The joint **C**opernicus **E**xpansion **M**issions CIMR, CRISTAL, ROSE-L **S**ea **I**ce **E**xperiment (CEMSIE)

Executive Summary

The **C**opernicus **E**xpansion **M**issions **S**ea **I**ce **E**xperiment (CEMSIE) is an international consortium led, multi-sensor, multi-scale remote sensing field-based campaign proposed on landfast sea ice joint with dedicated *CIMRair* and *CRISTALair* overflight campaigns scheduled for spring 2026 in Dease Strait near Cambridge Bay, NU, Canada. CEMSIE will provide a high-resolution, multi-scale dataset integrating in-situ, airborne, and satellite observations alongside coincident high spatio-temporal resolution snow and sea ice geophysical property measurements. CEMSIE builds on previous Arctic Sea ice campaigns, namely MOSAiC but shifts the focus from second-year ice to first-year ice (FYI), e.g., AKROSS and DEFIANT which increasingly dominates the Arctic Ocean. Led by Canadian and European sea ice scientists, CEMSIE will directly support the Copernicus Expansion Missions (CIMR, CRISTAL, ROSE-L) and existing Sentinel-1/-3 datasets, improving snow and ice retrieval algorithms critical for climate monitoring, numerical weather prediction, and operational forecasting.

Scientific Rationale and Objectives

Accurate satellite-based remote sensing of snow-covered FYI presents challenges due to complex snow geophysical properties that vary significantly in three dimensions across short spatio-temporal scales (decimetres to tens of metres and diurnally to seasonal) (Figure 1).

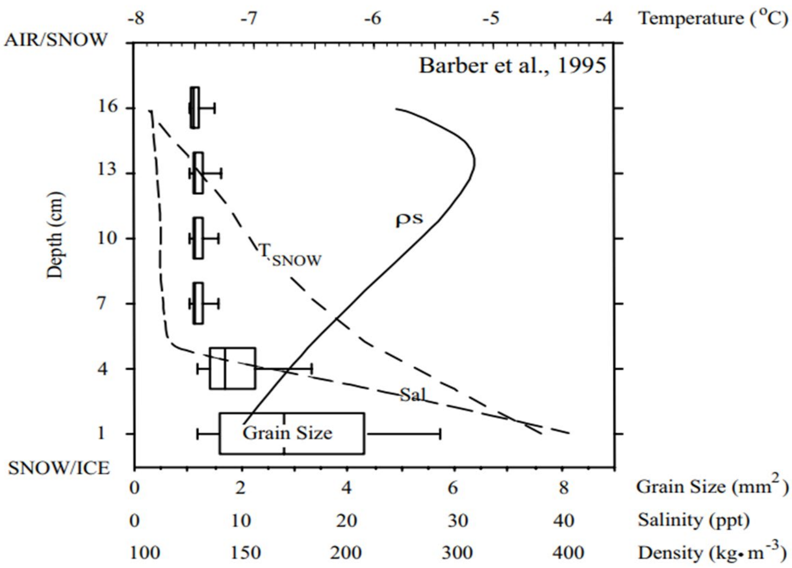

Figure 1: Cross-section of snow geophysical properties acquired from a single and typical 'snow pit' in late winter on Arctic first-year sea ice illustrating its vertical heterogeneity in snow properties.

In an Arctic pack environment, these challenges are exacerbated by numerous additional complexities described by Landy et al., 2020 (Figure 2) which make interpretation of satellite acquired EM signatures extremely challenging with large associated uncertainties (Ricker et al., 2014).

