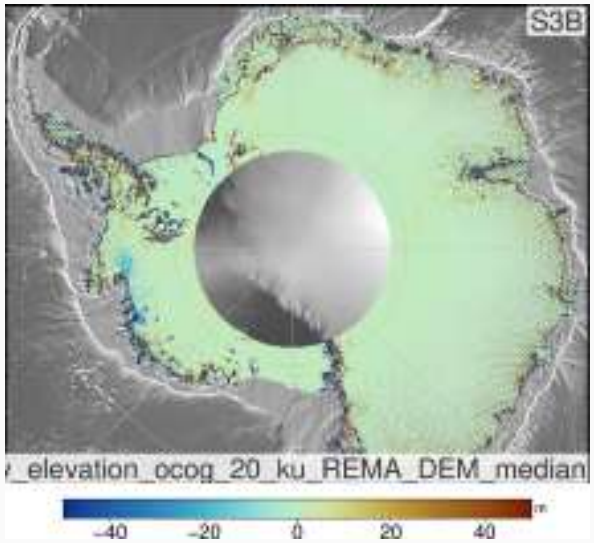
2025 Extremes



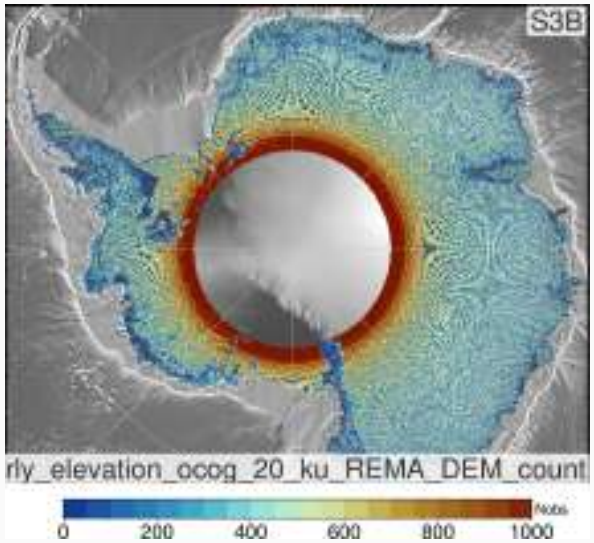
- Surface-induced variability, retracker sensitivity, environmental effects identify anomalous observations or irregularities.
- Baseline: data before 2025
- Yearly gridding was performed without spatial interpolation.

