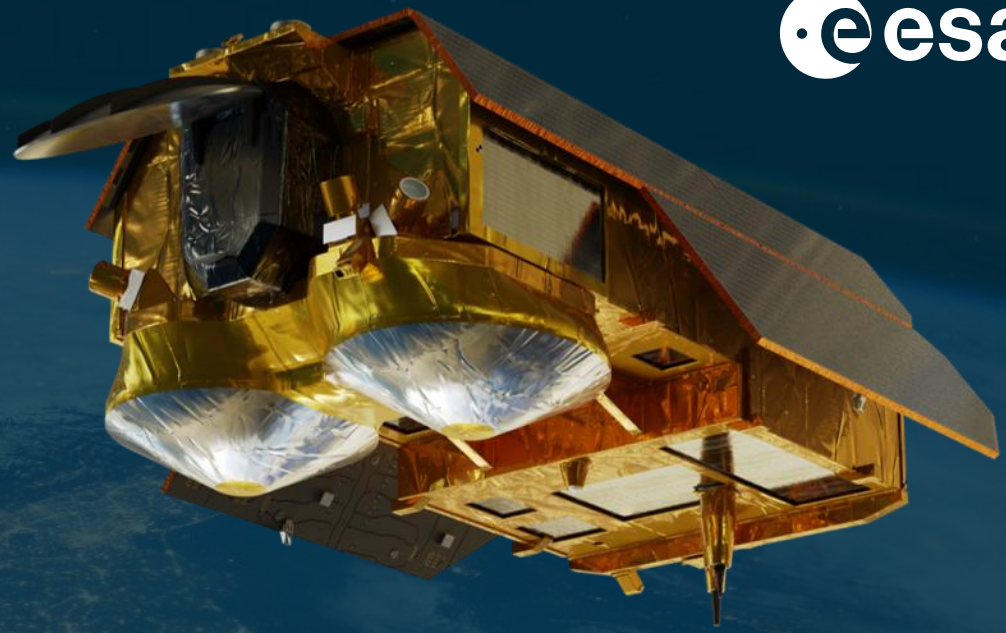


Enhancing Cryosphere Monitoring: The Copernicus CRISTAL Mission

Tânia Casal, CRISTAL campaigns coordinator
Paolo Cipollini, CRISTAL Mission Scientist

Franck Borde, Jérôme Bouffard, Filomena Catapano, Alessandro Di Bella, Kristof Gantois, Valeria Gracheva, Günther March, Michele Scagliola

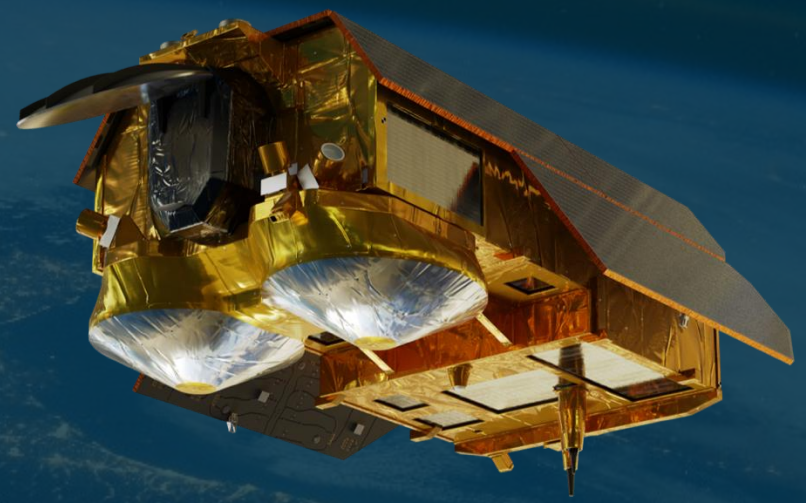
CRISTAL – the operational ice mission for Copernicus

Objectives: Monitor sea ice, icebergs, land ice, glaciers (primary), but also ocean, coasts and all inland waters

High inclination mission (92 deg), continues the legacy of CryoSat-2, with improved performance

