St3TART-FO
FRM for Sentinel-3 Land Altimetry

St3TART-FOLLOW-ON: FIDUCIAL REFERENCE MEASUREMENTS (FRM) - S3 LAND ALTIMETRY

Sea Ice FRM provision roadmap (TD-08_5), v1.1

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St3TART-FOLLOW-ON: FIDUCIAL REFERENCE MEASUREMENTS (FRM) - S3 LAND ALTIMETRY Sea Ice FRM provision roadmap (TD-08_5), v1.1			
Issue	**Revision**	**Date**	**Reason for the revision**
1	0	26/11/2024	Initial version
1	1	09/12/2024	Updated version for SPR following ESA feedback received on 04/12/2024

Modification status				
Issue	Rev	Status *	Modified pages	Reason for the modification
1	1	D, I	Subsection 5.3.2	Content on cruises in subsection 5.3.2 was outdated, it has been updated accordingly.

* *I = Inserted* *D = Deleted* *M = Modified*

Acronyms

AEM	Airborne ElectroMagnetic
ALS	Airborne Laser Scanner
AO	Announcement of Opportunity
API	Application Programming Interface
AWI	Alfred Wegener Institute
AWS	Automatic Weather Stations
Cal/Val	Calibration/Validation
CCI	Climate Change Initiative
CCR	Contract Close-out Review
CLS	Collecte Localisation Satellites
CIMR	Copernicus Imaging Microwave Radiometer
CO	Contract Officer
CRISTAL	Copernicus polaR Ice and Snow Topography ALtimeter
CS-2	CryoSat-2 mission
CSV	Comma-Separated Values
DOI	Digital Object Identifier
DSM	Digital Surface Models
DTU	Denmark's Technical University
EASE	Equal Area Scalable Earth
EEA	European Environmental Agency
eLTER	European Long-Term Ecosystem Research
EO	Earth Observation
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAQ	Frequently Asked Questions
FF	Fully Focused

FFP	Firm Fixed Price
FO	Follow On
FR	Final Review
FRM	Fiducial Reference Measurement
FRM-CC	FRM Collaborative Campaign
GCOS	Global Climate Observing System
GCP	Ground Control Point
GeoJSON	Geographic JavaScript Object Notation
GIS	Geographic Information System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GRDC	Global Runoff Data Center
IMBIE	Ice sheet Mass Balance Intercomparison Exercise
IPS	Ice Profiling Sonar
ITT	Invitation To Tender
KO	Kick Off
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (literally : Laboratory of Space Geophysical and Oceanographic Studies)
LiDAR	Light Detection And Ranging
LOCEAN	Laboratoire d'Océanographie et du Climat: Expérimentations et Approches Numériques (literally : Laboratory of Oceanography and Climate: Experimentations and Numerical Approaches)
MoM	Minutes of Meeting
MPC	Mission Performance Cluster
NetCDF	Network Common Data Form
NORCE	Norwegian Research Center
NSIDC	National Snow and Ice Data Center
NPI	Norwegian Polar Institute
OLCI	Ocean and Land Colour Instrument

ORR	Operation Readiness Review
OZCAR	Observatoires de la Zone Critique, Applications et Recherches (literally: Critical Zone Observatories, Applications and Research)
PM	Progress Meeting
POCA	Point of Closest Approach
PPP	Precise Point Positioning
PR	Progress Review
PVR	Product Validation Report
QA4EO	Quality Assurance framework for Earth Observation
QGIS	Quantum Geographic Information System
QWG	Quality Working Group
RB	Requirements Baseline
REMA	Reference Elevation Model of Antarctica
S3	Sentinel-3
S3VT	Sentinel-3 Validation Team
SAR	Synthetic Aperture Radar
SBLA	Single Point Laser Altimeter
ScalSIT	Super Cal/Val Site Identifier Tool
SfM	Structure-from-Motion
SI	Système International d’unités (literally: International System of Units)
SIMS	Sea Ice Measurement System
SIN’XS	Sea Ice thickness product intercomparison exercise
SLSTR	Sea and Land Surface Temperature Radiometer
SMB	Surface Mass Balance
SNO-GLACIOCLIM	Service National d'Observation GLACIOlogique et CLIMatologique des régions de montagne (literally: National Glaciological and Climatological Observation Service for Mountain Regions)
SoW	Statement of Work
SPR	Set-up Phase Review
SWOT	Surface Water and Ocean Topography