S3B Antarctica: 2025 Annual Elevation Assessment

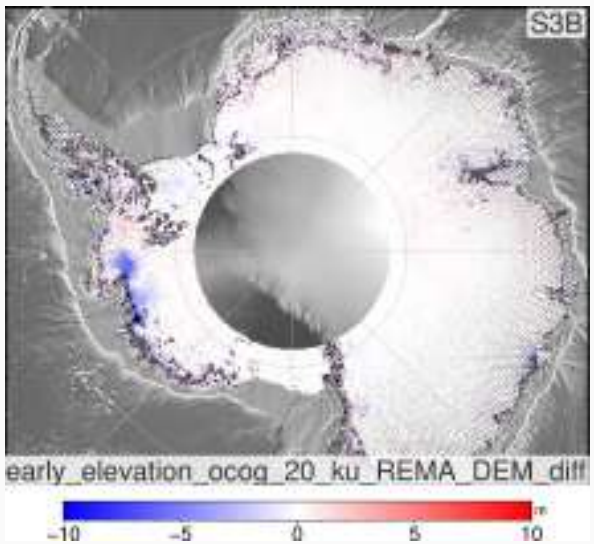
2025 Median



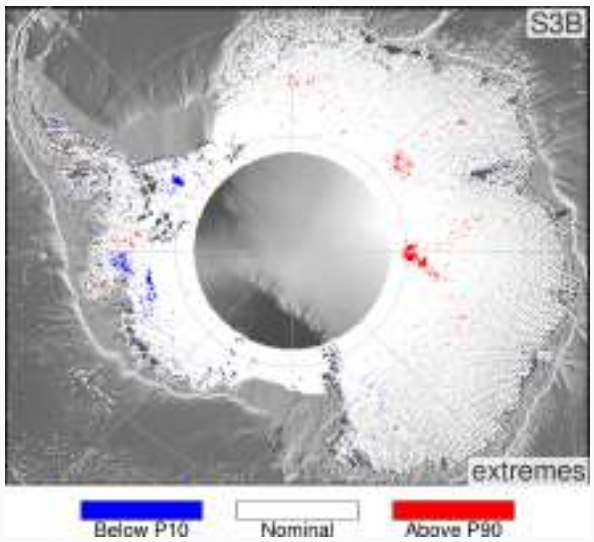
Counts



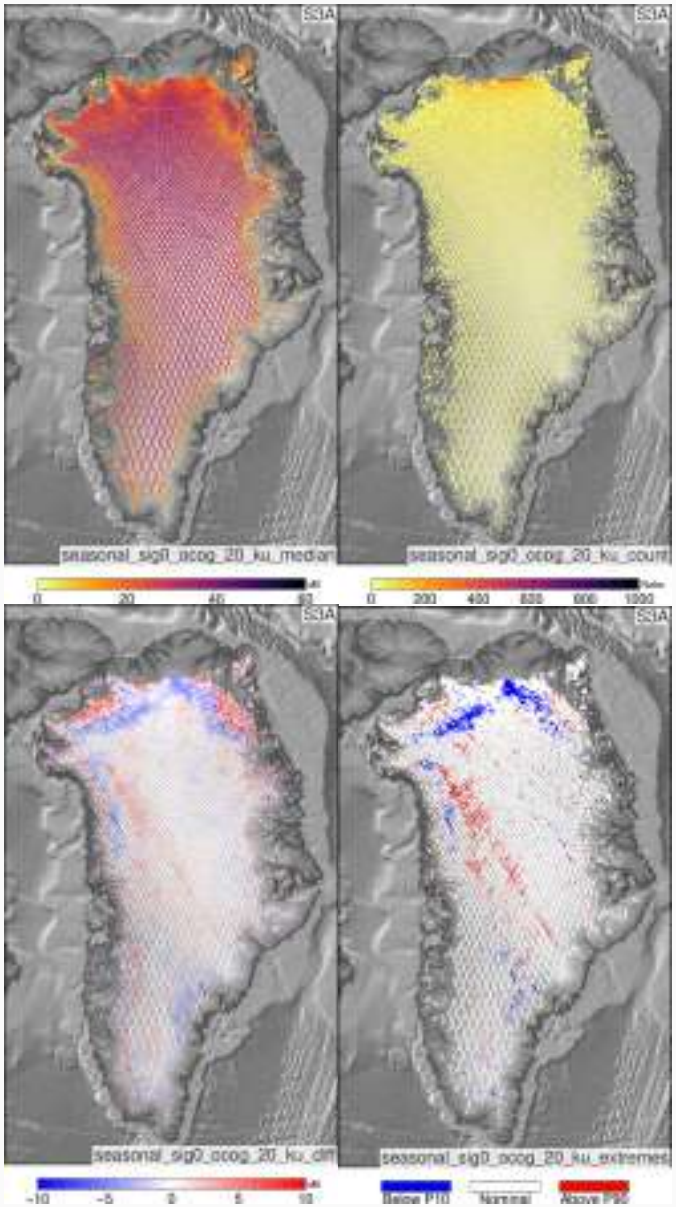
Diff to baseline



