Snow Depth Retrieval using **Multi-Frequency Altimetry** over **Antarctic Summer Sea Ice in the Weddell Sea** using **Air- and Spaceborne** Observations along **CRYO2ICE** Orbit

… Let’s change it up a bit!

A step on the way to cracking the snow code …

with multi-frequency altimetry exploration over Antarctic summer sea ice along CryoSat-2 and ICESat-2 (CRYO2ICE) orbit

Renée Mie Fredensborg Hansen, Henriette Skourup, Eero Rinne, Arttu Jutila, Isobel Lawrence, Andrew Shepherd, Knut Høyland, Jilu Li, Fernando Rodriguez-Morales, Sebastian Simonsen, Jeremy Wilkinson, Gaile Veyssiere, Donghui Yi, René Forsberg, and Tania Casal

In review in EGUsphere/The Cryosphere (Fredensborg Hansen et al., 2024, in review): https://doi.org/10.5194/egusphere-2024-2854

A step on the way to cracking the snow code …

with multi-frequency altimetry exploration over Antarctic summer sea ice along CryoSat-2 and ICESat-2 (CRYO2ICE) orbit

- To what extend do Ka- and Ku-band penetrate snow on Antarctic summer sea ice?
- How well can we retrieve snow depth consistently from airborne observations to compare with spaceborne estimates, following traditional hypotheses and assumptions?
- How well do derived airborne snow depths compare with spaceborne estimates from near-coincident laser and radar observations (CRYO2ICE)?

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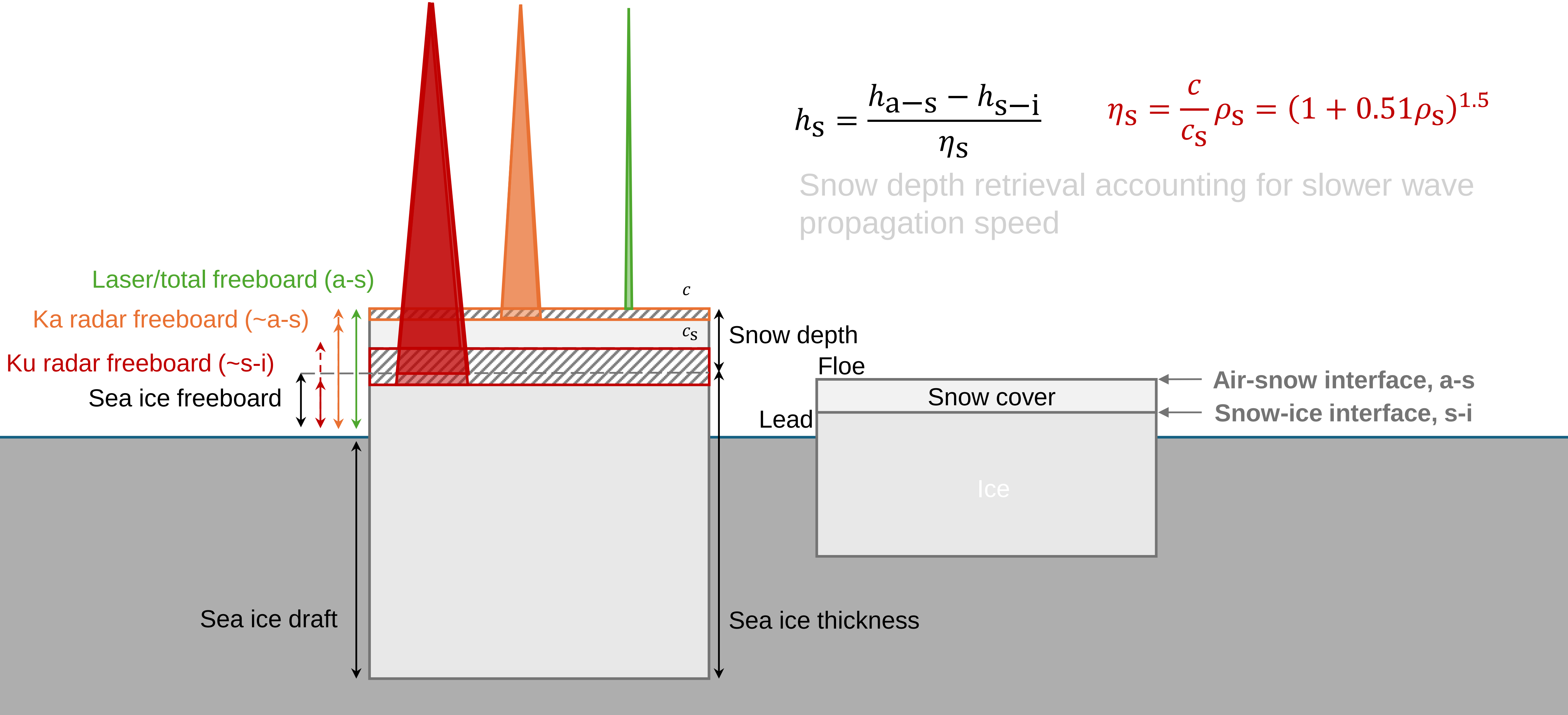
Basic method/assumptions

$$h_S = \frac{h_{a-s} - h_{s-i}}{\eta_S} \qquad \eta_S = \frac{c}{c_S}\rho_S = (1 + 0.51\rho_S)^{1.5}$$