St3TART	Sentinel-3 Topography mission Assessment through Reference Techniques (contract between 2021 and 2023)
St3TART-FO	St3TART Follow-On
STM	Surface Topography Mission
TBD	To Be Defined
TDP	Thematic Data Products
TO	Technical Officer
UAV	Unmanned Aerial Vehicles
UN	UNfocused
WP	Work Package

N°	Reference	Title
[RD1]	ESA- EOPG-EOPGMQ-SOW-80, Issue 1 Rev. 0 – 24/11/2023	Statement of Work - Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)
[RD2]	NOV-FE-1464-PR-004	Detailed Proposal
[RD3]	ESA Contract No. 4000144565/24/I-KE	ESA Contract – H2.2/2023/001 - FIDUCIAL REFERENCE MEASUREMENTS (FRM) - S3 LAND ALTIMETRY ST3TART (FOLLOW-ON)
[RD4]	NOV-FE-0899-NT-091	Sea Ice FRM compliancy Matrix
[RD5]	Da Silva, Elodie, Emma R. Woolliams, Nicolas Picot, Jean-Christophe Poisson, Henriette Skourup, Geir Moholdt, Sara Fleury, Sajedeh Behnia, Vincent Favier, Laurent Arnaud, and et al. 2023. "Towards Operational Fiducial Reference Measurement (FRM) Data for the Calibration and Validation of the Sentinel-3 Surface Topography Mission over Inland Waters, Sea Ice, and Land Ice" Remote Sensing 15, no. 19: 4826. https://doi.org/10.3390/rs15194826	
[RD6]	Isobel R. Lawrence, Thomas W.K. Armitage, Michel C. Tsamados, Julienne C. Stroeve, Salvatore Dinardo, Andy L. Ridout, Alan Muir, Rachel L. Tilling, Andrew Shepherd, 2021. Extending the Arctic sea ice freeboard and sea level record with the Sentinel-3 radar altimeters, Advances in Space Research, no 68-2, https://doi.org/10.1016/j.asr.2019.10.011.	
[RD7]	NOV-FE-0899-NT-042	FRM Protocols and Procedure for S3 STM Inland Water Products, NOV-FE-0899-NT-042, Issue 3.2, 2023, St3TART TD1
[RD8]	NOV-FE-0899-NT-043	FRM Protocols and Procedure for S3 STM Sea Ice Products, NOV-FE-0899-NT-043, Issue 4.1, 2023, St3TART TD2
[RD9]	NOV-FE-0899-NT-070	FRM Campaign log – Sea-Ice campaign in Upernavik and Qaarsut (Greenland), NOV-FE-0899-NT-070, Issue 1.0, 2023, St3TART TD12-2
[RD10]	NOV-FE-0899-NT-102	FRM Campaign Final Report – Sea-Ice, NOV-FE-0899-NT-102, Issue 2.1, 2023, St3TART TD13-2

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1. Introduction

1.1. Purpose and scope

This document is the Sea Ice FRM provision roadmap, initially developed for the St3TART project (2021 – 2023) and updated in this St3TART-FO project, [RD1].

[RD5]The roadmap (TD-08_5) provides a strategy for the future FRM setup to support the full operational validation of the S3 STM over sea ice within the MRTD requirement, on thickness of sea-ice (freeboard) accuracy to be within the requirement 0-50 cm or maximum 10% error and up-to-date user requirements from the sea ice community including the S3 MPC and Copernicus Services. The strategy is based on potential sensors and their SI traceability and uncertainty budgets, platforms, site selection, and a strategy of how to integrate and combine various sensors and measurement methods to make the full S3 validation over sea ice. Additionally, we provide a strategy for other drivers such as Processing Baseline evolution, science interest, and R&D, which may require additional sites/ campaigns.

