Anticipating CRISTAL: An exploration of multi-frequency satellite altimeter snow depth observations over Arctic sea ice 2018-2023

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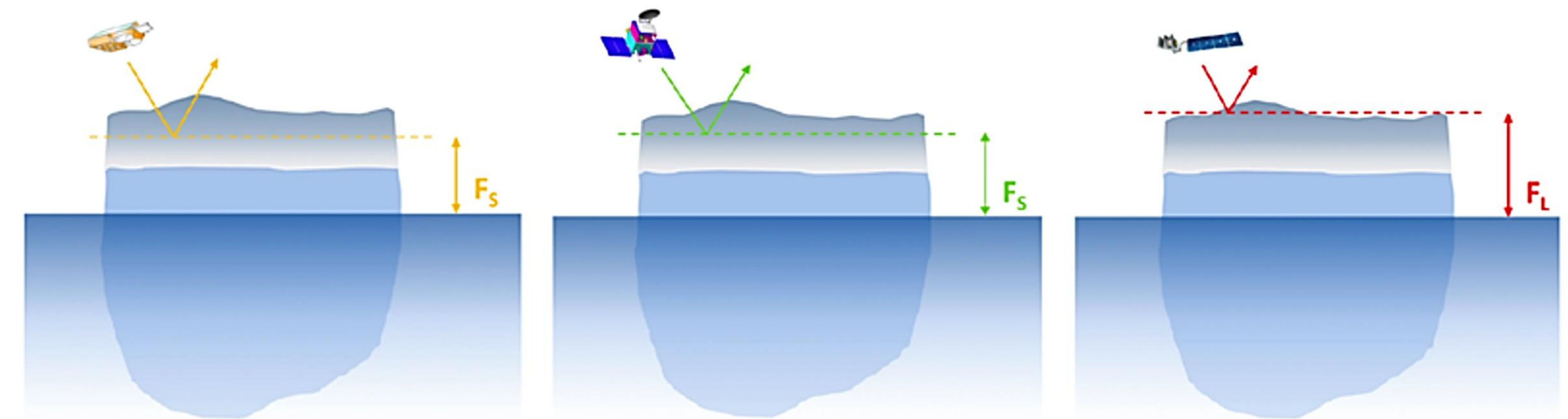
Challenge & Opportunity

- ESA plan to launch the EU Copernicus Polar Ice and Snow Topography Altimetry (**CRISTAL**) mission in 2028
- CRISTAL will carry twin Ku-band (13.5 GHz) and Ka-band (35.8 GHz) radar altimeters with an open-burst sensing mode capable of fully-focused SAR processing for 10s meters scale along-track resolution
- However, further research effort is required before we can take advantage of a primary mission objective: to measure **snow depth on sea ice** from the difference in height detected by the two frequencies
- The dominant height of radar scattering at both frequencies (Fig 1) may depend on variable snow properties such as the layering and basal salinity, and on the snow and sea ice interface roughnesses
- Here, we apply a **physical model for the backscattered radar altimeter echo** over sea ice to the ESA Ku-band CryoSat-2 mission and the ISRO/CNES Ka-band AltiKa mission as a test-bed for CRISTAL
- We compare the **radar freeboards** from CryoSat-2 and AltiKa to the **laser freeboards** measured by NASA's ICESat-2



Credit: Polar+ Snow on Sea Ice Team

Figure 1 | (Left) The CryoSat-2 radar freeboards are estimated to detect a mean scattering height somewhere between the base and centre of the snowpack, (Middle) the AltiKa radar freeboards are estimated to detect a mean scattering height somewhere between the centre and top of the snowpack, (Right) the ICESat-2 laser freeboards should measure the height of the top of the snowpack.