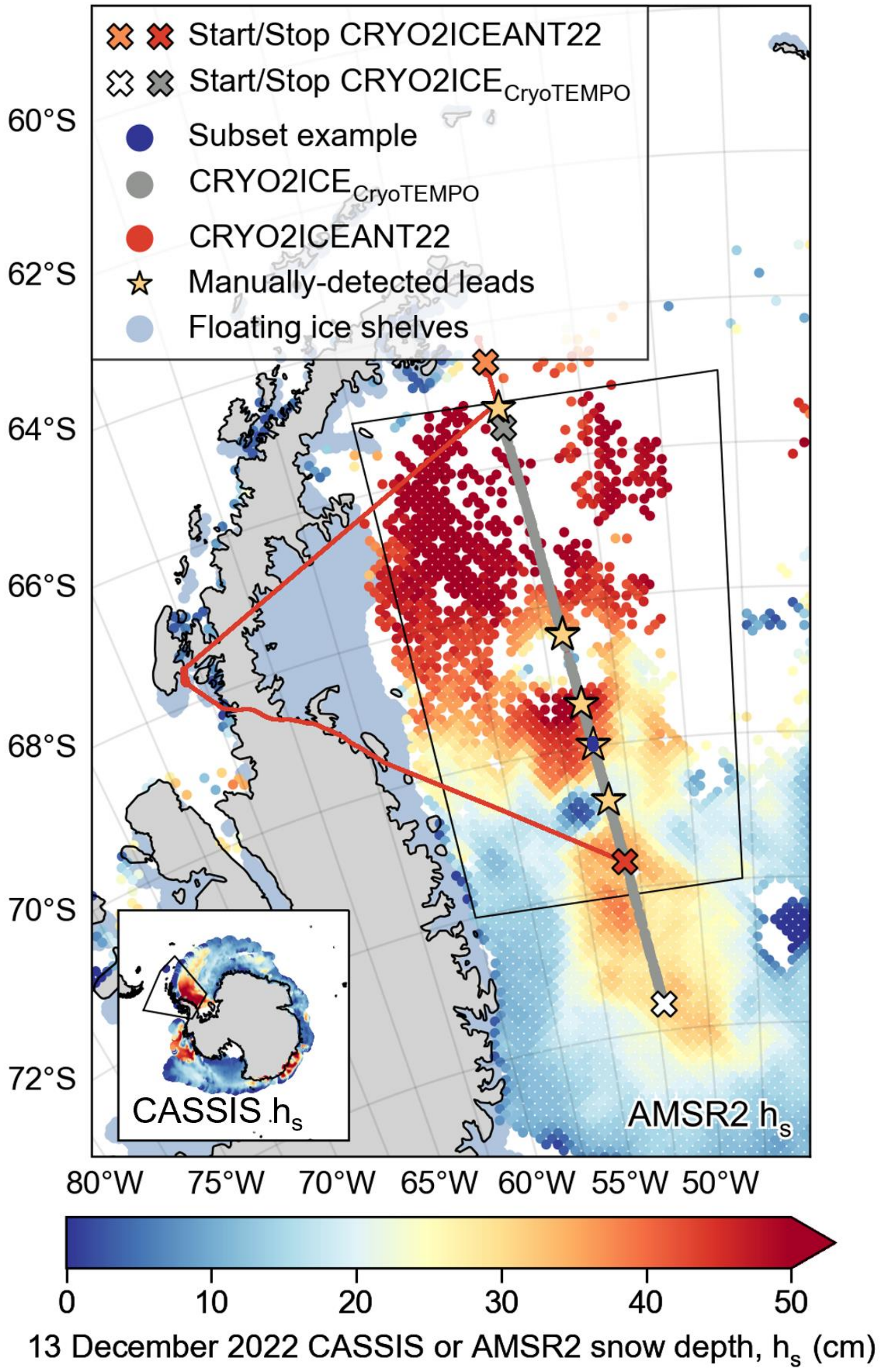
Snow depth retrieval accounting for slower wave propagation speed



CRYO2ICEANT22 under-flights in the Weddell sea

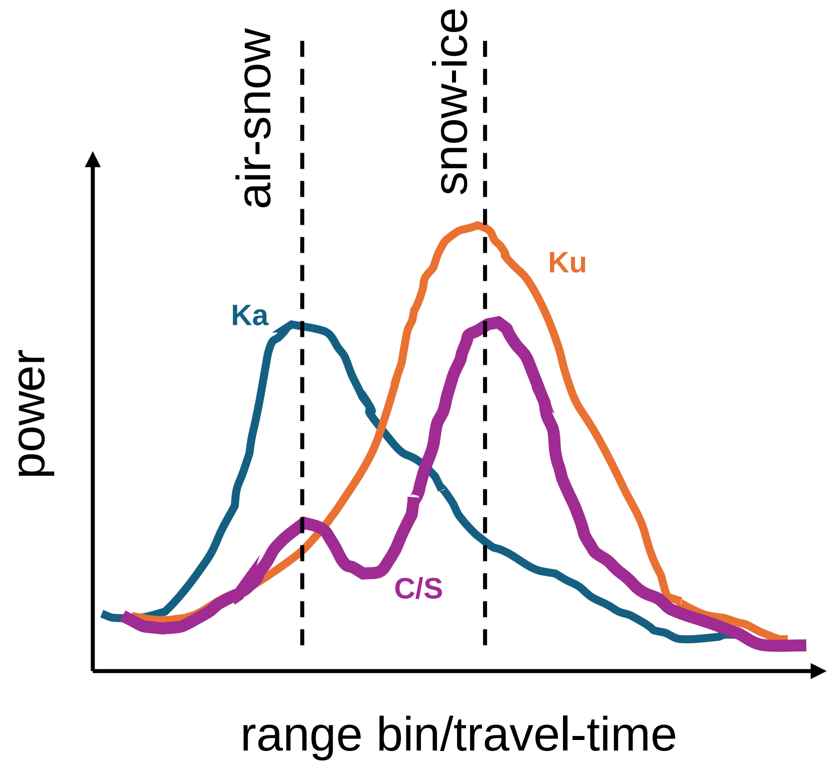
Overall objectives of (sea ice) campaign
- Good spatial sampling of sea ice in the Weddell Sea
- Under-fly satellite orbits – focus on CRYO2ICE

On 13th of December 2022, underflew CRYO2ICE orbit
- CS2 : ~20:16 UTC
- IS2 : ~17:36 UTC
- under-flight: ~18:48 – 21:46 UTC (full flight: 15.52 UTC – 00.29 UTC next day)



Waveform re-tracking and assumptions

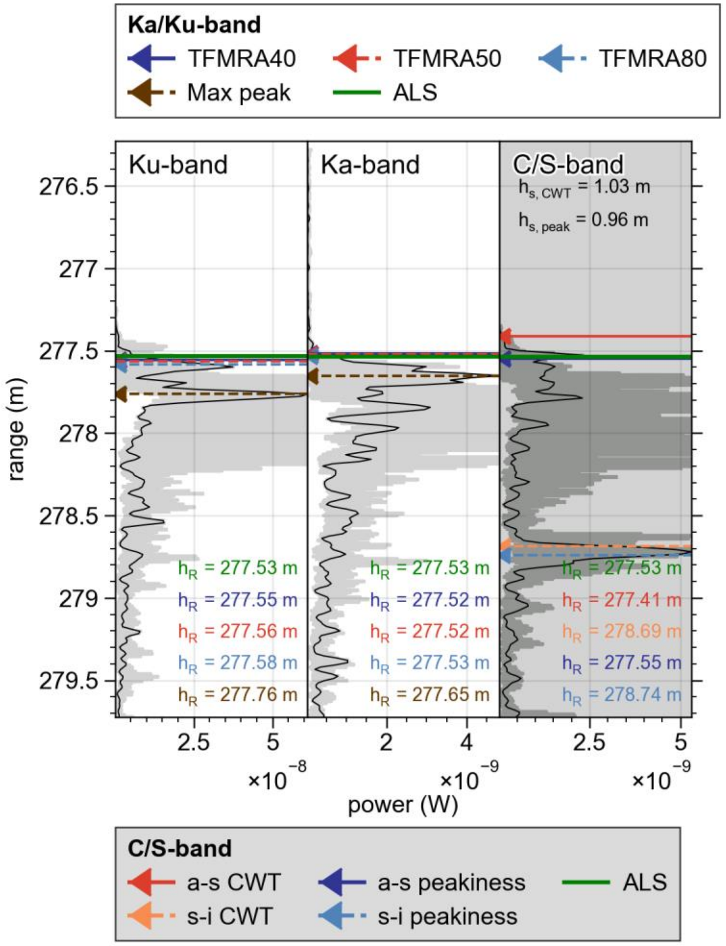
- Extracting the travel-time (~elevation) at which we believe the best estimate for the average surface within the footprint is located
- **Ka**/**Ku**-band: single interface is typically retrieved (primary contributor)
- **C/S**-band radar FMCW (2-8 GHz) assumes several interfaces can be detected (air-snow and snow-ice)
- Waveforms differ for surfaces → separation between leads/floes