The roadmap is based on components of the literature review of existing sensors & validation data, FRM compliancy matrix, the St3TART campaigns, and learnings from other related projects.

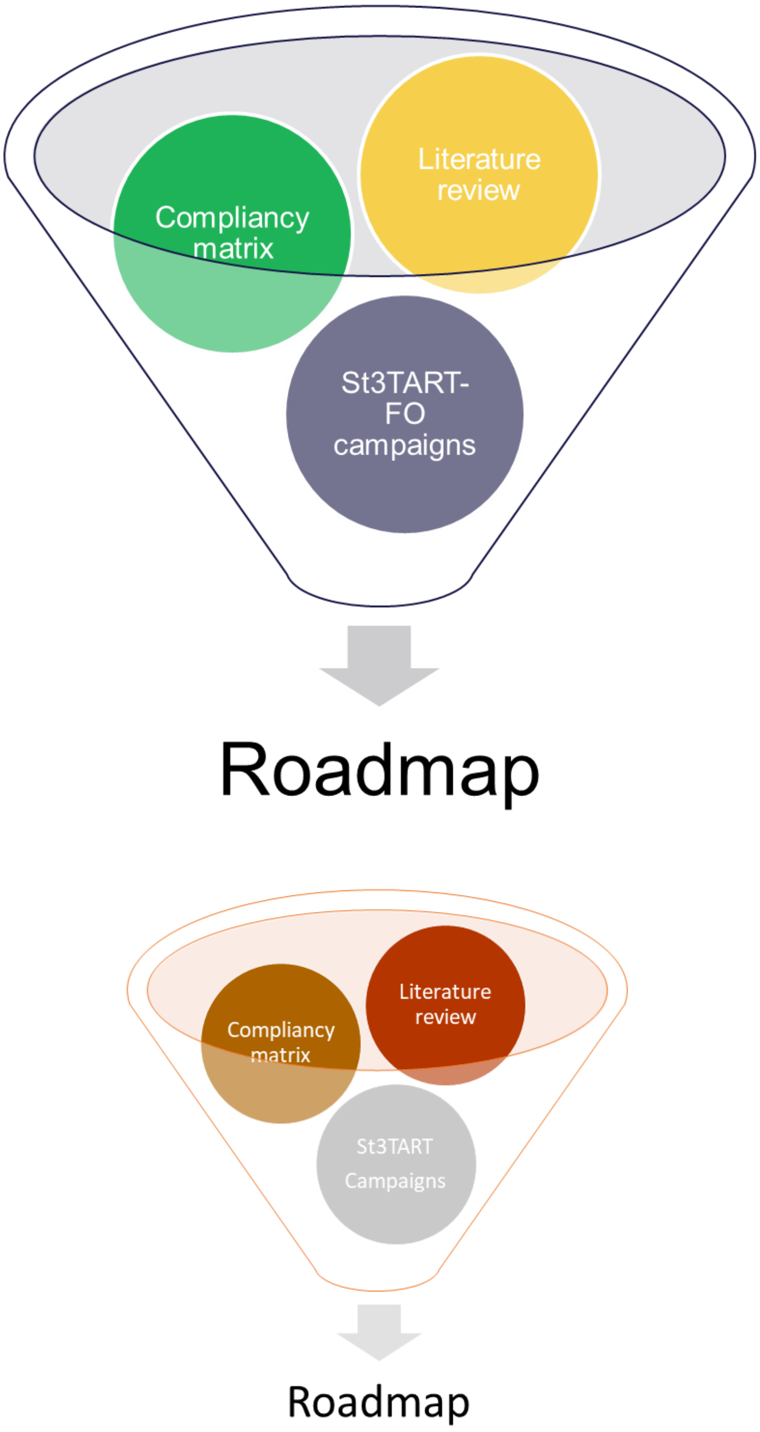

Figure 1 - Roadmap elements description

The roadmap for FRM for S3 over Sea Ice is based on several years of experience from related validation and calibration efforts for ENVISAT, ICESat-1/2, CryoSat, SARAL/AltiKa, and the experiences made within the original St3TART project. We are challenged compared to e.g. the inland water, as the sea ice environment is a remote and harsh environment to work and operate in, however, despite the challenges we have defined the FRM and in situ needs and suggested future scenarios to support the S3 STM Cal/Val.
In the following strategy for operational FRM provision over Sea Ice, we have considered:

- Identification of historical and/or existing in-situ data in the area

- Identification of all existing methodologies to measure Sea Ice Thickness (SIT), FreeBoard (FB) and Snow Depth (SD).
- Cross-calibration between satellite altimeters Sentinel-3A and Sentinel-3B but also CryoSat (88°N/S), ICESat-2 (88°N/S), SARAL/AltiKa (81.5°N/S) and SWOT (78°N/S), as well as other synergy missions like Sentinel-6.
- Support to R&D for ground processing (and/or processing Baseline) evolution
- Evaluation of new measurement methodologies for Fiducial Reference Measurement (FRM)

The roadmap follows the flow chart as visualized in Figure 2.

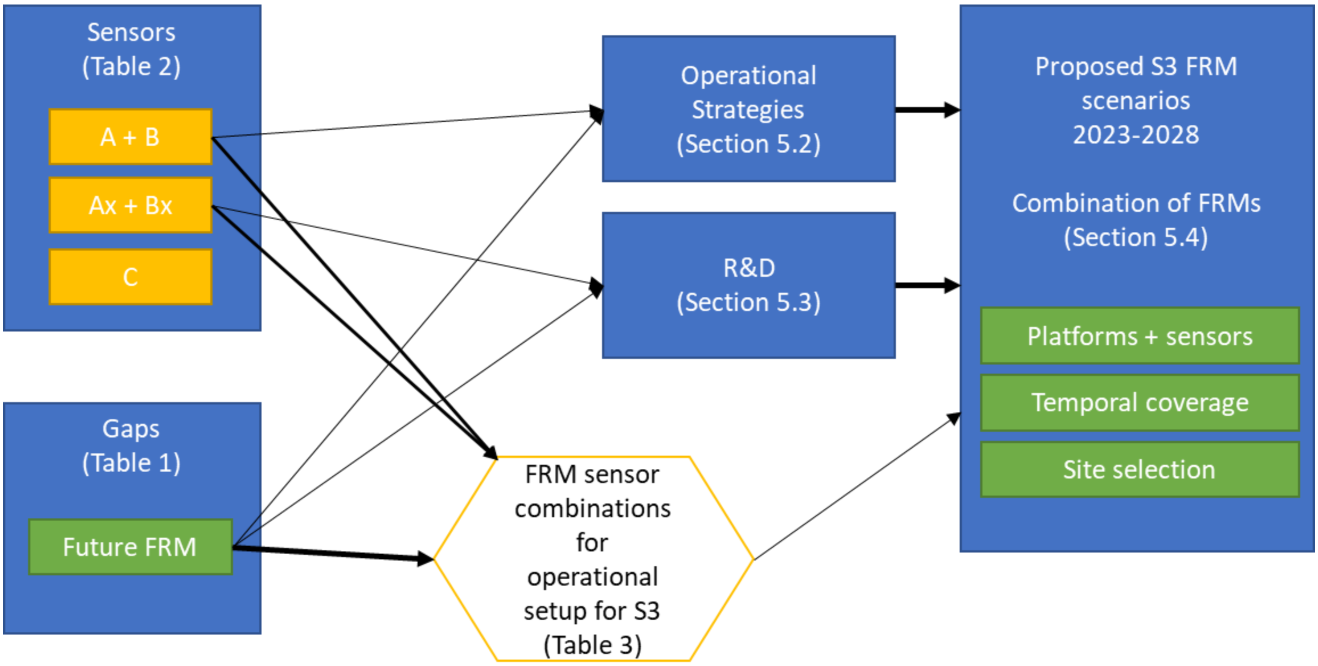

Figure 2 - Flow chart of the sea ice roadmap

1.2. Overview of this document

In addition to this Introduction chapter, this Roadmap for S3 STM Land FRM operational provision includes the following chapters:

- § 2. Theoretical definition of what is needed
- § 3. Identified gaps
- § 4. Recommendations of what could be used
- § 5. Strategy for operational FRM provision over Sea Ice
- § 6. Conclusions

2. Theoretical definition of what is needed

2.1. S3 altimetry measurement over sea ice

To fully validate the S3 LAND STM L2 sea ice product and determine the related uncertainty budget, the primary geophysical variables to be assessed over sea ice are ([RD8] Chapter 2):

- Sea ice freeboard (FB_{Ku});
- Auxiliary snow depth product, SD (to convert from FB_{Ku} –to FB_{ice},, which is the sea ice freeboard)
- Sea ice thickness (which requires the following input: FB_{ice}, SD, densities of snow and ice);

With auxiliary parameters
- Surface Type Classification Derived from Altimeter (leads, floes);
- Sea surface anomalies (needed to compute FB);
- Sea ice roughness (intermediate useful parameter).

The largest contribution to the uncertainties for the FB_{ice} is the snow depth, followed by the uncertainty of the penetration of the radar in snow and the impact of the roughness on the radar waveform.

Concerning the freeboard to Sea Ice Thickness (SIT) conversion, the main uncertainties come from the snow depth followed by ice density, which depends on the age of the ice (mainly between first year ice and multi-year ice, also referred as sea ice types). Snow depth measurements coincident with other measurements of e.g. radar freeboard and lidar are crucial for obtaining the needed accuracy for the FRMs.

2.2. User requirements

The ESA S3 MPC provides monthly evaluation reports based primarily on the last cycle of satellite data describing aspects such as, data coverage, and availability of geophysical corrections. In these monthly evaluation reports, there is currently no external validation data used over sea ice covered regions. Additionally, yearly evaluation and baseline updates e.g. using new processing strategies, and development of baseline algorithms, are provided. For these reports the demand for consistent long-term (over the S3 measurement period) FRMs are needed. They are of course also needed to better characterize the qualitative reliability and the quantitative uncertainties of the measurements.

Recently, the MPC has implemented their thematic processing chains, where observations over land ice, sea ice, and inland water have dedicated processing chains relevant for each thematic area. Over sea ice, this now includes the implementation of zero-padding and Hamming windowing, which has proved to make Sentinel-3 sea ice observations similar to the baseline mission, CryoSat-2, with a mean difference in radar freeboard of 1 cm (Lawrence et al., 2021 [RD6]). With this thematic processing chain, it is now possible to further evaluate the sea ice variables retrievable using Sentinel-3.

The identified FRM requirements to support the MPC cyclic and yearly reporting over sea ice have been summarized in the list below:

REQ 1 FRM shall be georeferenced.
REQ 2 FRM shall be fully traceable (storage of raw data, open-source post-processing code - if possible, in python, handbook with description of the instruments, the deployment, the post-processing, the sources of uncertainties and errors, the parameters, and a contact for further information).
REQ 3 FRM shall be provided with flag to mention bad data (eg, instrumentation failure) and shall be distinguished to no data (eg, no ice or no snow, which is a pertinent information and not a bad data).
REQ 4 FRM shall be provided with uncertainty estimates.
REQ 5 FRM shall be provided if possible, within a month and at least within a year.
REQ 6 FRM accuracy shall have an accuracy better than 10 cm for sea ice freeboards on independent measurements, and 50 cm for SIT.
REQ 7 FRM shall be themselves validated (e.g., with field measurements and/or alternative sensor such as for instance a snow-radar when comparing Ku radar measurements with Ka or laser).

REQ 8 FRM shall be acquired as far as possible in geographic positions that optimize the number of over-flights by the considered satellite orbit (eg for S3, bellow 81.4° but as close as possible to this high latitude, and if possible, at a S3A/S3B crossing).

REQ 9 FRM shall represent seasonal as well as regional coverage, if possible both FYI and MYI and both hemispheres. In particular, there is a dramatic lack of measurements in Antarctica and of summer measurements.