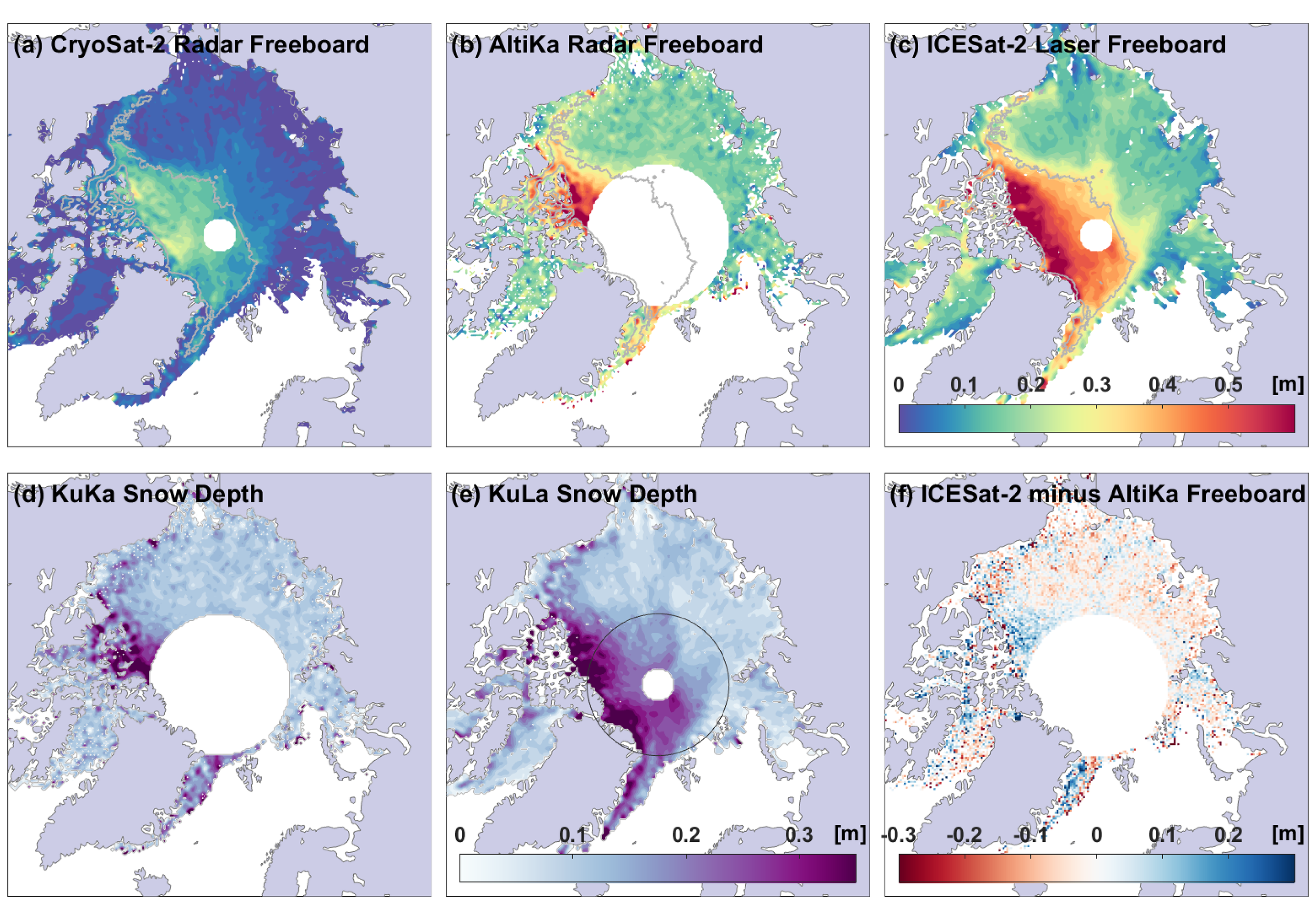


Figure 3 | Radar and laser freeboards in December 2018, and their differences.

Radar Echo Simulations

- We use the **Facet Based Echo Model (FBEM)** from Landy et al. [TGARS, 2019] to simulate the altimeter echo backscattered by rough snow or sea ice surfaces (Fig 2)
- Only a **single scattering surface** (snow or ice) is assumed, meaning that a height bias in the derived freeboards is likely associated with uncertainty in radar scattering mechanisms
- **Retracking** is performed by fitting the modelled echo to observed radar waveforms