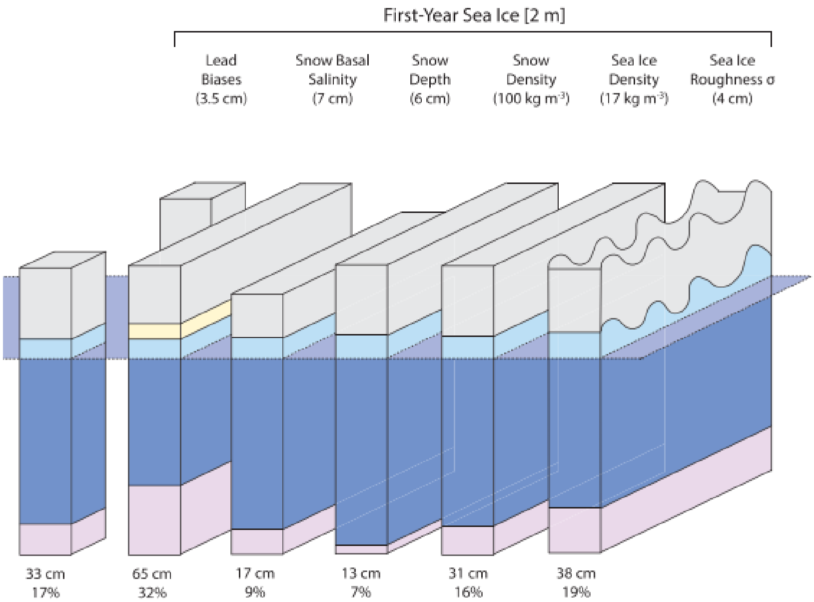

Figure 2. Schematic adapted from Landy et al., 2020 - Figure 8 illustrating the potential systematic bias in CryoSat-2-derived sea ice thickness introduced from the partial penetration of Ku-band microwaves into snow on first-year ice owing to lead detection biases, snow basal salinity, snow density, snow depth and sea ice surface roughness and sea ice density. Potential ice thickness biases are illustrated in pink for 2-metre-thick sea ice.

Landy et al., 2020 report that, over FYI, the 19% roughness uncertainty contributes more than the combined systematic errors from snow depth and density but is lower than the potential uncertainty introduced by unknown snow basal salinity. Furthermore, these properties co-evolve continuously throughout the annual cycle and the geophysical and thermodynamic interaction of these properties and processes, often largely a function of snow depth, drives strong variability in active and passive microwave signatures (Figure 3). In sum, these factors introduce systematic uncertainties in microwave emission and radar backscatter models, affecting the Copernicus CIMR, CRISTAL, and ROSE-L missions' ability to estimate snow depth and sea ice thickness accurately.

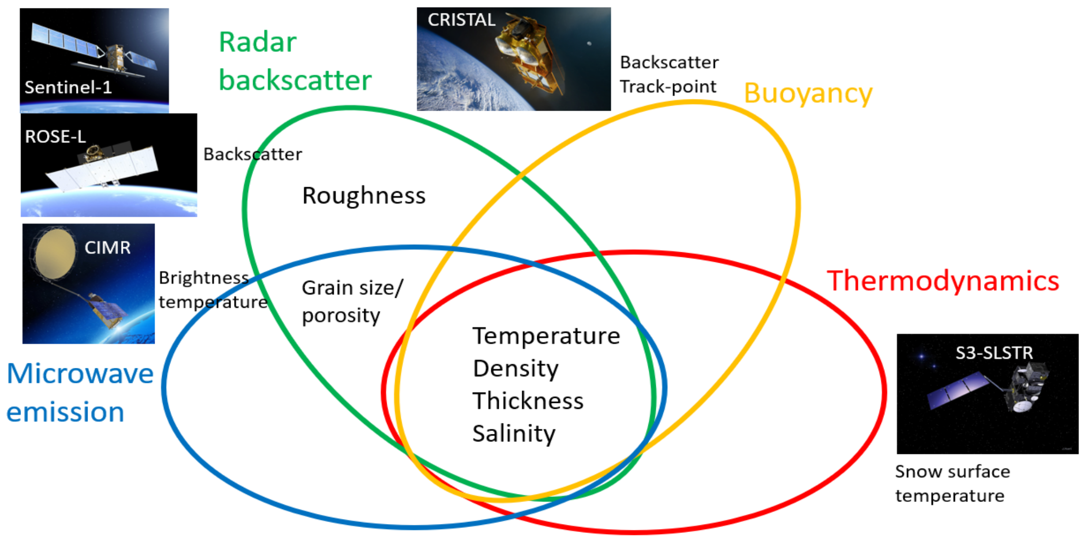

Figure 3: Overlap in snow and sea ice physical parameters affecting the microwave emission, radar backscatter, floe buoyancy and thermodynamics.

