CRISTAL Performance Assessment: End-to-End Simulation Approach

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CRISTAL mission

CRISTAL mission draws from the heritage experience of several in-orbit missions and from the on-going development of the Sentinel-6 and MetOp-SG programmes. It will carry a multi-frequency radar altimeter (IRIS) and a microwave radiometer to measure, and monitor sea ice thickness and overlying snow depth. It will also measure and monitor changes in the height of ice sheets and glaciers around the world. Measurements of sea-ice thickness will support maritime operations in polar oceans and, in the longer term, would help in the planning of activities in the polar regions.

CRISTAL modes

Compared with its precursor mission CryoSat-2 (CS2), CRISTAL will be monitoring the surface with enhanced modes that will allow a more precise determination of the different retrievals.

	CryoSat-2				CRISTAL			
Surface	**Mode**	**Tx. pattern**	**Rx window**	**Tracking**	**Mode**	**Tx. pattern**	**Rx window**	**Tracking**
Sea ice and icebergs	SAR	Closed Burst	60 m	[1]CL	**SARIn**	**Open Burst**	64 m	**OL** and CL
Ice sheets, interior	LRM	Closed Burst	60 m	CL	**SARIn**	Closed Burst	256 m	OL and CL
Ice sheet margins, glaciers	SARIn	Closed Burst	240 m	CL	SARIn	Closed Burst	256 m	OL and CL
Open ocean	LRM	Closed Burst	60 m	CL	**SAR RMC**	Closed Burst	**32 m**	[2]**OL**
Coastal region	SAR	Closed Burst	60 m	CL	**SAR RMC**	Closed Burst	**32 m**	**OL**
Inland waters	SAR / SARIn	Closed Burst	60 / 240 m	CL	**SAR RMC**	Closed Burst	**32 m**	**OL**

[1] Closed Loop: autonomous tracking relied on previous estimates. / [2] Open Loop: assisted tracking using a DEM

System and Instrument Retrieval Simulator GPP and simulator

SIS

The Altimeter System/Instrument Simulator (SIS) is composed by three modules:

- Scene generator, that generates the ground scene file, that defines the position and the Radar Cross Section of each simulated point target according to selected surface model.
- Field echo simulator, that generates the raw echoes gathered by the instrument according to selected timeline.
- Radar altimeter Simulator is in charge of simulating the Rx instrument chain and writing the ISP according to the selected format.

GPP

The Ground Processor Prototype for this activity has been designed within the CRISTAL Phase A/B1 and it is being implemented in Phase B2/C/D. It is composed by the following modules:

- L1A processor: in charge of performing calibrations in power, phase and range.
- Delay Doppler processor: it generates multi-looked along track geolocated and fully calibrated waveforms, coherence and interferometric phase difference.
- Fully-Focussed processor: two Fully-Focussed (FF) methods are being exploited: one in time and another in frequency domain. They generate along track geolocated, fully calibrated and fully focussed waveforms, coherence and interferometric phase difference.
- The Swath processor in charge of selecting and geolocating the swath measurements.
- The Geophysical retrieval module in charge of computing the final corrected elevation measurements.

PAT

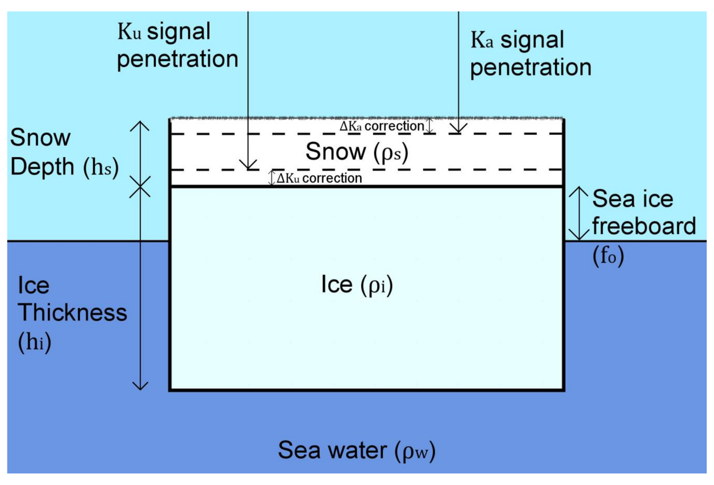
The Performance Assessment Tool (PAT) is in charge of closing the end-to-end chain. It crosschecks each of the geophysical parameters generated by the GPP against the corresponding requirement, starting from the knowledge of the simulated parameters by the SIS, assessing the data coming from the GPP, and validating the end-to-end performance chain.