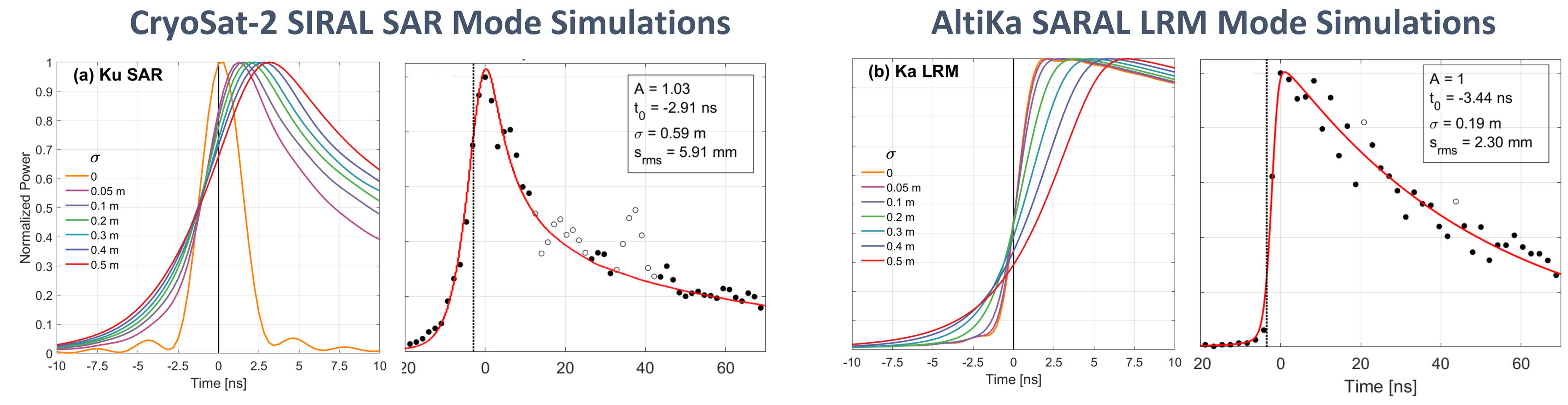


Figure 2 | Simulations of the radar altimeter echoes backscattered from sea ice surfaces with different roughness heights between 0 and 0.5 m standard deviation, alongside best-fitting model echoes for selected CryoSat-2 and AltiKa sea ice floe waveform observations.

Results

- CryoSat-2 freeboards are **significantly thinner** than both AltiKa and ICESat-2 freeboards across the entire 2018-2023 study period (Fig 3)
- Dual-frequency snow depths are estimated from the difference between AltiKa/ICESat-2 and CryoSat-2 freeboards, correcting for the delayed propagation speed of the radar in snow (Fig 3d&e)
- CRISTAL goal of <5 cm snow depth error, but **KuKa matches reference snow depths less well** (RMSE = 9 cm) than KuLa (RMSE = 7 cm) (Fig 4)
- Full snow + ice CRISTAL simulations indicate that multi-scale interface **roughnesses are more influential** on scattering than snow properties like grain size, temperature or salinity (Fig 5)

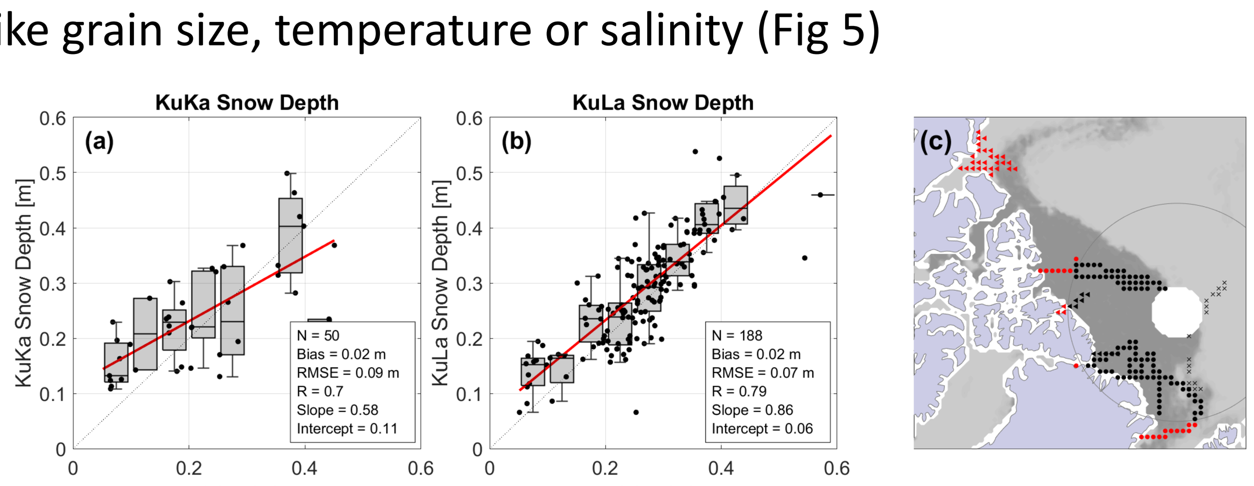


Figure 4 | Intercomparison between satellite and airborne/in situ snow depth estimates in Oct 2019-Apr 2020. (c) Red = KuKa + KuLa, Black = KuLa only.