Therefore, CEMSIE will deploy in-situ and airborne EM sensors, strategically integrating CIMRair and CRISTALair airborne instruments and overflights, to systematically assess these uncertainties.

The specific objectives include:

- ➢ Reducing uncertainties in SIC, SIT, and SD estimates by systematically mapping brightness temperature, radar backscatter, and related uncertainty sources for correction.
- ➢ Advancing synergistic retrieval methods that combine infrared and microwave radiometry with radar altimetry for improved SIT and SD estimates.
- ➢ Developing forward models for satellite data assimilation into sea ice models, reducing geophysical uncertainties, and enhancing operational forecasting.
- ➢ Establishing a representative dataset in a ready-to-use 'data cube', supporting next-generation satellite-based retrieval algorithms and Copernicus Expansion Mission applications.
- ➢ Enhancing synergy between CIMR, CRISTAL, and ROSE-L and existing Sentinel missions for integrated sea ice monitoring.
- ➢ Advance assimilation techniques for Copernicus Expansion Mission datasets, improving numerical weather and climate models.

CEMSIE will address these objectives by:

- ➢ Improving multi-sensor retrieval algorithms for SIC, SD, and SIT using data from CIMR, CRISTAL, ROSE-L, Sentinel-1/-3, and supporting missions (see Figure 4, WP's 1 and 2).
- ➢ Generate a high-resolution data cube integrating in-situ, airborne, and satellite observations, ensuring compatibility with the Copernicus Expansion Mission - Product Algorithm Laboratory.
- ➢ Quantify the impact of snow geophysical and thermodynamic properties on microwave retrievals and compare results with second-year ice data from MOSAiC.
- ➢ Develop AI-based retrieval models to improve snow depth and sea ice thickness estimation from multi-sensor satellite data.
- ➢ Providing a roadmap for Copernicus and ESA operational strategies, ensuring multi-mission datasets contribute effectively to Arctic environmental monitoring.

Copernicus Expansion/ Next Generation mission and Sentinel synergies

Microwave emission and scattering is a function of complex snow/sea ice geophysical properties including temperature, microstructure, surface roughness, salinity, density and thickness as a function of frequency (Figure 4). Having coincident microwave altimeter, scatterometer, SAR and radiometer measurements of the snow and sea ice at the same time is advantageous for three reasons: 1) to understand the simultaneous scattering and emission processes, 2) building combined scattering and emission models for inversion and assimilation applications, and 3) will lead to increased confidence to the reduction of geophysical uncertainties in satellite products. It is also an advantage when deriving snow depth and sea ice thickness to have combined satellite measurements from infrared and other sensors.