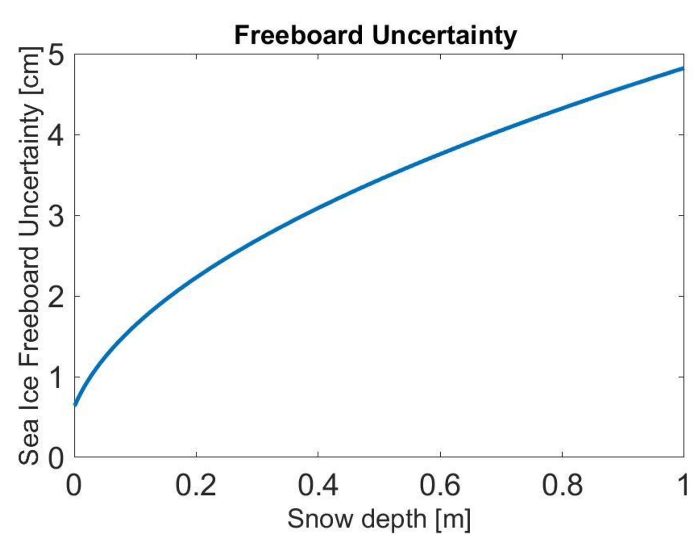
Sea ice freeboard accuracy < 3 cm

CryoSat-2 mode over sea ice is SAR Closed Burst. In contrast, CRISTAL will operate in SARIn Open Burst. The expected CRISTAL sea ice freeboard **uncertainty** can be computed as the combination of the uncertainties (σ) from the retracked sea level and sea ice measurements.

$$\sigma_r^2 = \sigma_{ret}^2 + \sigma_{iono}^2 + \sigma_{wet}^2 + \sigma_{dry}^2 \qquad \sigma_{f_s}^2 = \sigma_{r_i}^2 + \sigma_{r_s}^2 + \eta^2 r_s \left(\left| \theta - \alpha \right|^2 \sigma_\theta^2 + \theta^2 \sigma_\alpha^2 \right) + \sigma_{\delta h_s}^2$$

Freeboard and thickness budget components	Uncertainty values
(r_s) Retracked and corrected sea level range from values	2.88 cm
(q) Angle of Arrival	0.0063889 deg == 23 arcsec
Dry tropospheric correction	1 cm (1Hz)
Wet tropospheric correction	3 cm (1Hz)
Ionospheric correction	1.1 cm (1Hz)
(r_i) Retracked uncorrected sea ice range	3.3 cm (LARM), 3.9 cm (Gaussian), 4.1 cm (TFRMA70), 3.8 cm (TFRMA50)
(h_s) Snow depth	5 cm (25km) == 1.2 cm (1Hz)
(a) Across track slope	20 microradians
(r_w) Water density	0.5 kg/m³
(r_s) Snow density	60-81.6 kg/m³
(r_i) Ice density	35.7 kg/m³ FYI, 23.0 kg/m³ MYI



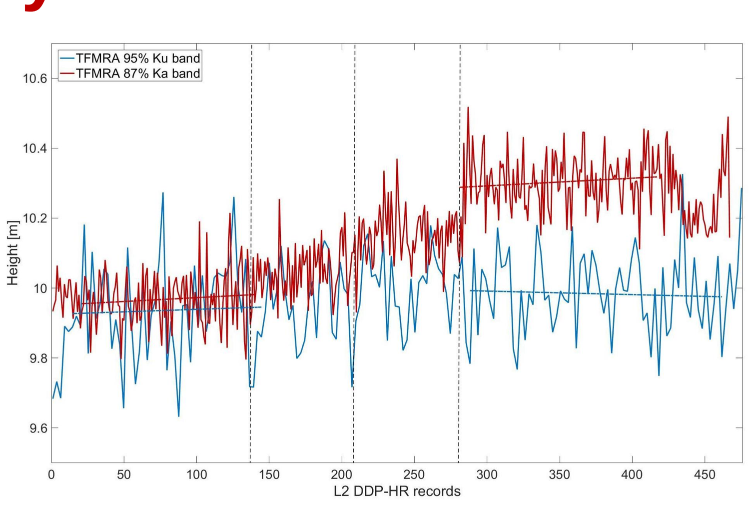


Snow depth uncertainty < 5 cm

Snow depth is calculated using the difference between Ku and Ka range, as the Ku waves penetrate the snow but reflect off ice, while the Ka waves reflect off both snow and ice. This depth is corrected for the refractive index of snow, which corresponds to a decrease in the speed of light through it.