Dual-frequency Ku/Ka SAR altimeter, Ku is interferometric

Improved bandwidth: 500 MHz in both Ku and Ka



- SARin over all ice surfaces
- Open burst over sea ice and icebergs → improved azimuth (along-track) resolution & range precision
- Flexible open loop/closed loop tracking everywhere
- AMR-CR radiometer with HRMR for oceanography, coastal altimetry, ice classification, snow parameters

Status: CDR successfully completed July 2024 – Now in Phase D, being built!
Fully on track for CRISTAL-A launch in Q3/Q4 2027
(CRISTAL-B at some point in next decade)

CRISTAL Mission – key products and requirements

- **CRISTAL performance and latency requirements**:

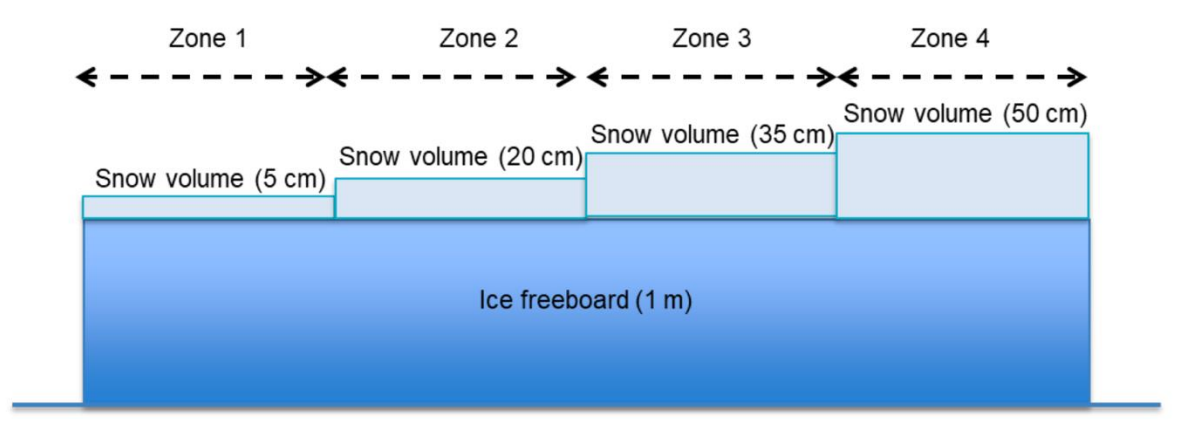
Applications / Geophysical Products	Measurement uncertainty	Latency requirements
Sea ice freeboard	**< 3 cm** (goal < 2 cm) over segments ≤ 25 km in winter	6 hours
Sea ice thickness	**< 25 cm** (goal < 15cm) over segments ≤ 25 km in winter	24 hours
Snow depth on sea ice	< 5 cm goal over segments ≤ 25 km in winter	24 hours
Land ice/glacier elevation	**< 2 m** for slopes 0.2° to 1.5° **< 0.5 m** for slopes < 0.2° values for 20-Hz	NTC (< 30 d)
Iceberg detection		24 hours
Ocean L2 products	**< 3.5 cm** for 1-Hz SSH NTC	NRT (< 3 h) STC (< 48 h) NTC (< 30 d)
Ocean L1 products		STC (< 48 h) NTC (< 30 d)

New products for **Snow depth** and **Iceberg detection**

Most Products **already validated** (CryoSat-2) and **further enhanced** with **higher accuracies.**

CRISTAL performance

End to end simulations have verified that the expected performance matches the requirements. Example:



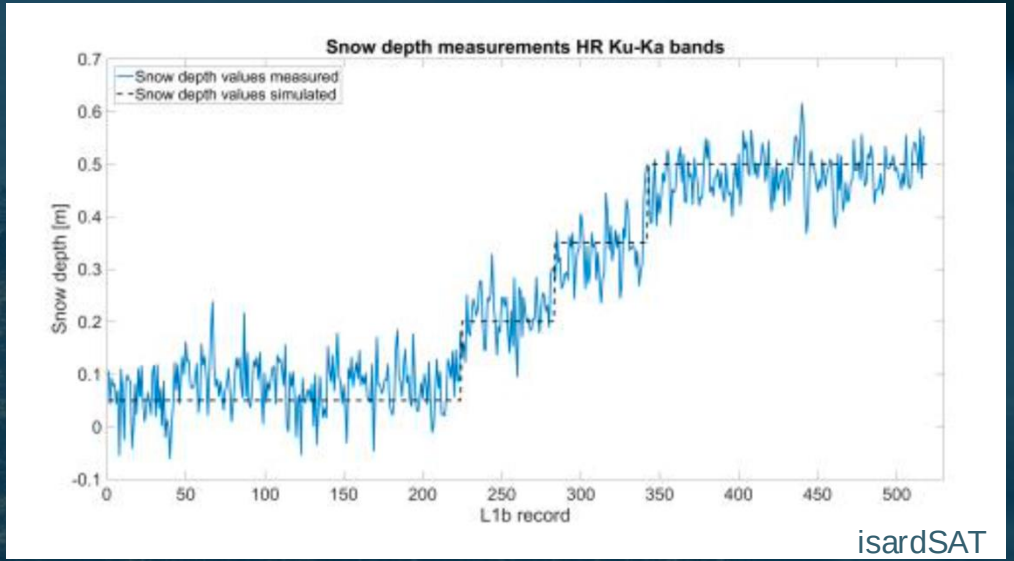


Table 3-31. Snow depth simulation results

Segment	Snow depth mean [cm]	Snow depth uncertainty [cm] (90 m / 25 km) (Goal: 5 cm)	Ku Range uncertainty [cm] (26 Hz / 1Hz)	Ka Range uncertainty [cm] (70 Hz / 1Hz)
1 (5 cm)	8.58	4.22 / 0.26	2.35 / 0.46	2.08 / 0.25
2 (20 cm)	21.40	4.47 / 0.27	2.40 / 0.47	2.69 / 0.32
3 (35 cm)	32.85	4.89 / 0.30	2.44 / 0.47	3.06 / 0.37
4 (50 cm)	47.71	4.31 / 0.26	2.25 / 0.44	3.00 / 0.36

See a full account in Garcia-Mondejar et al, next talk!

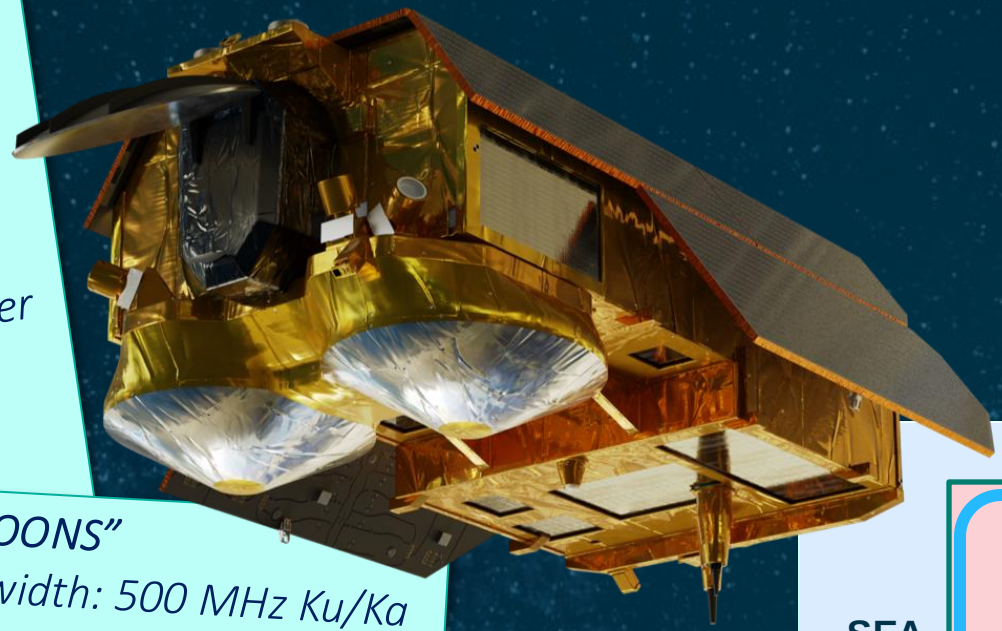
CRISTAL: innovation in the wake of CryoSat