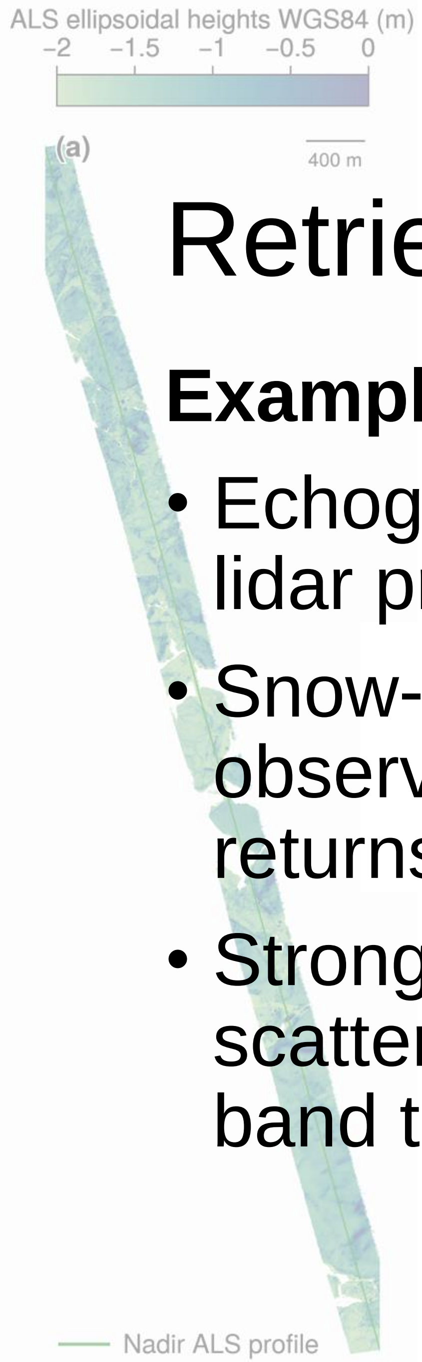


Ka-, Ku-, S/C-band and lidar (NIR) observations

Ellipsoidal elevations

- **Lidar**: swath and nadir-vertical-profile (within 5 m footprint of radars)
- **Radar(s)**: waveforms
  - Re-tracking of surface (**TFMRA** at 40, 50 or 80% and **MAX** for Ka/Ku; **CWT, PEAK** and **MAX** for snow-radar) … **centroid** for Ka/Ku to evaluate consistency with ground-based results.
  - **Offset calibration** per band through manually detected leads - depends on re-tracker used!
  - **Lead/floe discrimination** (pulse peakiness), ~40% (18.29% leads, 21.06% mixed) discarded for snow depth observations