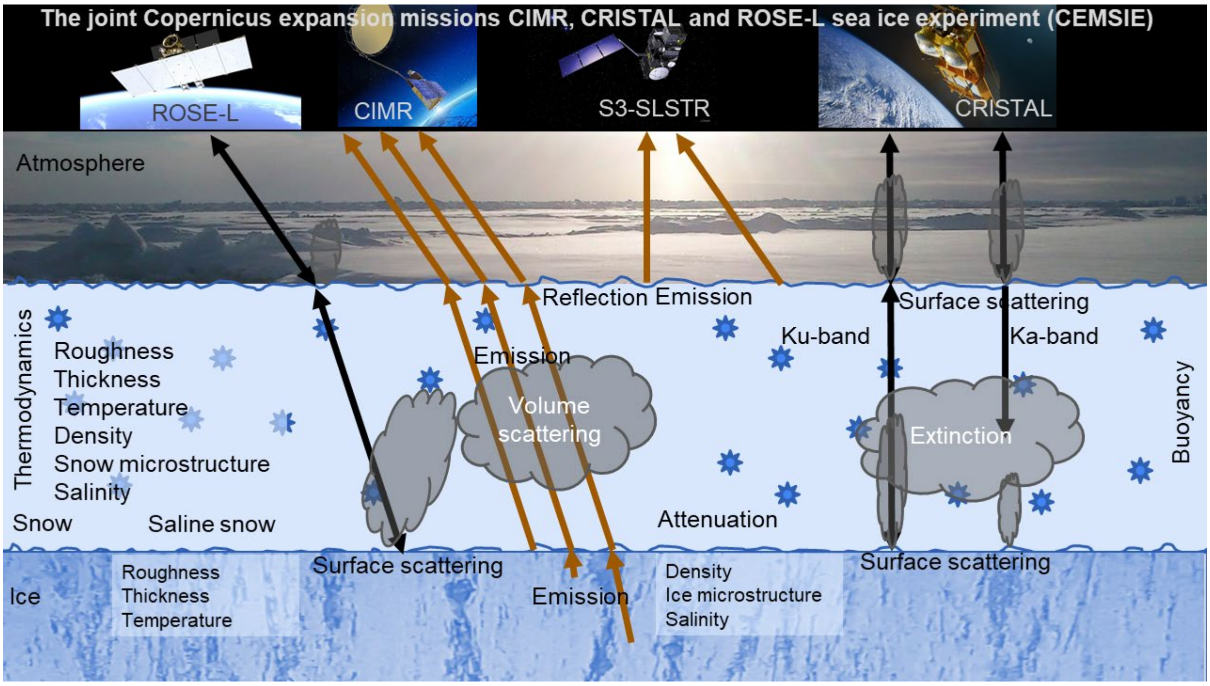

Figure 4: Conceptual figure showing the emission and scattering processes on snow-covered sea ice from ROSE-L, CIMR, CRISTAL and S3- SLSTR. By combining data from these different missions in the thermodynamic and buoyancy equation for the sea ice floe it is possible to retrieve much more information than from each of the individual sensors alone.

Work Packages and Methodology

CEMSIE is structured into four integrated work packages (WPs) to maximize scientific impact and ensure effective and efficient data acquisition and utilization:

WP1: Field Campaign and Data Collection

- ➢ Surface-based, multi-frequency radar/altimeter/scatterometer/radiometer measurements with coincident snow/sea ice geophysical data collection focussing on snow depth, microstructure, salinity, density, roughness, and ice thickness.
- ➢ Airborne surveys using CRISTALair and CIMRair simulators will provide high-resolution spatial measurements, upscaling field-scale data to satellite observations.
- ➢ Satellite synergy combining CIMR, CRISTAL, ROSE-L, Sentinel-1 SAR, Sentinel-3 SLSTR, and supporting missions (RCM, SWOT, SMAP, AMSR-3, CryoSat-2) to enhance sea ice parameter retrievals.

The organization of in-situ measurements will be similar to that of Remote Sensing City during MOSAiC (Nicolaus et al., 2022) (Figure 5). However, our campaign will be based on landfast FYI in Dease Strait, Nunavut, Canada. This has several advantages, which we outline below.