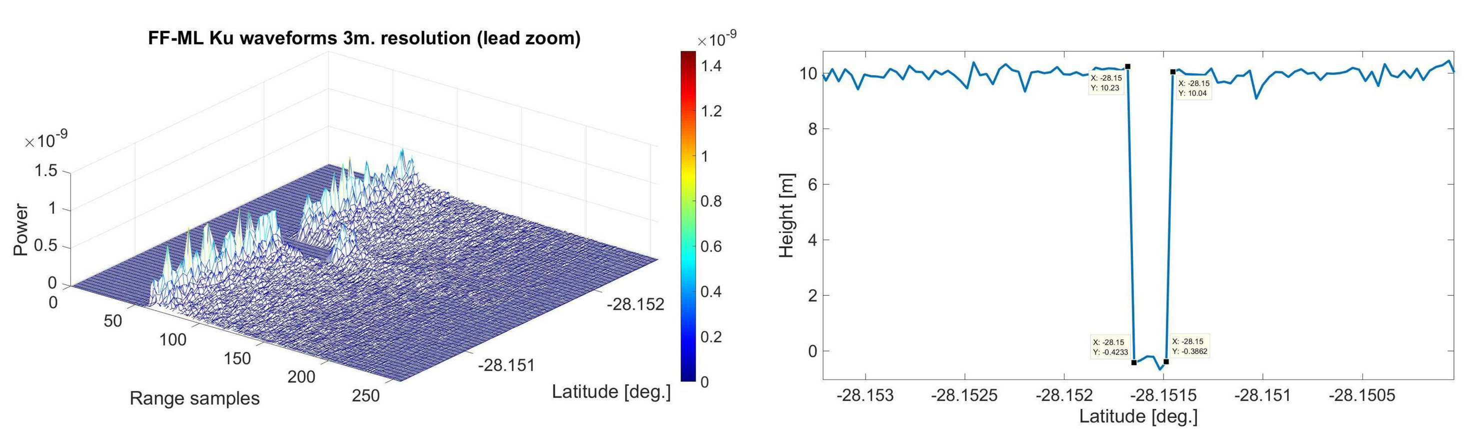
The selection of the retracker method to perform the range estimates for both Ku and Ka is a key element to retrieve the depth of snow on sea ice.

The plot shows the elevation retrievals from simulated data over different snow depth sections. At the beginning, 5 cm snow depth and at the end 50 cm snow depth with a transition zone in the middle.