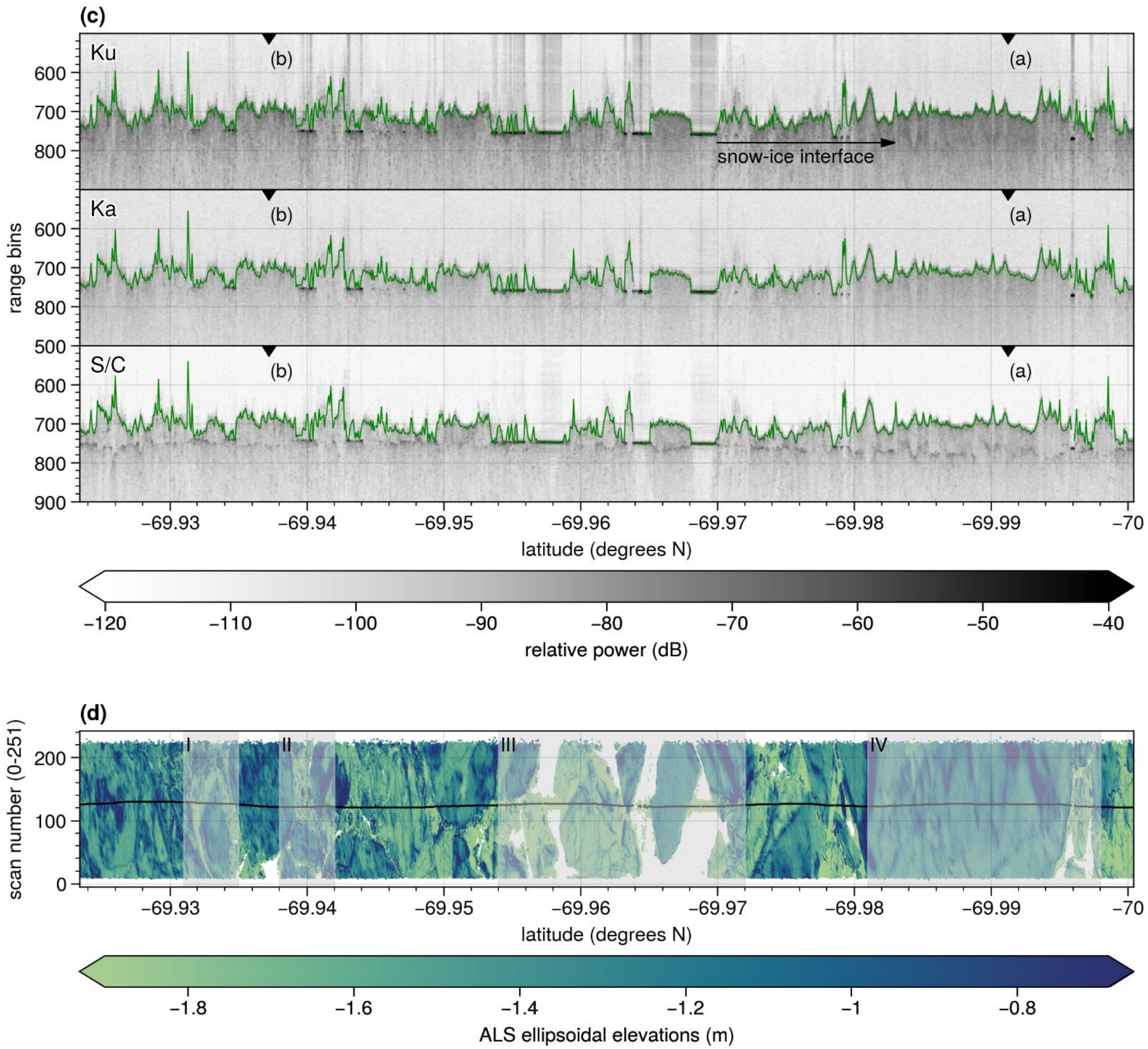




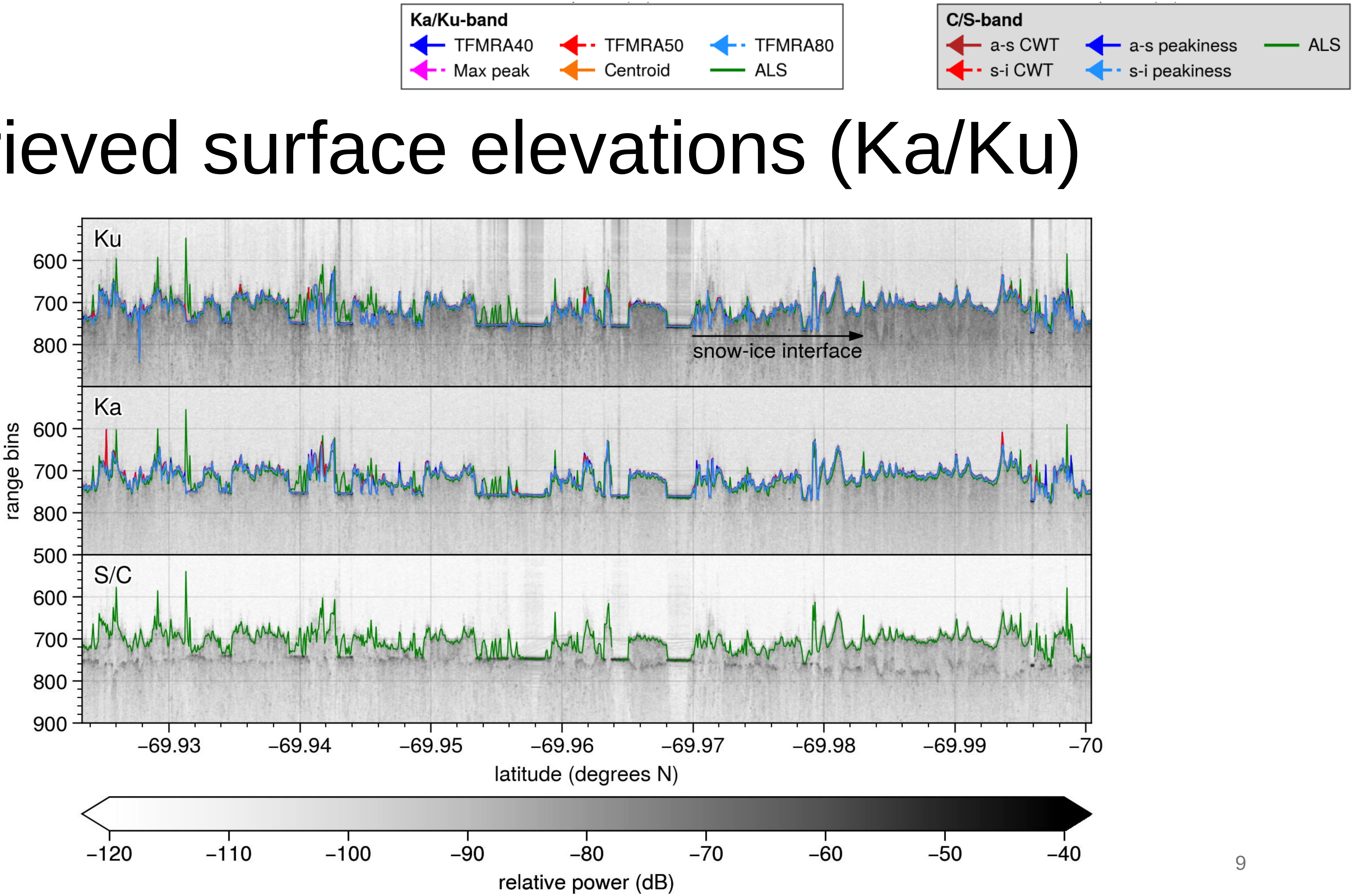
Retrieved surfaces

Example 5-km transect…

- Echograms with vertical lidar profile overlaid
- Snow-ice interfaces observed in S/C, some returns in Ku-band
- Stronger returns and scatter observed in Ku-band than Ka-band



Retrieved surface elevations (Ka/Ku)