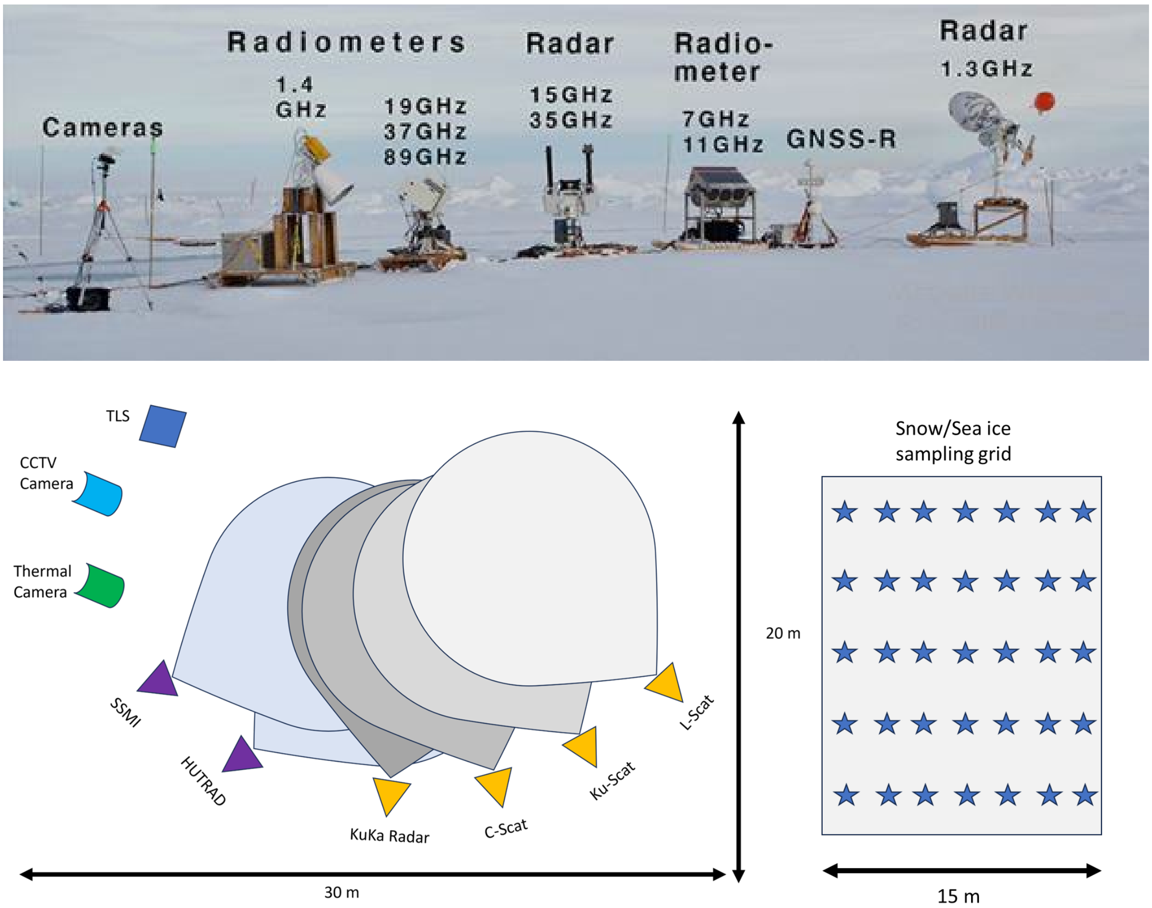

Figure 5: On-ice sampling site setup for in-situ remote sensing and snow/sea ice geophysical measurements. Top image is from MOSAiC Leg 3 Remote Sensing City (Nicolaus et al., 2022).

The landfast nature of the experimental field campaign (Figure 6) offers significant advantages towards minimizing confounding factors that impact the interplay of snow and sea ice geophysical properties and variable and constantly changing surface roughness influencing radar altimeter waveforms, microwave backscatter, and brightness temperature.

1. The stationary, thick ice allows for safe, extended fieldwork, including throughout the diurnal cycle during the spring transition period. This enables the collection of a comprehensive, high-quality dataset on surface and airborne EM properties, as well as snow and sea ice characteristics (e.g., snow depth, grain size, salinity, layering, sea ice roughness, and dielectrics). In particular, such ice is ideal for studying the bounds of mm-cm radar scale roughness of snow and ice interfaces and the external factors controlling these roughness variations in time and space (Landy et al., 2024)

2. It supports time series analysis of snow and sea ice thermodynamic processes, aligned with surface, airborne (CIMRair, CRISTALair, and drone-based sensors), and satellite data. Since the snow-ice system evolves under consistent atmospheric conditions from winter to late spring, the ice remains stationary and unaffected by spatially variable weather systems or differing solar radiation at different latitudes.