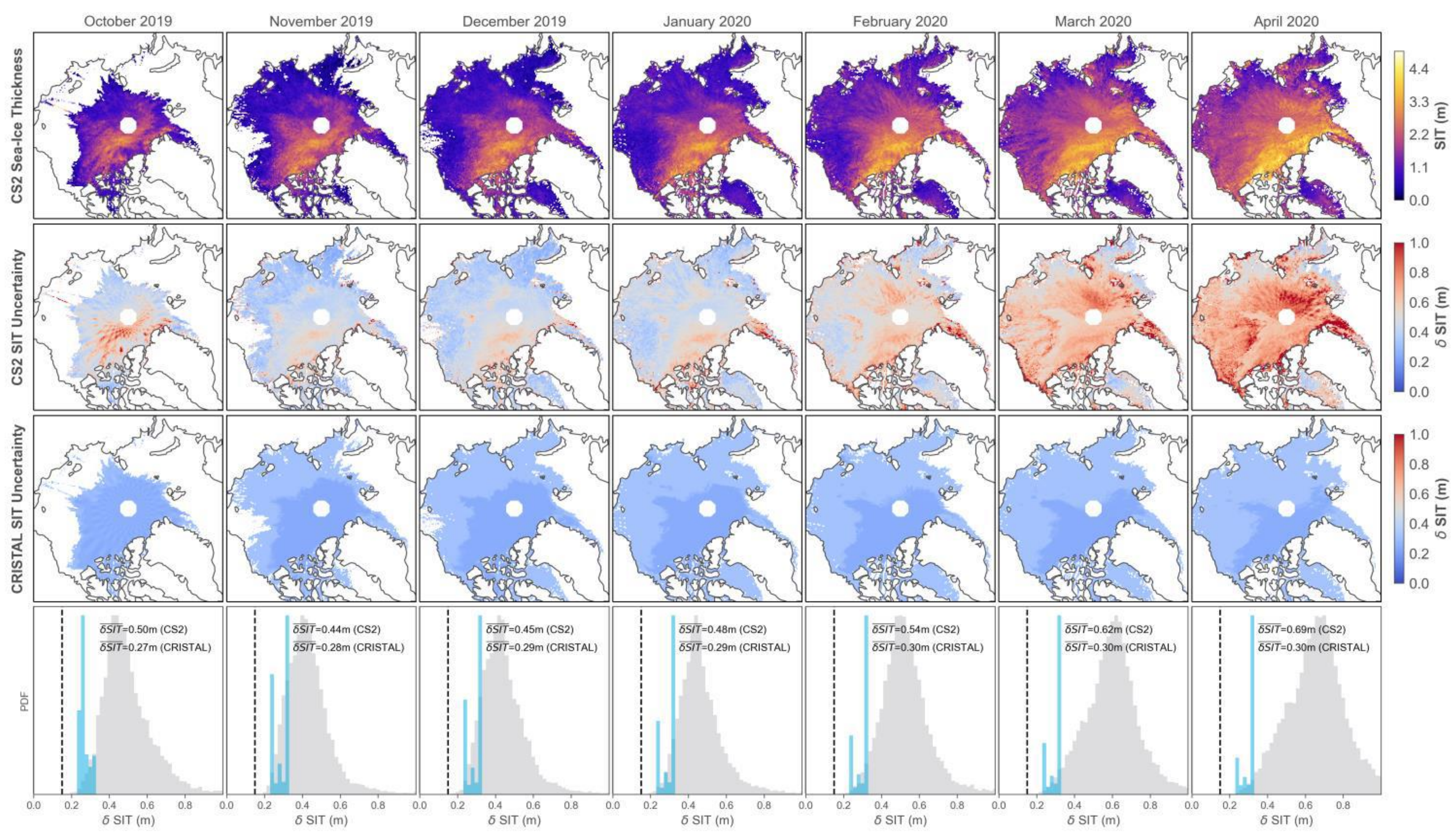
Detect leads > 10 meters

The processing will enable the generation of ML FF waveforms every 5 meters or less and the elevation of the lead is properly detected by thresholding the peakiness of the echo. The waveforms are computed by averaging SL FF waveforms generated at a finer resolution. The resolution of the SL has been chosen as a trade-off between the required noise reduction for the ML waveforms and the processing time available to generate the product.



The left plot shows the **waveforms** for sea ice simulated scenario with a lead (10 meters wide) in the middle. The **height** retrievals (*right*) for both sea ice and the lead demonstrate the capabilities when using FF-SAR waveforms.