"FIRSTS"

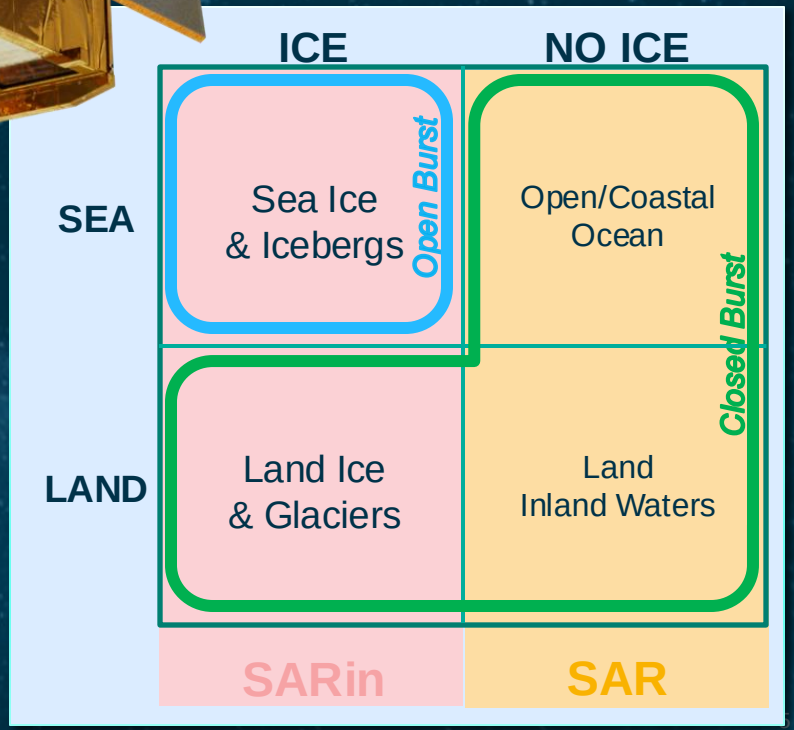
- ✓ First operational radar altimeter for the cryosphere
- ✓ First Ka-band SAR mode nadir-viewing altimeter in space
- ✓ First Ku/Ka dual-band frequency altimeter
- ✓ First combination altimeter/radiometer poleward of 82°

"BOONS"

- ✓ Increased bandwidth: 500 MHz Ku/Ka
- ✓ Interferometric in Ku
- ✓ Flexible tracking (closed/open loop)
- ✓ Open Burst over sea ice – allows Fully-Focused processing
- ✓ Full coverage of all hydrological targets