Such stationary ice also facilitates 'repeat-pass' airborne and drone flights throughout the field campaign as atmospheric forcing changes (i.e., it warms up). Smooth FYI will be selected for on-ice sampling setup (Figure 3) so that temporally evolving snow properties and thermodynamically induced changes in basal brine layer snow dielectrics is isolated in a manner free of scattering effects from heterogeneously distributed macroscale surface roughness and/or deformed ice features. Distributed sampling will take place over 'rougher' sea ice locations tens to several hundred km away via helicopter and/or twin otter such that the macroscale surface roughness can be evaluated (Landy et al., 2020) towards thicker snow accumulation measurement.

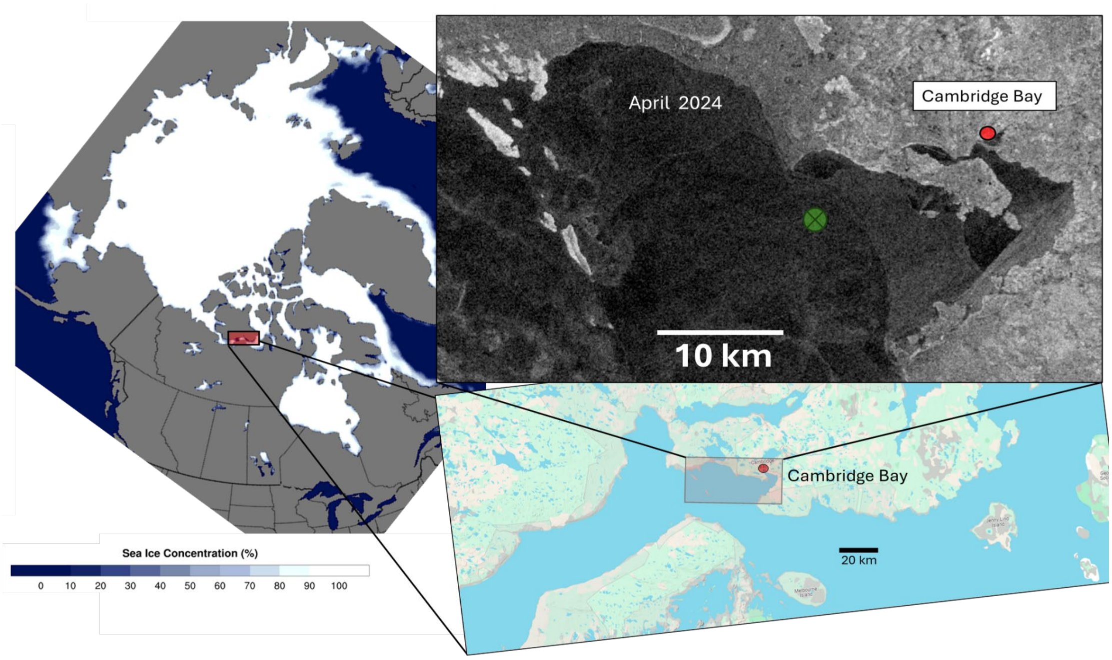

Figure 6: Sentinel-1 SAR image typical of landfast first-year sea ice roughness conditions in Dease Strait, Nunavut, Canada acquired in April 2024. Dark regions correspond to smooth FYI while brighter regions represent rougher sea ice. Green circle represents the approximate on-ice experiment site location. Note that rougher sea ice is commonly found throughout the Strait with typical snow thickness averaging between the range of 5 (smooth ice) and 35 (rougher ice) cm (see Figure 1 in Saha et al., 2025 for visual examples of ice roughness)