REQ 10 FRM shall consist of long enough time series, e.g. few days long or yearly regional/seasonal acquisitions, to be able to detect anomalies in the evolution of the in-situ/altimetry data comparison metric (namely RMSE).

REQ 11 FRM shall provide as far as possible the necessary parameters to retrieve the Sea Ice Thickness and the Snow Depth (e.g., two of the following parameters: SIT, SD, FB_{ice} , FB_{total}, draft, SIT_{total}, FB_{Ku} - ‘total’ means including SD).

The requirement REQ 1 is generally satisfied for the various types of FRMs. However, some limitations exist. For instance, in certain airborne campaigns, optical images are georeferenced only to the center point of the image, rather than to every individual pixel.

The requirements REQ 2 to 4, concern the post-processing, the data distribution and the associated information (handbook, uncertainties, etc.). The satisfaction of these requests relies essentially on a wide dissemination of clearly formulated recommendations and agreements between producers, users and funders of data.

The requirement REQ 5, concerning the delay in data access, depends on which type of data is acquired as well as the effort and resources dedicated to post-processing and data dissemination. For instance, the moorings below the ice must be lifted out of the water by an icebreaker to retrieve the data, which is usually done only once a year during the period of minimum sea ice extent. But most of the time the problem comes from a lack of planning or a lack of means to process the data. For example, airborne operations are complex and costly, so we generally try to multiply the number of sensors and measurements. But this requires foreseeing an adapted and consequent support in return of mission to treat and diffuse these big quantities of data.

The requirements REQ 6 and 7 recall that the FRM shall be precise and validated to be reliable. While this may seem obvious, one does not necessarily think upstream of the mission about validation methods (e.g. measuring snow depth to validate Ka/Ku measurements) or about explaining and quantifying downstream the validation of distributed data.

The requirements REQ 8 to 10 underline the importance of the choices of the position and the period of the measurements. The choices shall satisfy 3 conditions: 1) optimize the number of over-flights by the considered satellites, 2) optimize the coverage of the different regions and periods, and 3) provide long enough time series. Given the small number of measurements on the ice pack, these last two conditions, space-time coverage and revisit frequencies, are clearly contradictory. It is therefore necessary to ensure that one or the other is satisfied.

The requirement REQ 11 is related to the fact we have a dramatic lack of snow depth measurements of the ice pack. This parameter, of climatic, meteorological, biological and operational interest for navigation, is one of the least known. A significant effort is needed to try to systematize its measurement on each occasion. For example, by combining a snow radar with other measurements as it was done on the Ice-T buoy in the St3TART project. They should be systematized and carried along on airborne measurements, and they could be coupled with SIMS or carried by drones.

3. Identified Gaps

From the analysis of the current S3 MPC Land product and the associated validation procedures, we have collected the identified gaps in Table 1. We describe and comment each of them according to current and future FRM and S3 TDP. This analysis supports the Recommendations presented hereafter.

Table 1 - Gap analysis of S3 FRM and TDP.

Identified Gaps	Existing/Current		Future	
	FRM	TDP S3 STM	FRM	TDP
Protocols & procedures	• Reference data is not properly described according to FRM protocols & procedures, and uncertainties are in general not well quantified and/or flagged	• No systematic strategies concerning validation against FRM because of missing FRM	• FRM data shall be properly described according to FRM protocols & procedures as described in [RD8] Section 7.3, by 1) defining the measurand, 2) preparing uncertainty traceability diagram, 3) Effects Table, 4) calculating the FRM and its associated uncertainty and 5) documentation, see example in [RD8] Section 7.5 and Appendix B.	• Put in place some systematic validations when FRM data will be available
Long-term monitoring	• No guarantee for future Airborne Campaign. • Only AWI IceBird airborne campaign is planned until 2025.	• Existing long-term monitoring programs are used for S3 baseline evaluation and consistency of ECVs.	• **Support long-term monitoring programs for consistent validation of S3:** • **airborne campaigns** • **ULS moorings** • Secure access to classified data.	• Secure consistent long-term monitoring programs to support validation of S3 baseline evaluations and ECVs.