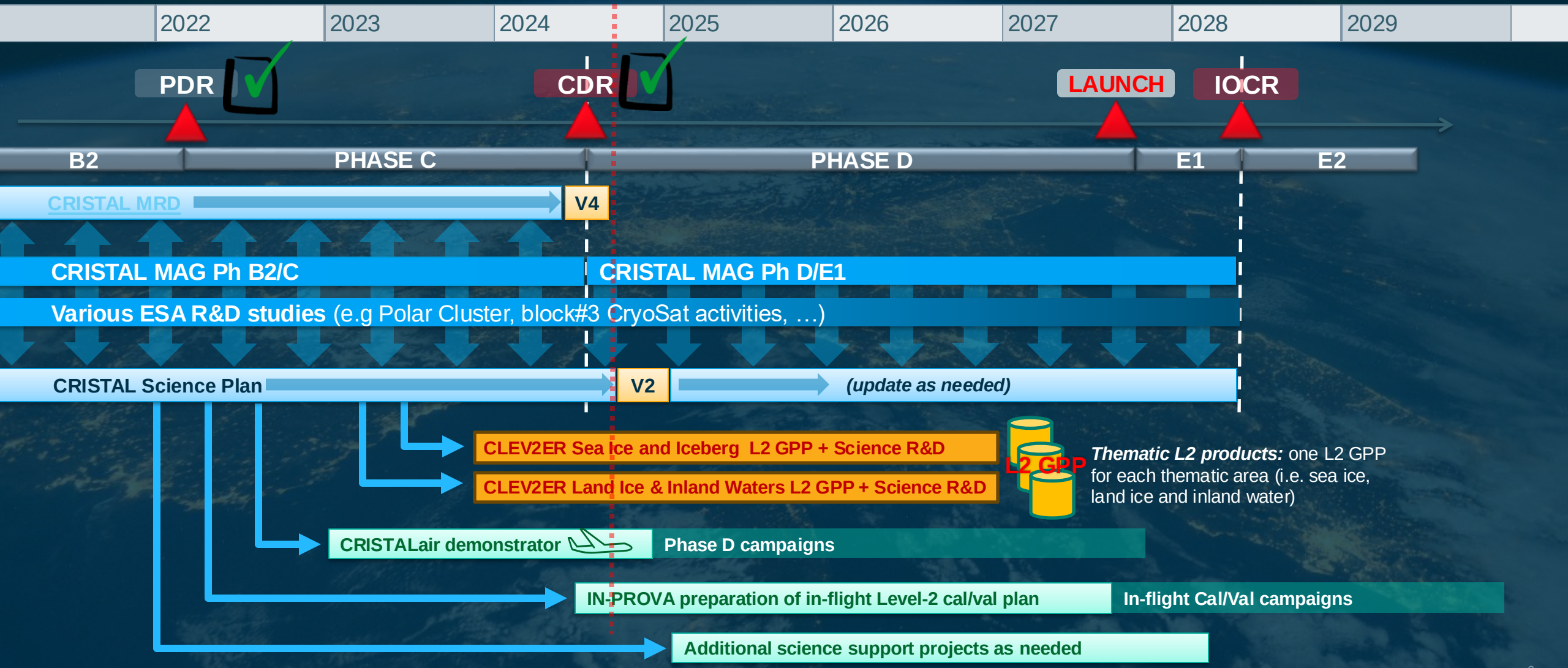


CRISTAL mode matrix



Strong CryoSat-2 heritage, but also significant innovation
→ R&D needed to fully exploit the new, improved data

CRISTAL science R&D timeline



RESEARCH & DEVELOPMENT

ON GOING ACTIVITIES

See presentations by Mal McMillan et al later this morning

Land ice

- ✓Algorithm development for the retrieval of penetration depth from dual band altimetry
- ✓Improved methods for uncertainty estimation
- ✓Assessment of the divergence of Ku and Ka echoes over ice sheet surface
- ✓Determination of an optimal mispointing for swath processing

Sea Ice

- ✓Quantifying the impact of surface conditions and snow properties and defining retracking approaches to produce multi-band freeboard and snow depth estimates:
- ✓Exploiting interferometry and FF processing for sea ice freeboard (and snow) retrieval
- ✓Adapting sea ice classification schemes to the CRISTAL configuration including FF processing
- ✓Standard and novel approaches to establishing the uncertainty budget for the geophysical variables

Inland water

- ✓Lake Ice Thickness (LIT) retrieval

R&D in the CLEV2ER projects

CAL/VAL ACTIVITIES & FRMs

CRISTAL PRE-LAUNCH CAMPAIGNS

CRISTAL is the first altimetry satellite mission operating simultaneously at both Ku and Ka frequencies to support estimate of the Snow Depth (SD), which is crucial to retrieve reliable Sea Ice Thickness (SIT).

The few existing SD processing algorithms are not yet fully mature

Studies on SD retrievals are critically lacking validation data

Campaigns are urgently needed:

- **To collect the necessary SD + SIT validation datasets**
- **To meet mission requirement at IOCR**
- **To enable a full operational exploitation of CRISTAL dual-frequency capabilities.**

The proposed campaigns will allow to:

- ✓ **build an extensive dataset** of precise and well-characterised reference measurements **(Fiducial Reference Measurements - FRMs; Goryl et al, 2023)** which is necessary to develop, test & improve retrieval algorithms
- ✓ lay the **foundations on which to build the CRISTAL post-launch cal/val activities** during and after the commissioning phase (*the relevant cal/val plan is in preparation within the IN-PROVA project*)