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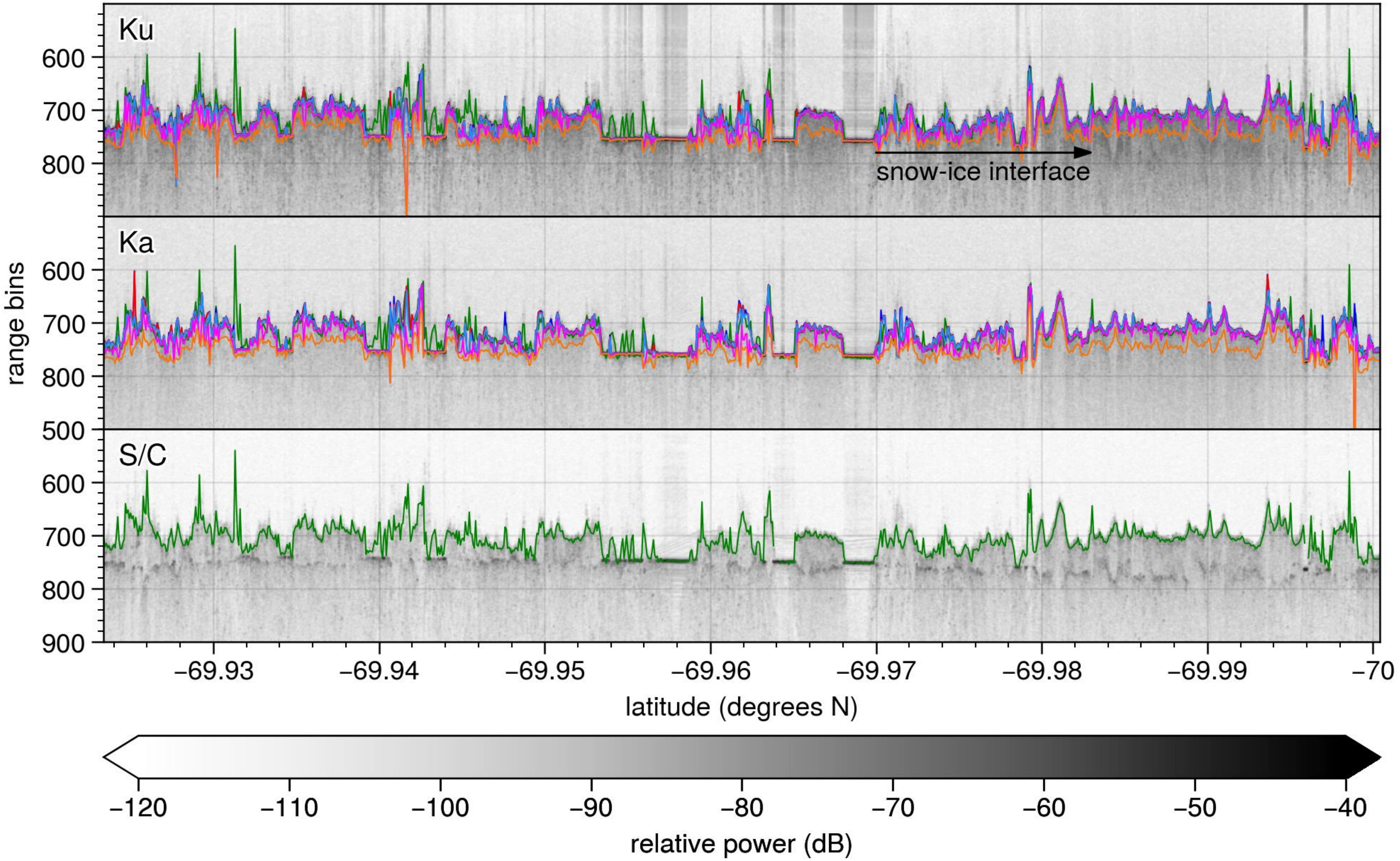
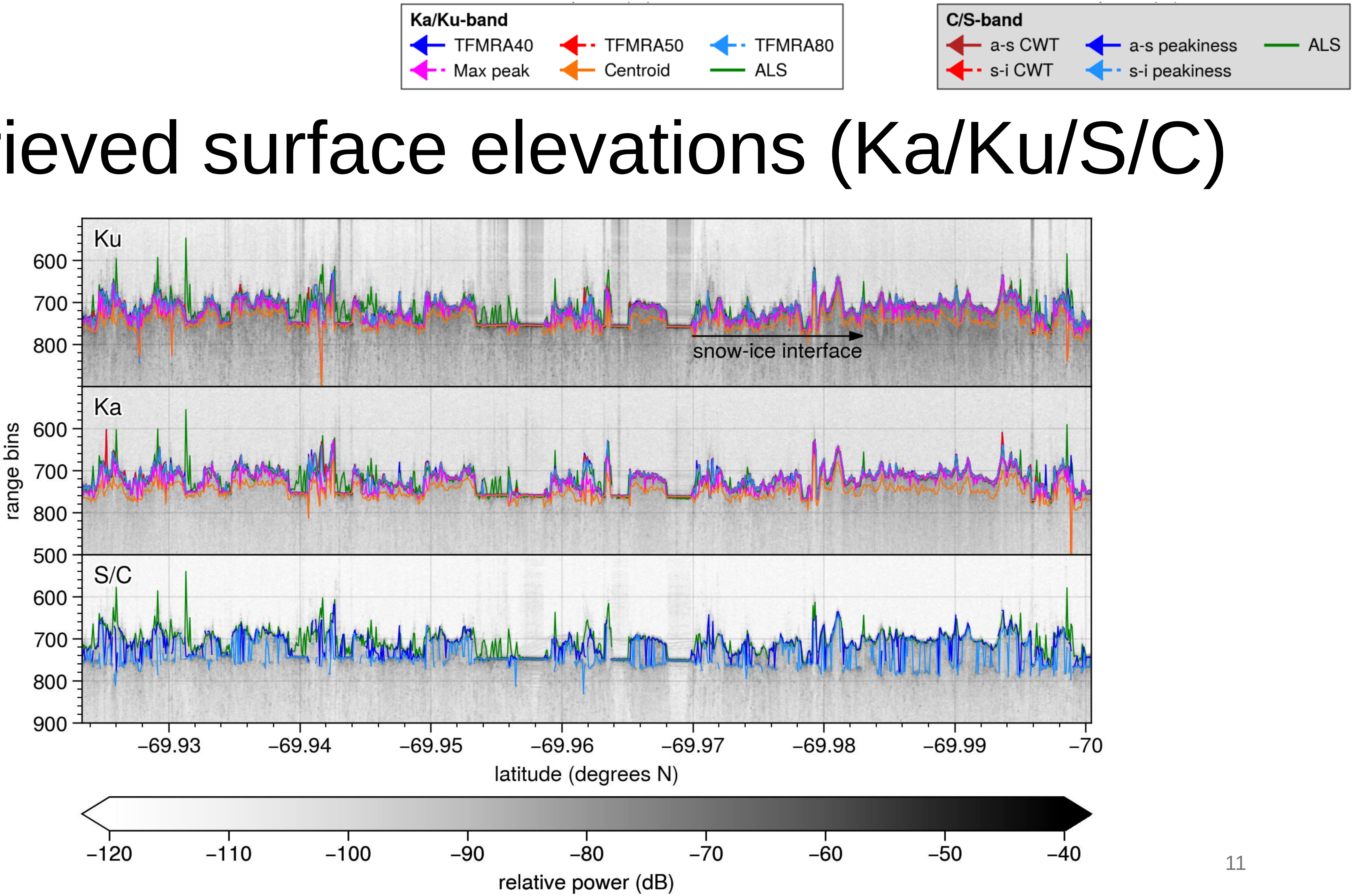


Retrieved surface elevations (Ka/Ku/S/C)