2025 Extremes



Summer 2023 changes

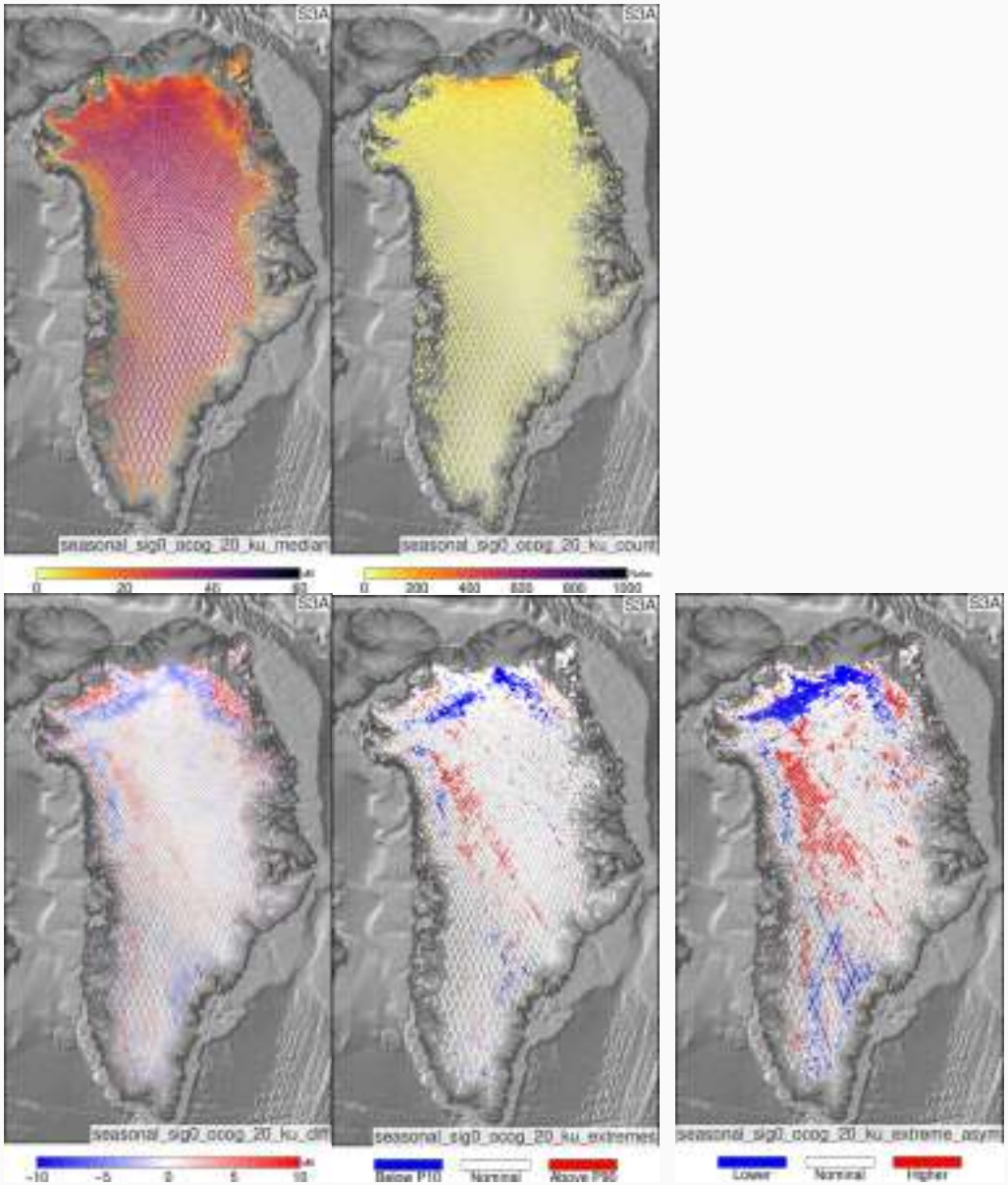


Surface melt

polarpotalen.dk

- Strong summer spatial structure.
- Extreme and asymmetry maps highlight melt-sensitive zones.