CRISTALair: the airborne demonstrator for CRISTAL

Interferometric Dual-Frequency Airborne Altimeter Instrument

- Interferometry in both Ku- **and** Ka-band
- 1 GHz bandwidth (sampling of full bandwidth)
- Range window: 300 m
- Altitude range: 1000 m – 4000 m (AGL)
- Currently optimized for Twin-Otter aircraft
  - We will also get it certified for Basler aircraft
- Included:
  - LIDAR (rented)
  - Colour infrared camera
  - Stabilized platform
  - Inertial Measurement Unit
  - GNSS receiver

Ready early 2025

See also the CRISTALair poster

CRISTALair proposed campaigns summary schedule

Campaign	Objectives	Time / Duration	SSP activities & Mission Obj.s
CRISTALair Functional Flight Campaign in the Arctic (includes a local/ European test ground/flight)	- Cal/sync flights - Radiometric / elevation accuracy / slope /point target response and other req verifications - Flights over corner reflectors - Antenna pointing verification - Performance evaluation over altitude - Verification of the CRISTALair Level1 ground processor	Feb 2025 / 4 days (~20 hours over 4 flights)	SP07, SP08
CRISTALair Functional Campaign add-on in the Arctic (Station Nord)	- Collocated snow measurements to validate snow depth - Drone/aircraft snow radar measurements	Feb 2025	SP03, SP07, SP08
CRISTALair for AWI	Certification of CRISTALair in AWI aircraft	TBD	
CRISTAL first Science Campaign in the Arctic (or Svalbard)	- Snow, sea/land ice measurements to develop & consolidate snow depth measurements - Characterize radar return at both frequencies - Validate snow retrievals	TBD (2025)	SP06, SP07, SP08
Copernicus Expansion Missions CIMR, CRISTAL and ROSE-L synergy campaign	Collocated measurements of CRISTALair, CIMRair, snow radar, radiometer (airborne) with ground measurements	Spring 2026	SP06, SP07, SP08
CRISTAL Science Campaign in Antarctica	Additional measurements for developing retrieval methods based on Antarctica snow conditions which differ considerably from Arctic snow	Dec 2026	SP01, SP02,SP06 SP08