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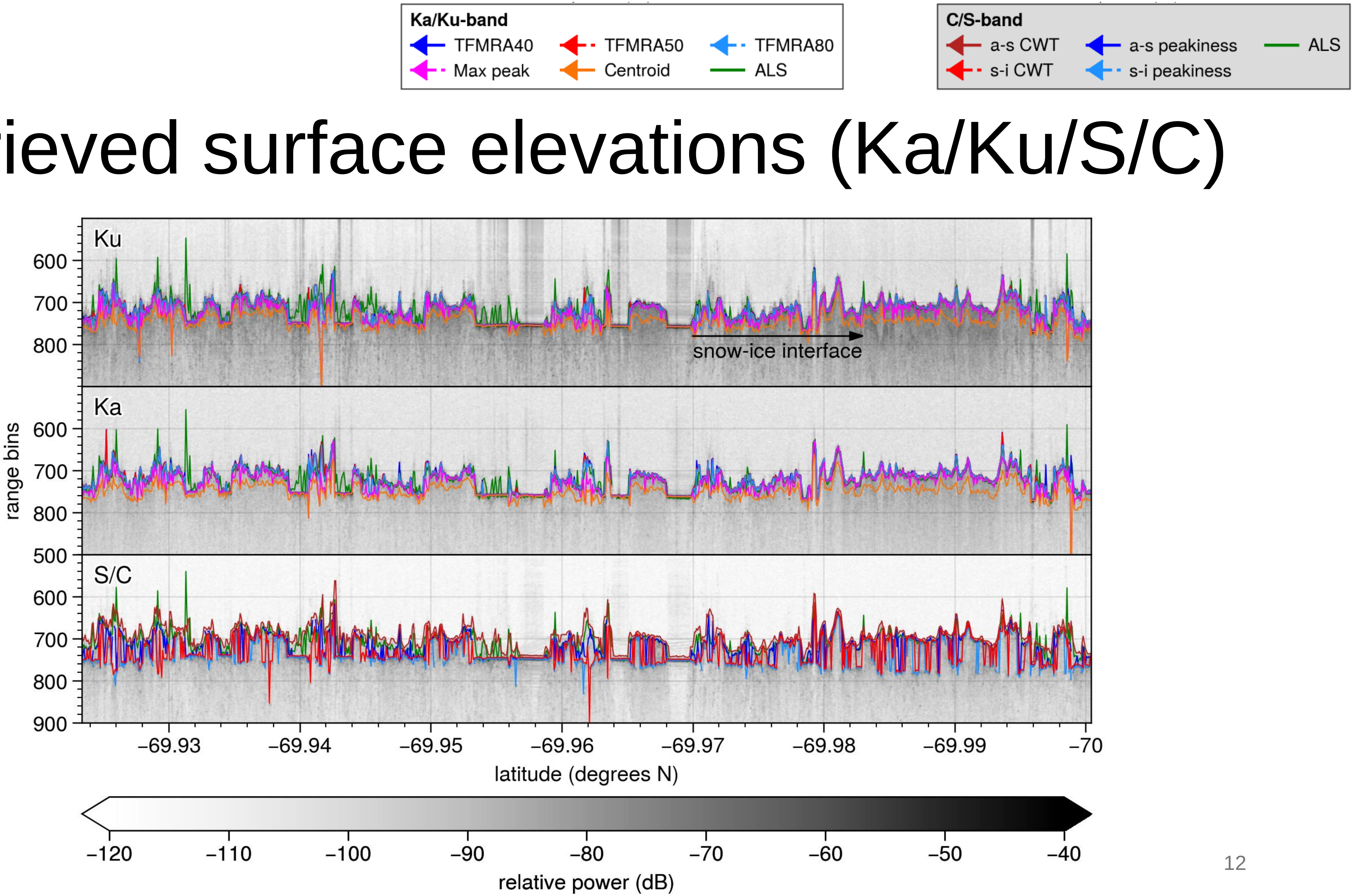
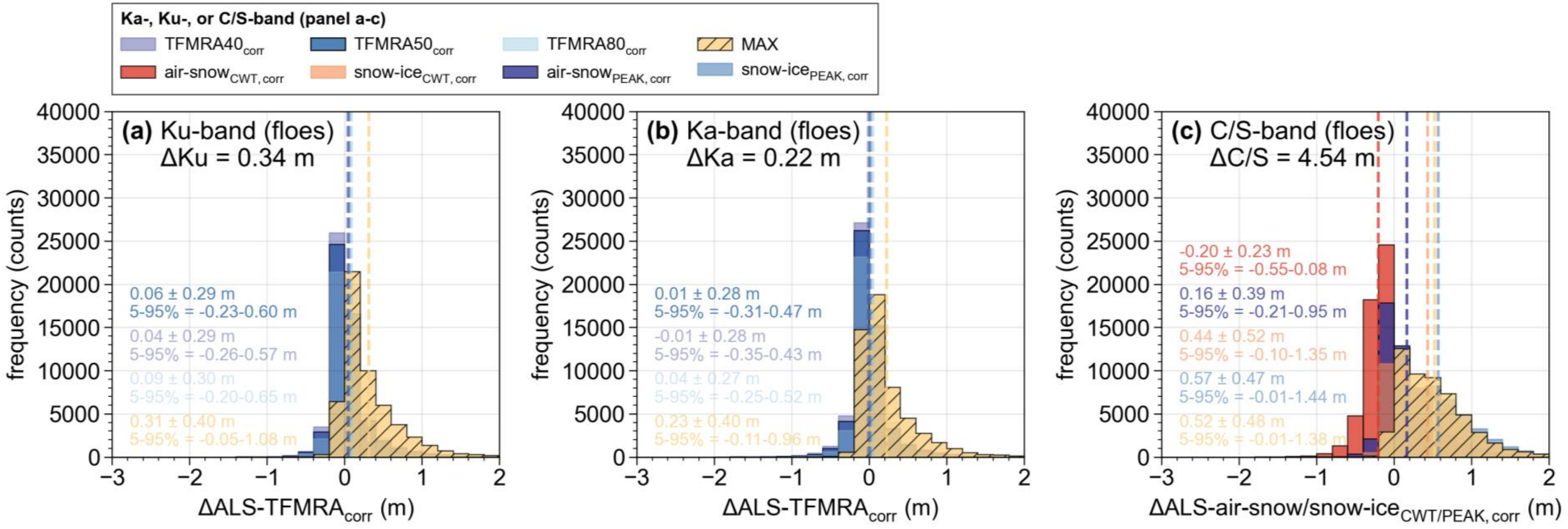
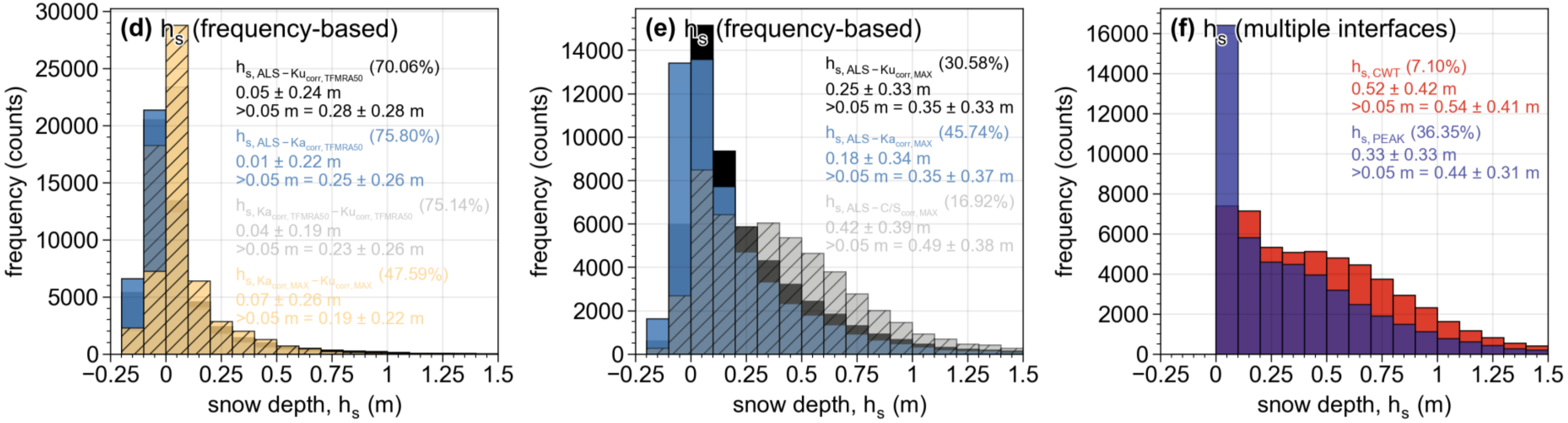


Scattering interfaces (over floes)



- Ka and Ku are both ~at the air-snow interface when using **TFMRA**!
  - Significant scattering from air-snow interface contributing
  - **MAX** on average below air-snow interface (~30 and ~20 cm for Ku- and Ka-band, but ~50 cm for C/S-band!)
- C/S-band: >10 cm difference in snow depths using **CWT** and **PEAK!**
  - **PEAK** closer to ALS air-snow interface on average
  - **PEAK** closer to MAX snow-ice interface (~5 cm difference, using all observations)