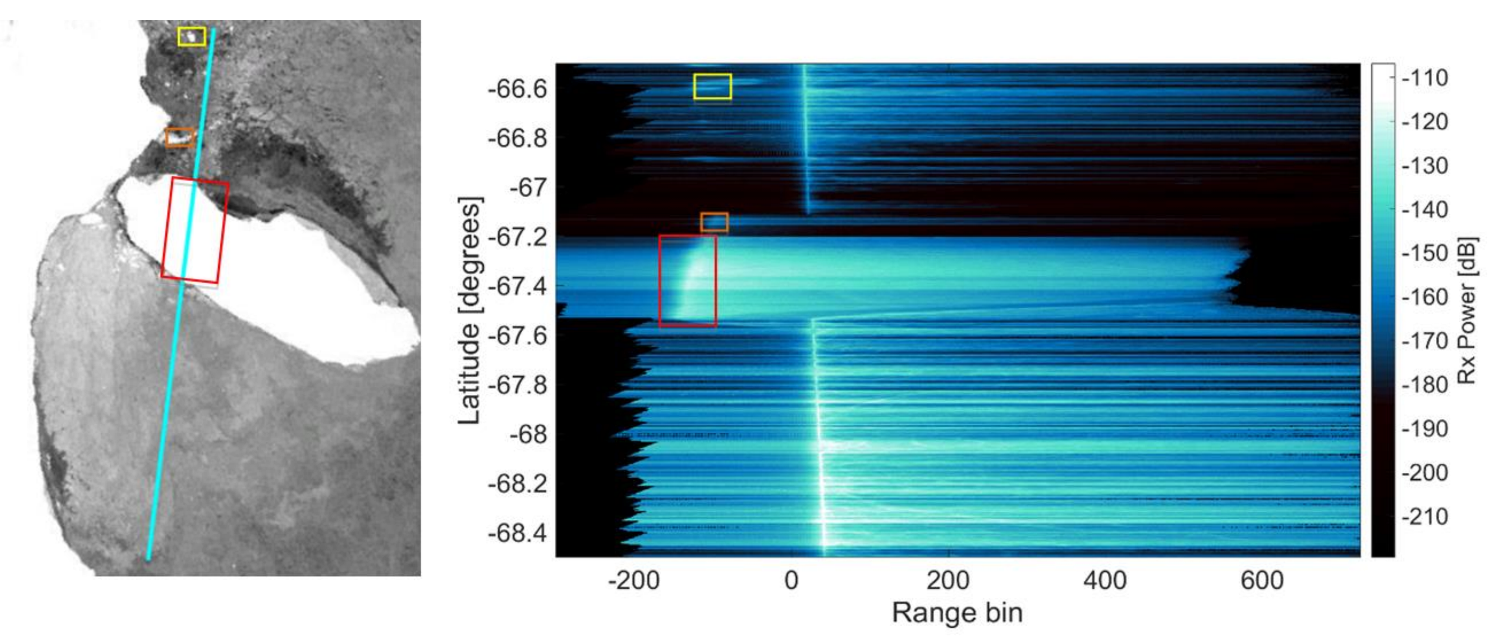
Sea ice thickness uncertainty < 0.15 m



CryoSat-2 results for first-year ice with a thickness of 2 m had an uncertainty of about 40 cm, and for multi-year ice with a thickness of 3 m had an uncertainty of about 90 cm. From CS2 results, the CRISTAL sea ice uncertainties can be also estimated considering only freeboard and snow depth uncertainties.

- CryoSat-2 Uncertainty: 0.5-0.69 m (average) all uncertainty components
- **CRISTAL Uncertainty: 0.27-0.30 m** (average) freeboard & snow depth uncertainties

Iceberg freeboard up to 25 m

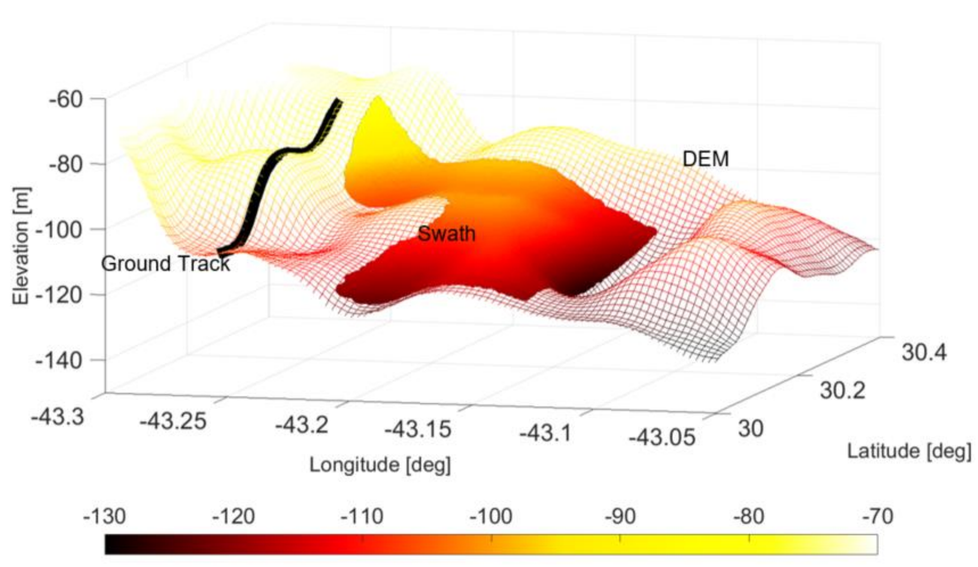


Example of CS2 L1B waveforms over **A-68 iceberg** area, Sentinel-1 image (*left*) with the CS2 ground track, everything acquired on 13 August 2018. Waveforms have been aligned between them to show their relative elevation. The squares indicate the icebergs and their echoes.

Land Ice elevation < 2 m

Swath processing output after processing simulated CRISTAL SARIn Closed Burst data over a sloped land ice surface.

Swath processing output elevations plotted over the original DEM data used by the simulator. The ground track is plotted with a black line, the DEM is plotted with the mesh grid surface (the colour of the grid represents the elevation) and the swath output is the coloured surface located in the middle (they are in fact individual bullet points very close to each other, a zoomed view would show strips of points across track). The width of each of the swath strips will depend on the coherence of the echoes which is to related with the slope of the terrain.



This poster gives an overview of the expected performances of the CRISTAL mission based on the end-to-end validation activity carried out in this project. The results presented here highlight the cryosphere related performances, although open ocean and inland water analysis are being assessed as well.