Summer 2023 changes

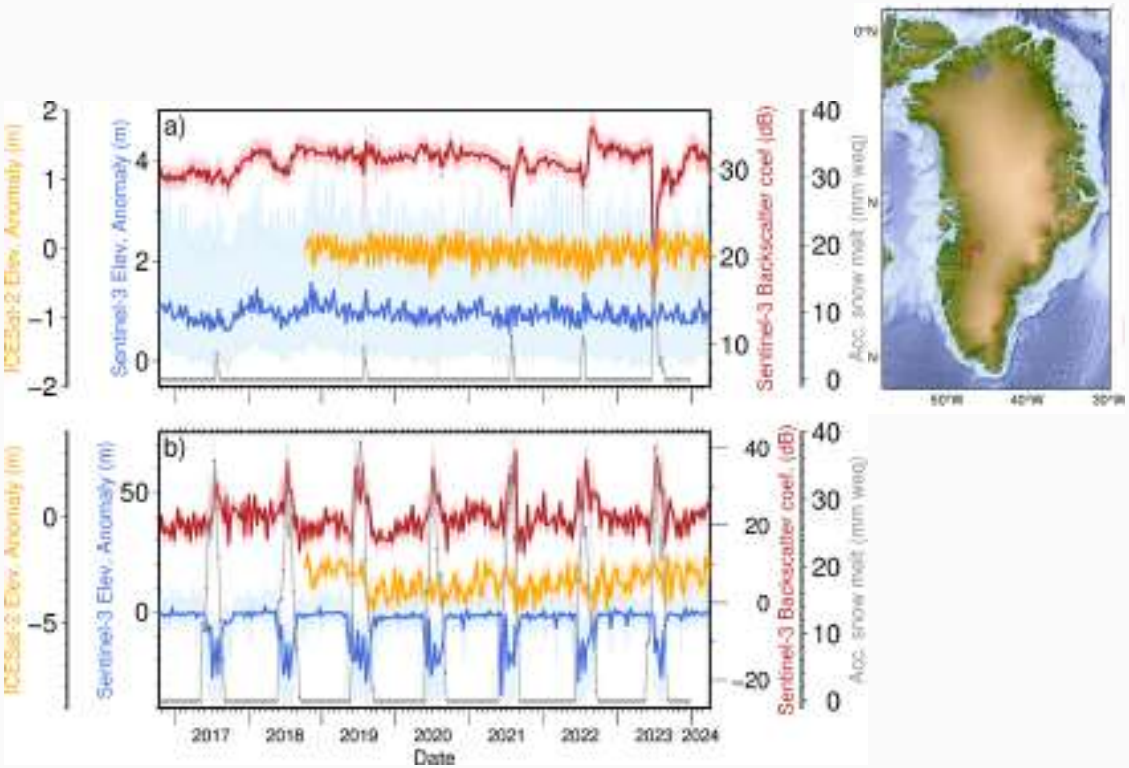


Surface melt

polarpotalen.dk

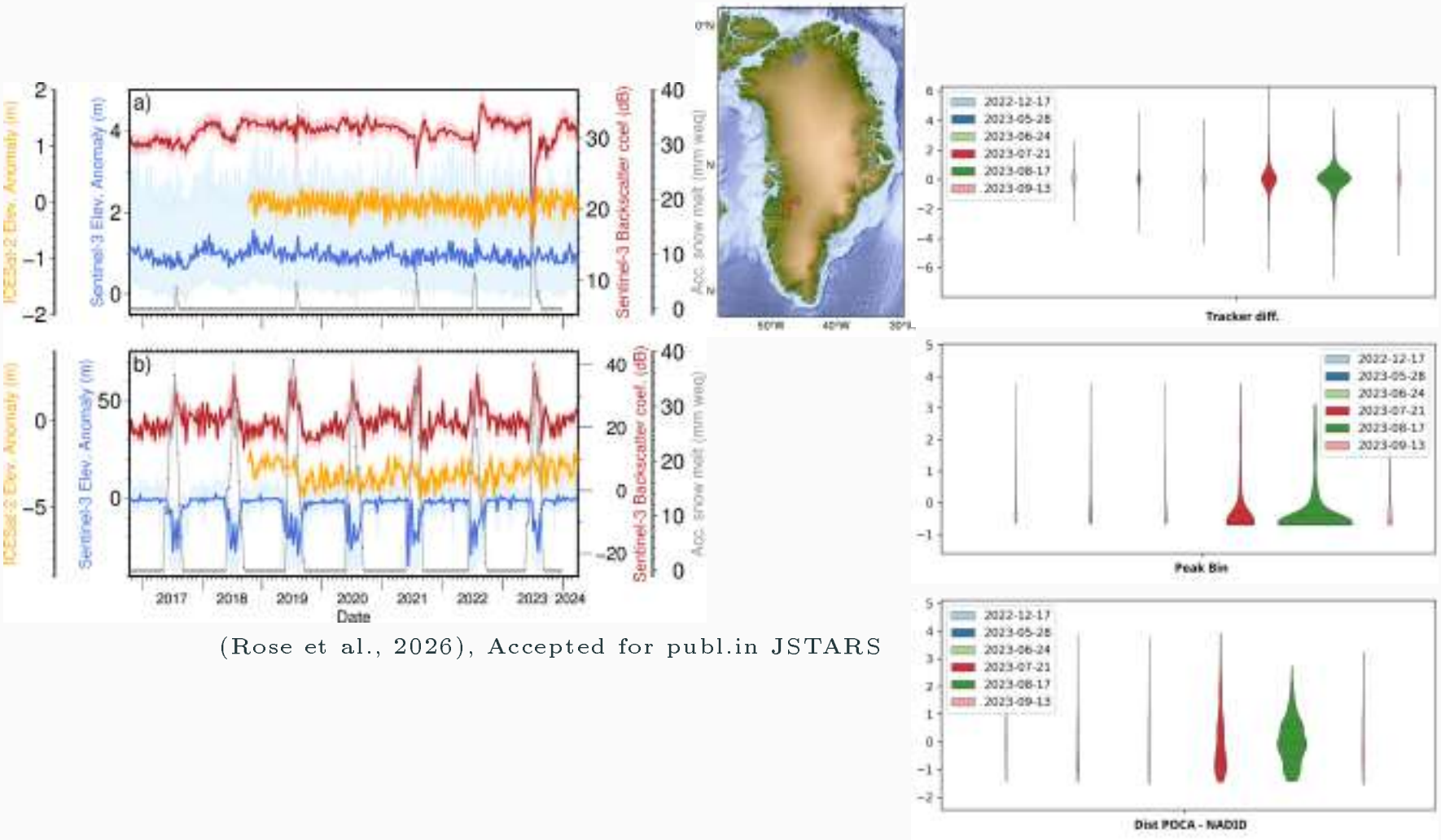
- Strong summer spatial structure.
- Extreme and asymmetry maps highlight melt-sensitive zones.