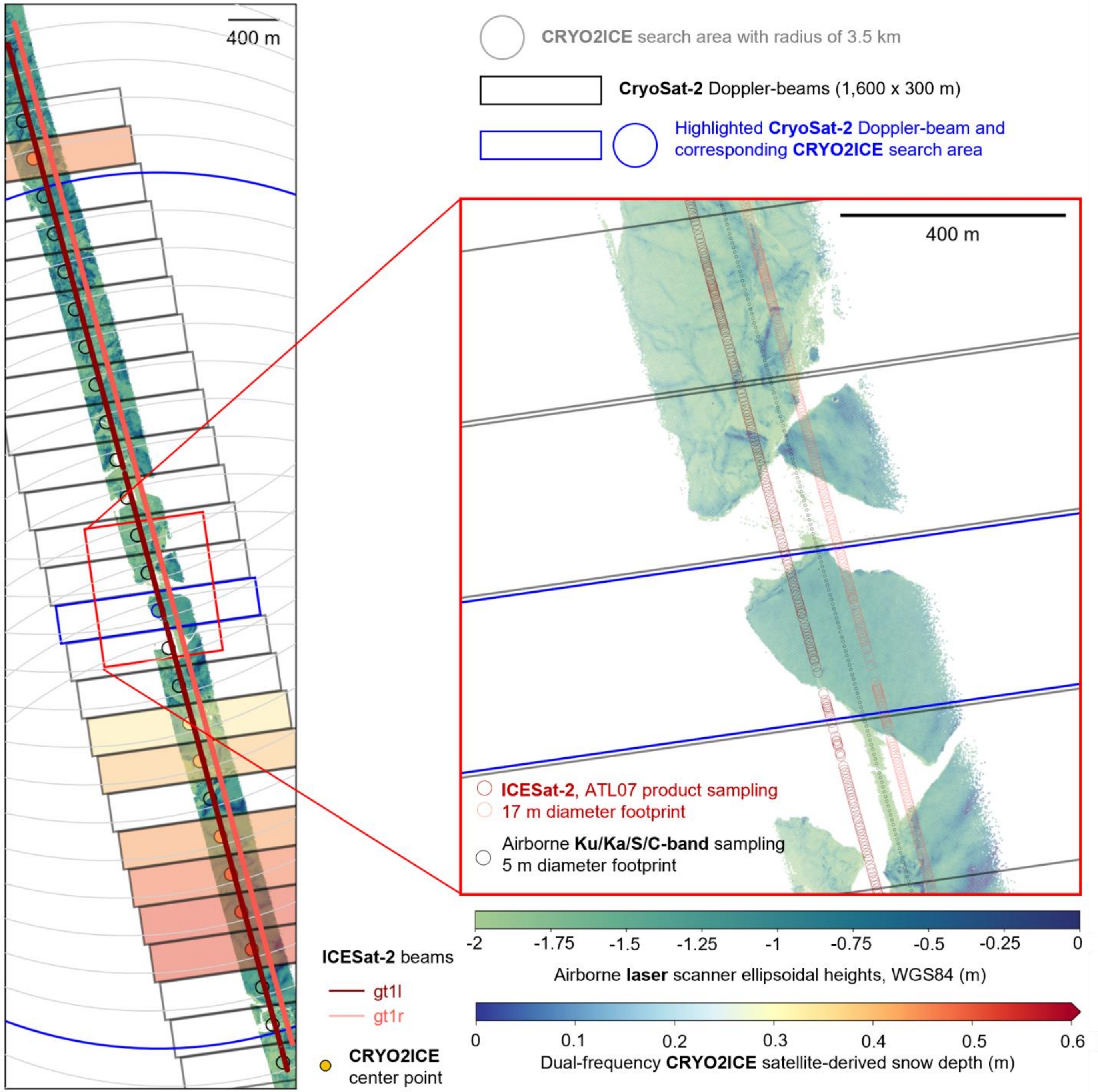
Snow depth (over floes)



- Ka and Ku snow depths using **TFMRA** present limited snow information (**>70%** are less than 5 cm)
  - **MAX** on penetrates deeper (still snow depths <5 cm in ~50% of cases)
- Using ALS as air-snow and **MAX** (> 5 cm): Ka and Ku-band of ~**35 cm, whereas C/S-band average snow depth is almost 15 cm thicker**
- CWT and PEAK show **differences** in average snow depths derived
  - PEAK more strict on which waveforms to use – CWT rarely has snow depth thinner than 5 cm
  - CWT on average observes **10 cm thicker** snow than PEAK, botth re-trackers ~**5 cm** from ALS and C/S MAX

Key findings

- In almost 50% of cases, **the air-snow interface is the primary scattering horizon at Ku-band**
  - Snow-ice interface is not always the primary contributor to maximum backscatter at Ku-band, but **instances with well-defined peaks occur lower** (not max)
  - **Ka- and Ku-band penetrates into the snowpack**, but Ka-band **on average 10 cm less than Ku-band**! C/S-band penetrates on average 20 cm more than Ku-band!
  - Assumption of a **single dominating interface** does not hold up – common re-trackers (TFMRA) may not represent the interface we think!
  - **Range resolution** of airborne data calls for different assumptions and processing!
  - **Understand** the scattering mechanisms at airborne scales for translation into spaceborne is key! Ground truth, who?
- Snow radar re-trackers **are not consistent**
  - First time PEAK re-tracker is used on 2-8 GHz – **more studies** necessary, i.e., use more airborne data (also past campaigns!) for tweaking of re-tracker
  - Following Kwok et al. (2017), what is the **correct** location to re-track the air-snow and snow-ice interfaces?
- **Scattering mechanisms differ with lasers and radars** (preferential sampling): how to align/limit this impact!



Comparison with CRYO2ICE

What do the **satellites** say?

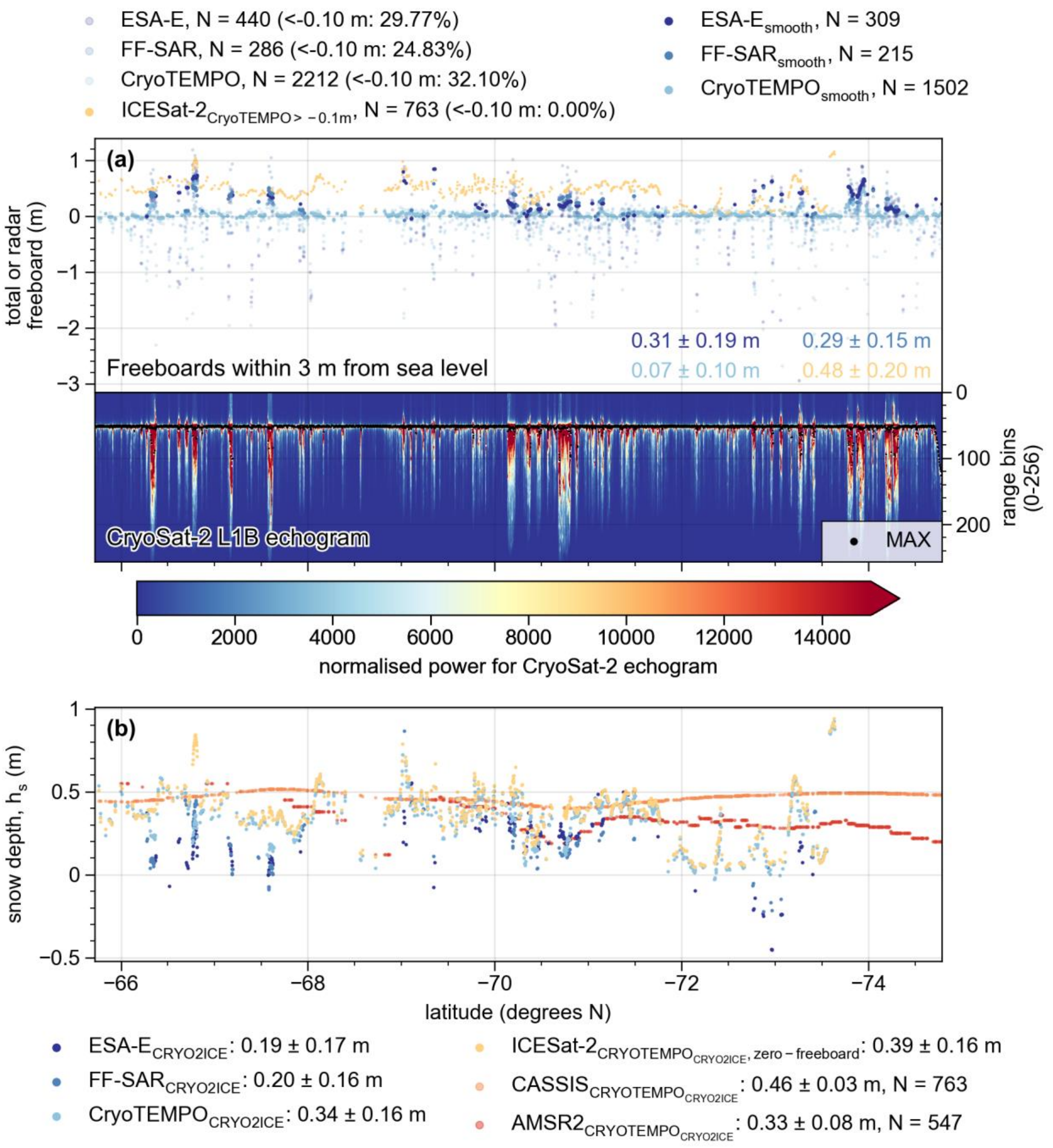
Following methodology of Fredensborg Hansen et al (2024, ESS) to align ICESat-2 and CryoSat-2