Identified Gaps	**Existing/Current**		**Future**	
	FRM	**TDP S3 STM**	**FRM**	**TDP**
Near Real Time provision & Latency time	• Only drifting buoys with Iridium uplink can provide NRT data. But these NRT data are, as far as we know, not distributed. • Airborne campaign data typically have a few months up to 1 year latency time depending on the size of the campaign and the allocated resources for the processing. • ULS moorings are collected once a year, and take 1-2 months of post-processing. • For non-dedicated validation data it typically takes 2-5 years from observation to online provision of data ([RD8] Table 5.1).	• Currently no reference data is used for the monthly cyclic evaluations	• Resources shall be prioritized & allocated to decrease the latency time • Automatization of post-processing shall be prioritized • Data transmission via Iridium is rather expensive and alternative solutions, shall be investigated	• There is a need to have FRM data for S3 validation to support the monthly cyclic evaluations, or at least the yearly report, and to prepare evolutions of the S3 processing chain. • Provision of FRM data shall preferably not exceed 1 year.
Data processing - higher level products	• Airborne radar freeboard data are missing from e.g. CryoVEx campaigns (2004-present).		• Development of systematic and consistent methods & production of airborne radar freeboards	
	• Freeboards & snow depths are missing in Operation IceBridge Antarctica data (2009-2019)		• Production of freeboards & snow depths for Operation IceBridge Antarctic data	
Surface classification	• Lacking	• Validation data is limited to satellite images • Few efforts have used airborne data. By using airborne data these are challenged by drift corrections, collocation in time & space	• **Develop methods using IR camera from airborne platforms and drones** • **Exploitation for lead/floe classification validation**	

Identified Gaps	**Existing/Current**		**Future**	
	FRM	**TDP S3 STM**	**FRM**	**TDP**
Snow depth products with inter-annual variations	• Lacking • Only data from OIB snow radar collected in spring (March) in the Arctic. OIB Snow depth in Antarctic exists but hasn't been processed. • AWI snow depth buoys only include snow accumulation, which is difficult to interpret.	• None • Snow depth is currently the largest source of uncertainty in FB_{Ku} -> FB_{ice} -> SIT conversions. • Warren climatology is totally out-dated and covers only central Arctic. • Other innovative or experimental solutions (KaKu, AMSR, models, …) cannot be validated.	• **Include snow radars on airborne platforms, drifting buoys and any forthcoming solutions (drones, SIMS, etc.)**	• Develop snow depths from combined - SARAL/AltiKa and S3 or ICESat-2 and S3
Surface roughness	• Lacking consistent training data to support development of retrackers based on physical models. • Surface roughness can be estimated by laser scanners from aircrafts and drones, but are limited to the swath width of the laser scanner	• Commonly used TDP processing algorithms do not correct for roughness	• **Develop procedures to estimate large scale sea ice roughness as input data for physical retrackers** • Fly parallel lines laser scanner from aircraft and drones to "fill" out the S3 SAR footprint area. For such a setup a long-range laser scanner (~1 km) with larger swath width (~1 km) is recommended instead of the commonly used laser scanners with 3-400m swath.	• Support further development of physical re-trackers
Summer estimates	• There is not consistent FRM data during summer	• There are currently no summer sea ice estimates • -Melt ponds contaminate the radar signal • -Wet snow on sea ice which permit no penetration into the snow at Ku-bands	• **There is a need for collecting dedicated summer FRM data**	• Development of summer sea ice estimates
Consistent information of sea ice type	• Lacking	• Sea ice types are commonly based on AMSR or satellite scatterometer data which are limited by an insufficient resolution.		• Try to use the satellite radiometer to estimate the sea ice type.