Summer 2023 changes



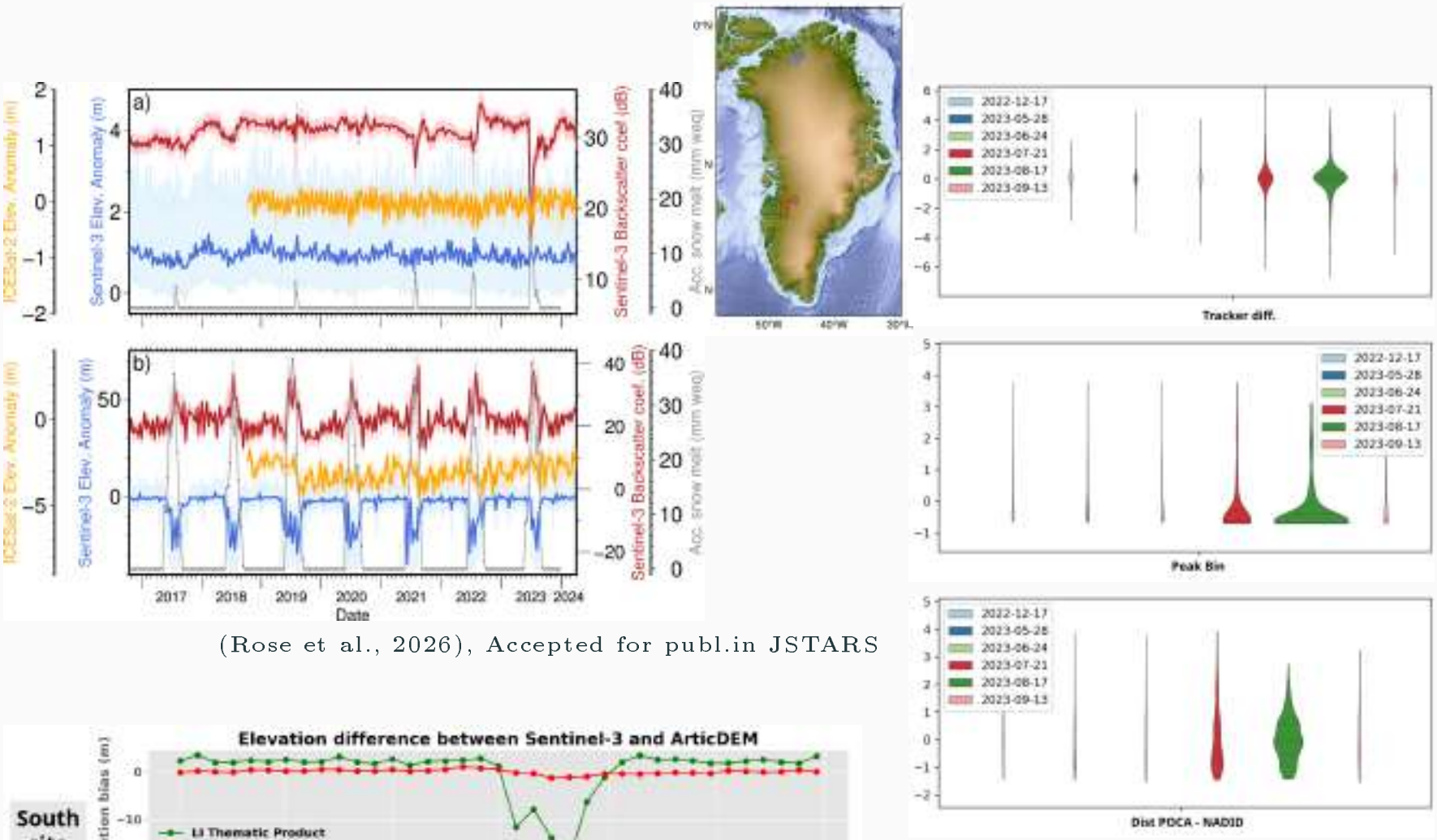
(Rose et al., 2026), Accepted for publ.in JSTARS