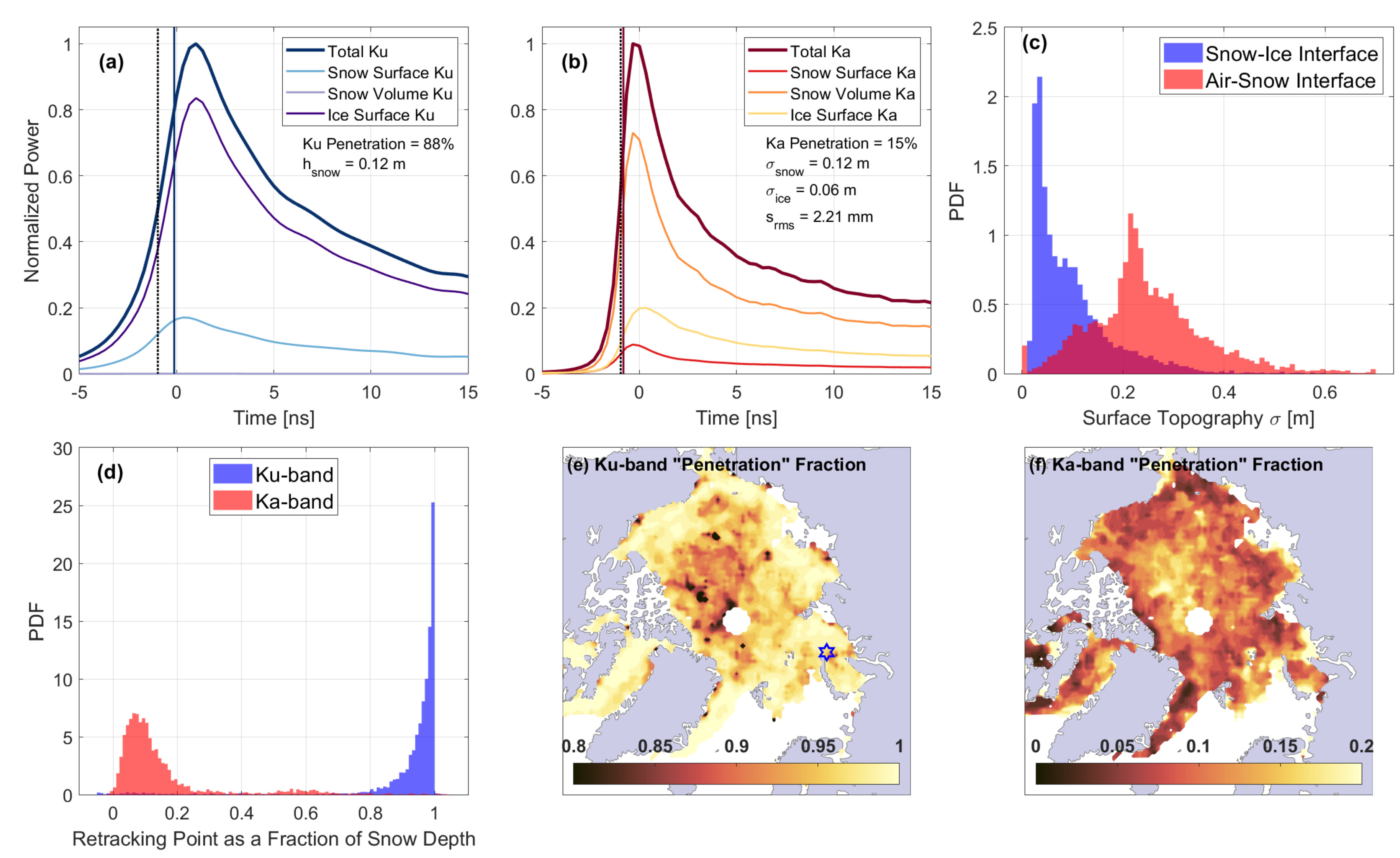


*Figure 5 | Simulated Ku- and Ka-band waveform returns from snow-covered sea ice for **CRISTAL in delay-Doppler SAR mode**, for April 2019. (a) and (b) show Ku- and Ka-band component echoes simulated for the grid cell highlighted with a blue star in (e). The air-snow interface is identified by the dotted black line, the snow-ice interface by zero time, and the retracking points of the waveforms in blue and red. (c) shows the pan-Arctic distributions of gridded snow-ice(σ_{ice}) and air-snow interface topography (σ_{snow}) for the month, as obtained from CS2 and IS2, respectively. (d) shows distributions of the expected retracking points of Ku- and Ka-band waveforms, as fractions of the snow depth. (e) and (f) show geographic variations in the "penetration" fraction of the snow depth, where 0 = air-snow interface and 1 = snow-ice interface.*

Link to Polar+ Snow on Sea Ice Website

Outlook

- Our observations support the **physical basis of the "KuKa" mission CRISTAL** to measure snow depth on sea ice
- The footprint-scale slope distribution of the snow-ice interface is **consistently smoother** than the air-snow interface (Fig 5c), which suggests that the radar return is dominated by snow-ice interface scattering at Ku-band (Fig 5a,d&e)
- Waveform simulations and AltiKa freeboards suggest that the CRISTAL Ka-band returns will comprise more **air-snow interface backscatter, and snow volume backscatter**, than snow-ice interface backscatter (Fig 5b,d&f)