Three CryoSat-2 products radar freeboards:
- Ice Baseline-E: TFMRA70% and Giles et al (2007) fit over specular (waveform parameter classifications)
- CryoTEMPO: SAMOSA+ (un-restricted classification)
- FF-SAR (signal to noise ratio classification)

ICESat-2 ATL10 total freeboards (weak + strong beams)

Satellite freeboards

- Many negative freeboards (~30%)
- CRYO2ICE radar freeboards differ depending on processing:
  - CryoTEMPO using SAMOSA+ → smaller freeboards (less restrictive)
- CryoTEMPO CRYO2ICE snow depths agree within a cm with AMSR2 and within 12 cm for CASSIS
  - Higher variability

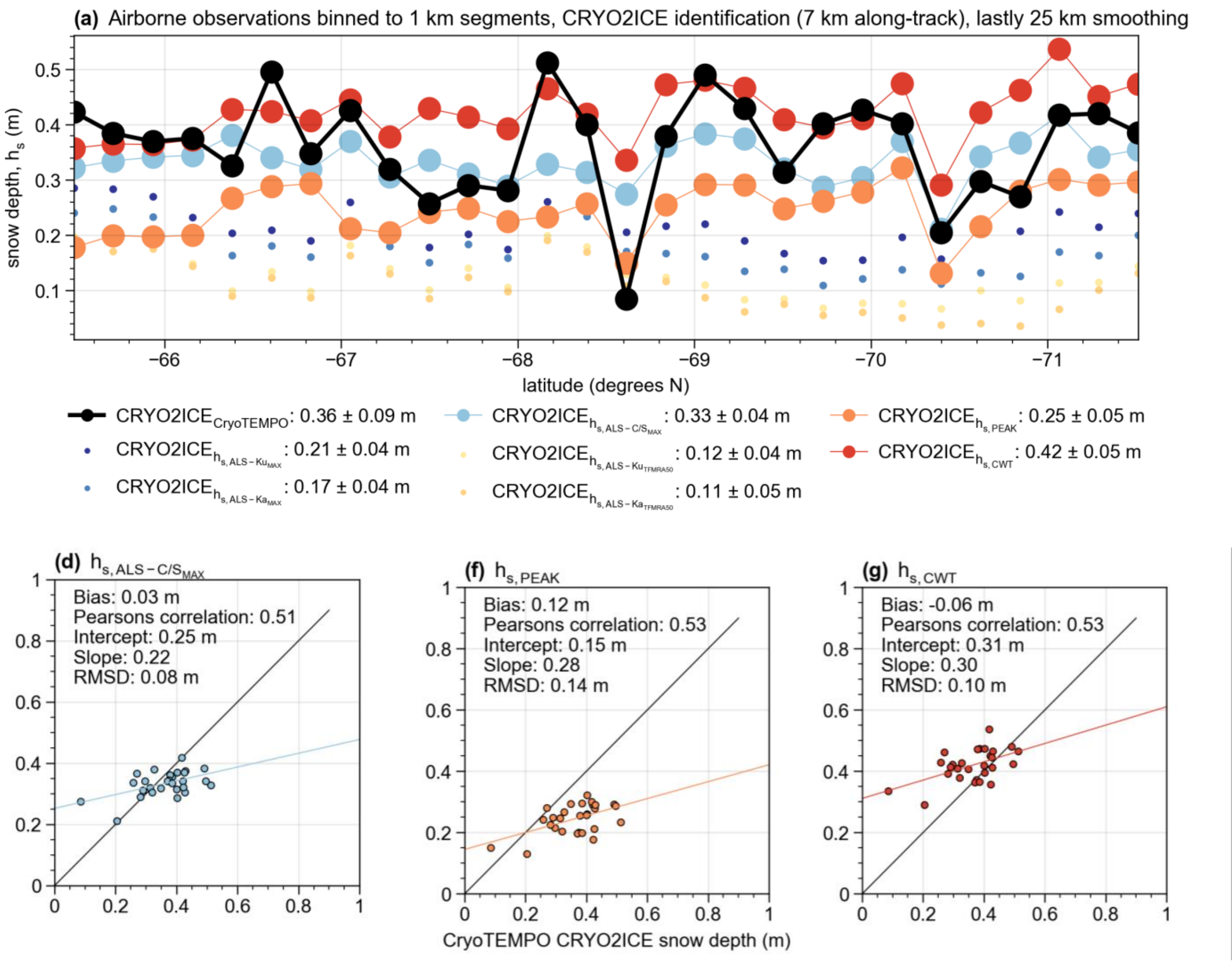


Smoothed to 25 km segments: **airborne**

- ALS-C/S MAX shows best comparison
  - Slightly higher correlation for PEAK and CWT (other combinations have worse stats)
- We need to smooth to larger scales (25 km) to reach moderate to high correlations → different mechanisms and spatial scales impacting!

How to **consolidate air- and spaceborne** observations when **dominated** by different **scattering mechanisms** due to difference in **footprints and scales**:

- Explore more data from available campaigns (different sensors, systems)
- Scattering models considering these aspects!



Thank you!

Any questions? Come find me during the Symposium, reach me at **rmfha@space.dtu.dk** or have a look at our preprint! **See here!**