Summer 2023 changes



(Rose et al., 2026), Accepted for publ.in JSTARS

Summer 2023 changes



(Rose et al., 2026), Accepted for publ.in JSTARS

J. Aublanc

Summary of Key Findings

Takeaway

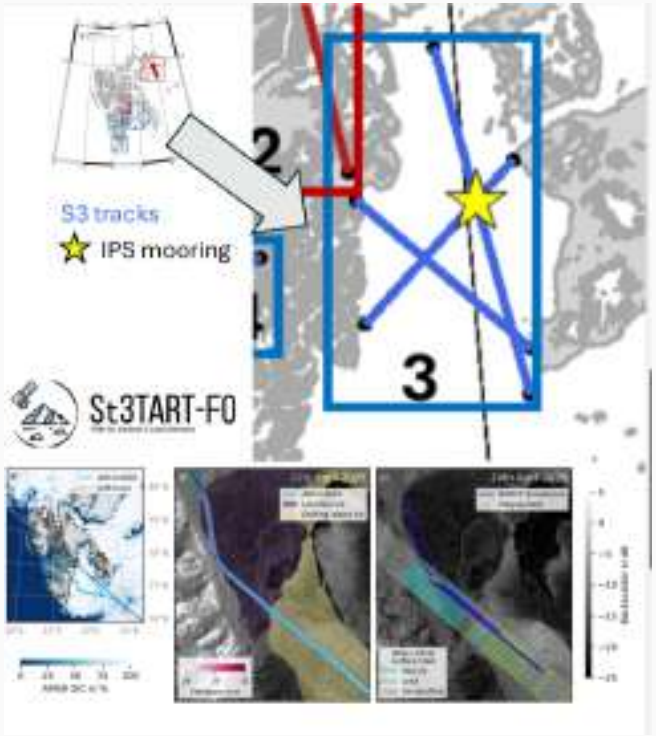
- S3 is robust over flat interior ice-sheet regions, but performance degrades in rough and steep terrain
- Terrain slope is the dominant error driver in margins
- Over favorable terrain, un-correlated precision is at decimeter scale ($\sigma(dh < 1\,\mathrm{m}) \sim 35$ cm)
- New GNSS dataset at Summit; Residuals 14 cm (S3B), 12 cm (I2)
- Correlated elevation anomalies range from decimeters to meters depending on region and season
- AMPLI-style quality filtering improves retrieval quality in challenging areas
- Ice sheet wide yearly examinations give
- Summer 2023 Sig0 signals clearly picks up melt, Current PB have 15 m elevation offset, AMPLI more physical correct
- Uncertainties propagate directly into SEC and mass-balance assessments

QWG Recommendation

- Explore the possibility of new improved retracker, maybe round robin approach with different retrackers, to better handle complex waveforms over land ice
- Continue monitoring and characterizing snowpack penetration effects, especially in SAR altimetry
- AMPLI: Implement advanced terrain correction techniques to mitigate slope-induced errors
- Expand validation efforts using a wider range of in situ data and across more diverse land ice regions
- Correction/flagging of melt season observations, which are more likely to be affected by surface changes and may have lower quality
- 80 Hz UF-SAR processing
- More focus on Mountain glacier processing

S3C Commisioning and Validation (Sea Ice)

- Overall radar altimeter performance over the same sea ice conditions
  - "Normal" performance assesment by impact of processing, performace between S3's, precision, uncertainty quatification
  - Comparisins against other sats.; (radar/laser), eval bias
  - Investigate the consistency over near-coincident sea ice targets and surfaces
- **Validation activities**
  - **Align with St3TART-FO 2027 Campaign in April 2027 (Drone in Storfjorden and IPS mooring (S3B))**
  - **Potentially AWI IceBird flying in Beaufort Sea spring 2027 => could fly a S3B**
  - **Align S3-C Tandem Phase with S3B for Spring 2027**
- Far fetched (?) ... but fun stuff!
  - Lower S3A altitude
  - Impact of the footprint size
  - Sensitivity to different sea ice conditions
  - Eval. of noise over different sea ice targets



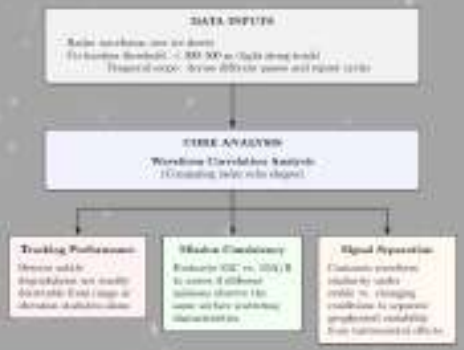
Credits:

Henriette Skourup, Renée M. Fredensborg, Kristina Belinska.