First Arctic Campaign and CEMSIE

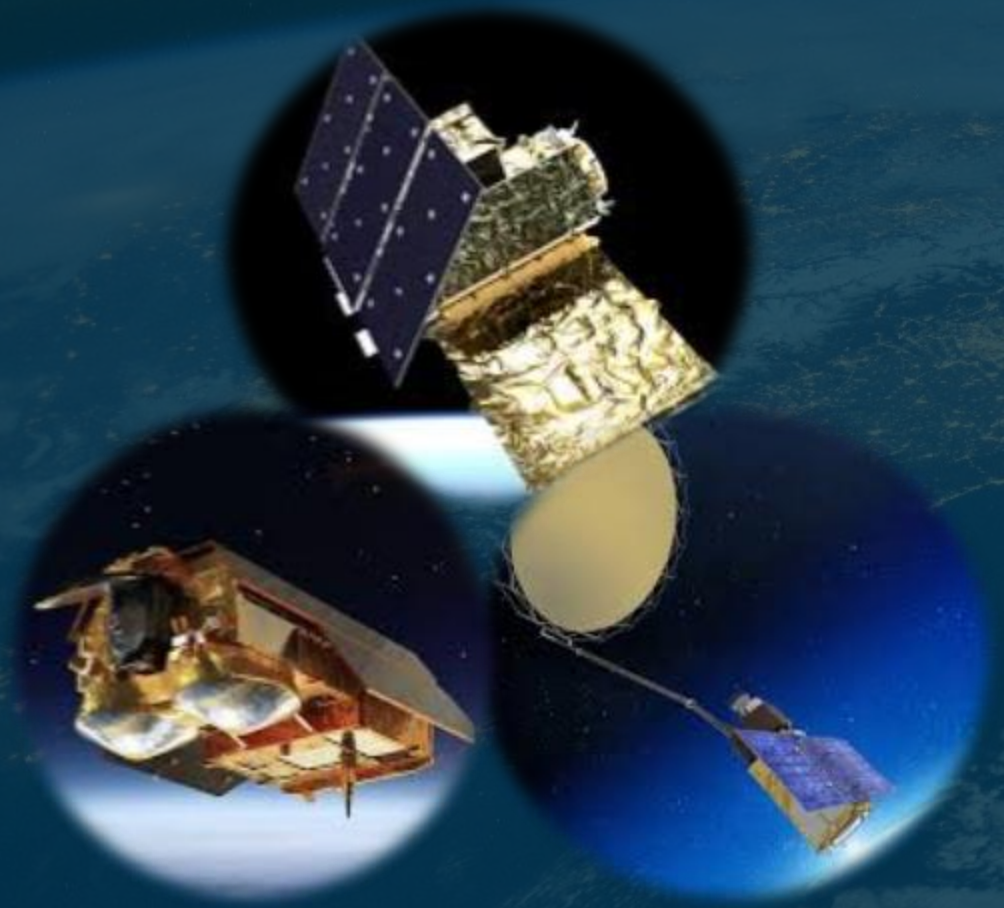
First Arctic Campaign

- Objective 1: develop and consolidate snow depth measurement retrievals
- Objective 2: verify the across-track collocation of the radar return at both frequencies
- Expected outcome: Collect sufficient airborne Ka/Ku/La + snow radar and in situ data to validate the snow retrievals
- Study how snow depth measurements vary with the spatial scale observed and snow conditions
- Place TBD <81.5° (Svalbard)? Time possibly 2025, airborne+drones+in situ

Synergy Campaign

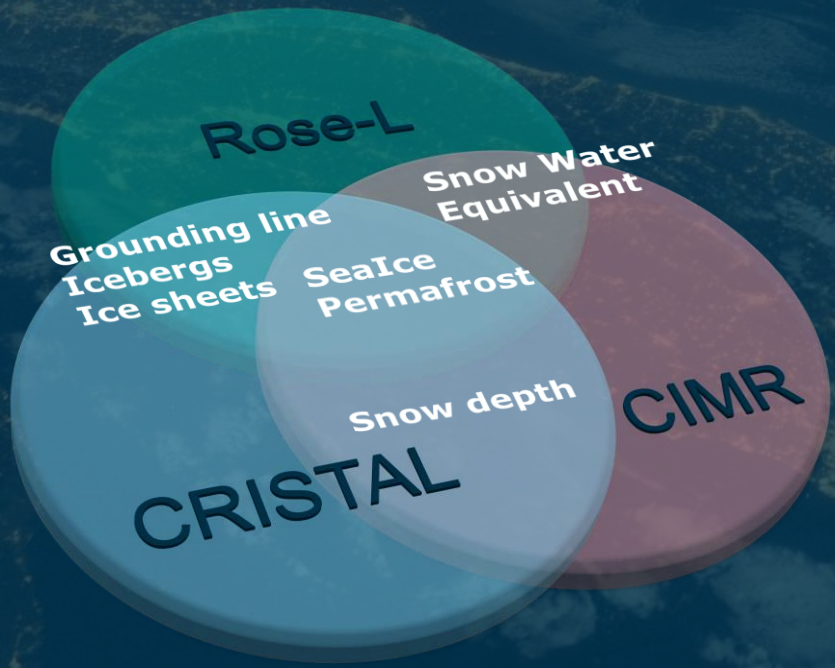
- CIMR, CRISTAL and ROSE-L Sea Ice Experiment, proposed by John Yackel (Univ. Calgary) and Rasmus Tonboe (DTU)
- To reduce uncertainties and improve retrievals for Sea Ice concentration/thickness, Snow Depth
- Cambridge Bay (First-Year Ice), Spring 2026
- Extensive set of in-situ instrumentation
- Possible NASA/JPL concurrent campaign

CRISTAL synergies



Three Copernicus Expansion missions
CIMR, CRISTAL and ROSE-L
support the implementation of the EU Arctic Policy allowing enhanced monitoring of the cryosphere

CRISTAL, ROSE-L and CIMR will operate on the same domains and will have common Mission objectives



CRISTAL, a state-of-the-art altimeter for the cryosphere

…with expected excellent performance for oceanography and hydrology too!

It is an **operational mission** → sustained (~20 years) high-quality observations in support of services

but for its innovative character it will also enable **lots of new research**!

CRISTAL video