WP2: Data Processing and Integration

The surface-based, airborne and proxy satellite measurements from e.g., CryoSat-2, Alti-Ka, AMSR-2, SWOT, Sentinel-1A,1C and 1D, NISAR, ALOS-2, ALOS-4 and/or Sentinel-3 among others, simulating the three expansion missions (CIMR, CRISTAL, ROSE-L) will be combined to develop a "ready to use" properly curated and validated **Reference Open Dataset** for the scientific community for further science and developments in this domain and in CEMSIE. Data processing and integration efforts will include:

- Development of a multi-sensor data cube, merging in-situ, airborne, and satellite observations for improved retrieval accuracy.
- Implementation of advanced data fusion techniques, ensuring compatibility with the Copernicus Expansion Mission - Product Algorithm Laboratory.

WP3: Scientific Analysis, Modelling and Algorithm Development

Demonstrate the synergistic use of CIMR, CRISTAL and ROSE-L Copernicus Expansion Missions in models and algorithms to fully exploit the complementary information, and the synergistic capacity offered by the three missions.

- ➢ Application of physical and AI-based models to improve SIC, SD, and SIT retrieval algorithms.
- ➢ Development of forward operators to enhance microwave emission and scattering models for assimilation into climate models.

WP4: Operational Applications and Roadmap Development

- ➢ Testing retrieval algorithms in operational ice models, evaluating their impact on climate simulations and Arctic Sea ice forecasting through collaboration will SUP-1 projects focusing on Arctic Operations through proactive involvement of stakeholders and end-users throughout the co-design, development, and validation phases of application development.
- ➢ Support Arctic ice services monitoring goals, contributing to sea ice hazard forecasting through collaboration will SUP-1 projects focusing on consolidation of representative datasets
- ➢ Providing recommendations for future ESA and Copernicus mission planning.

Key Outcomes and Impact

CEMSIE will produce a **high-value <u>Reference Open Dataset</u> and scientific outputs** that will address the ESA objectives within the call:

1. Improve snow depth and sea ice thickness retrievals by integrating surface- to satellite-scale active and passive remote sensing measurements, reducing uncertainties in Arctic climate monitoring and enhancing the accuracy of multi-mission retrieval models, including AI-based approaches.
2. Enhance numerical weather prediction and climate models by investigating the interplay between snow and ice thickness, including in sea ice deformation zones, and incorporating these relationships into combined emission and scattering models for improved Arctic weather and ice forecasts.
3. Advance Copernicus multi-mission data assimilation by addressing long-standing challenges in sea ice remote sensing. The project will collect critical datasets to develop and improve forward operators, which currently have severe limitations in simulating multi-sensor data over sea ice.
4. Quantify the role of snow salinity and other snow geophysical properties over FYI and assess its impact on microwave estimates relevant to the three Copernicus Expansion Missions. Results will be compared with the second-year ice floe remote sensing experiment from MOSAIC to refine retrieval techniques.
5. Assess snow and ice thickness, including deformed ice, to quantify and evaluate the impact of seasonal freshwater fluxes in the Arctic, improving its representation in climate models and better constraining Arctic freshwater budgets.

6. Develop innovative merging strategies to fully exploit the synergy between presently operational and forthcoming multi-observation missions, producing the next generation of multi-mission retrievals of surface processes and sea ice parameters for Copernicus missions CRISTAL, CIMR, and ROSE-L.
7. Establish methodologies and best-practice for handling multi-scale observations, ensuring consistency across on-ice, airborne, and satellite measurements. This includes estimating uncertainties related to upscaling and downscaling, critical for operational readiness in ESA and CSA missions.

Tentative Budget (Total Budget: 800,000 Euros)

Item	Estimate
Science Plan and Scientific Road Map Reports	20,000
CRISTALair and CIMRair campaigns	525,000 (~ 66% of total budget)
Field Expenses (Instrumentation shipping, logistics, accommodation, travel)	90,000
Data Processing (field, airborne and satellites)	90,000
Algorithm Development	75,000
Total	**800,000 Euros**