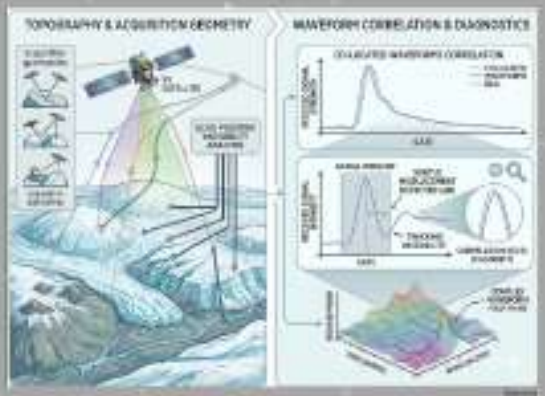
S3C Commisioning and Validation (Land Ice)

Additional Analysis

Waveform co-location



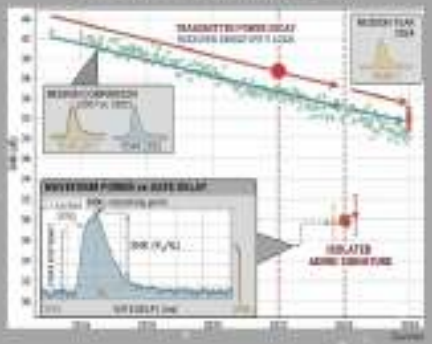
OLTC Performance Diagnoses



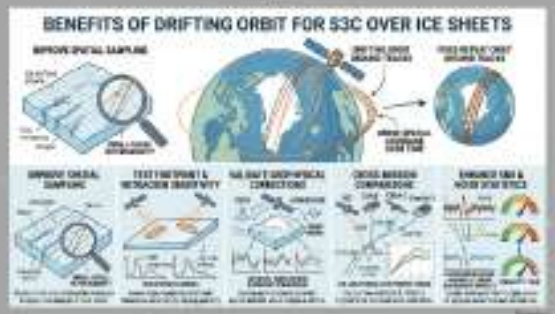
Speckle Noise

Additional Analysis

Instrument Aging (S3A)



Drifting Orbit



The Crazy ideas

- Harmony-style communication between the tandem satellites
- After tandem phase, lower S3A altitude to a drifting orbit for:
  - Extended co-location studies
  - Evaluate impact on footprint size
  - Noise evaluation

Thank You for Listening!

R. L. Hawley, D. J. Pickell, J. R. McConnell, T. A. Neumann, D. Felikson, and S. W. Dorsi. Icesat/icesat-2 traverse: Monthly gps surface elevation data at summit station, greenland, 2026. URL https://doi.org/10.5067/UNBV80EA7YBW. [Data set]. Accessed: [Date Accessed].

D. J. Pickell, R. L. Hawley, D. Felikson, and J. C. Good. Icesat-2 surface elevation assessment with kinematic gps and static gnss near the ice divide in greenland. *The Cryosphere*, 20(1):483–494, 2026. doi: 10.5194/tc-20-483-2026. URL https://tc.copernicus.org/articles/20/483/2026/.

S. K. Rose, S. B. Simonsen, L. S. Sørensen, J. Aublanc, A. Chamyau, F. Catapano, and A. Di Bella. Advancing land ice altimetry with sentinel-3: Performance assessment and error budget characterization. In review in the proceedings volume *State of the Art in Satellite Altimetry Calibration and Validation*, 2025.

S. K. Rose, L. S. Sørensen, K. M. Scanlan, J. Aublanc, F. Catapano, A. Di Bella, P. Féménias, and S. B. Simonsen. Regional differences in sentinel-3 radar backscatter over greenland and its impact on ice sheet altimetry applications. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 2026. In Review.