Identified Gaps	**Existing/Current**		**Future**	
	FRM	**TDP S3 STM**	**FRM**	**TDP**
Sea ice drift	• Lacking • Validation data for sea ice drift products from satellite observations are very limited. • Some from drifting buoys GNSS positioning. • Some ULS moorings are equipped with sea ice drift sensors. • Drift products based on satellites are not yet FRM compliant (e.g., no uncertainties, cf BIPM workshop)	• None • Direct underflights of satellite tracks need to be adjusted for sea ice drifts, whereas this is not needed if data is compared to gridded products ([RD8] Section 7.4).	• Increase the validation data by deployment of drifting buoys. • Add ice drift sensors to existing ULS moorings. • Develop methods to assign uncertainties to drift products. • Deploy drifting buoys during airborne campaigns	• Support development of drift corrected gridded products, which can provide daily SIT maps (development within CCI+ SI).
Sea ice density	• Lacking observations and methods • Methods are limited to in situ measurements, which are not consistently collected. • Recent studies by AWI IceBird using a combination of AEM & laser & snow radar measurements can be used to provide densities on regional scales	• None • Commonly used procedures are to use 2 values; FYI (917 kg/m^3) & MYI (882 kg/m^3), respectively. These are dependent on the classification of sea ice types	• Develop techniques to measure sea ice densities by drifting buoys	
Sea ice salinity	• Lacking observations and method			
Snow density	• Lacking			
Salinity in snow	• Lacking			
Marginal Ice Zone studies	• Lacking	• The intrusion of ocean waves impacts the freeboard estimates		

Identified Gaps	Existing/Current		Future	
	FRM	TDP S3 STM	FRM	TDP
MSS				• The choice of MSS impacts the FB estimation in particular in areas with a low lead density (Skourup et al. 2017), up-to-date and common MSS should be used for FRM and TDP ([RD8] Section 7.3).
Gridded products				• Development of gridded products

4. Recommendations of what could be used

4.1. Assessment of existing and new in-situ and FRM sensors

To support the future S3 FRM strategy we have made an extensive literature review of existing sensors & new technologies, and identified 40 different sensors including radar and laser altimetry, snow radar, EM sensors, cameras for visual images, in situ technologies, ice mass balance & snow depth buoys, upward looking sonars, reflectometer and radiometer [RD8].

We have selected 36 categories and described each sensor according to sensor functionality, resolution, measurand, stability, uncertainties, technological readiness level (TRL), scientific readiness level (SRL), latency time (NRT provision) and costs [RD8] and [RD4].

We have selected 6 of the categories which are most important to define which sensors are FRM compliant to act as S3 operational FRM provision over sea ice, where the accuracy of the measurand and the traceability for documenting uncertainties is ranking high:

- Accuracy/uncertainty level of Measurand
- Traceability of uncertainty of Measurand
- Technical Readiness Level (TRL)
- Scientific Readiness Level (SRL) - this includes development of higher-level products
- Near Real Time Provision (NRT) - based on latency time
- Costs - based on an overall cost-effect

The overall ranking of sensor FRM compliancy has been adapted from [RD7], and is defined as follows:

Rank:

- A = To be preferred for operational FRM provision ('A+' identify the sensor with the best ranking)
- Ax = Similar to A, but with a low TRL or SRL, meaning that they need further R&D
- B = To be used to complement rank "A" sensors ('B+' identify the sensor with the best ranking)
- Bx = Similar to B, but with a low TRL or SRL, meaning that they need further R&D
- C = Not recommended for operational FRM provision**:**

The full overview comparing the strengths and weaknesses of all sensors for an operational FRM provision with categories, legends, and rankings are provided in [RD8] Appendix A. In Table 2, we have provided a commented summary of [RD8] Appendix A, including the major conclusions and gaps analysis for each sensor type including learnings from St3TART campaigns [RD10].

It is important to note that in the polar regions, validation data are scarce, see e.g. [RD8] Section 5.2, both in terms of spatial and temporal coverage, but also in terms of quality and uncertainty estimates, see [RD8] Section 5.3. Thus, even ranked C sensors can currently play an important role, such as the visual ship observations (ASPeCt program) and the draft measurements from submarines. As long as there are not enough metrological methods of substitution, it is important to support all ongoing techniques, including those poorly classified in terms of reliability or traceability: some data is better than no data.

In the roadmap we include only sensors categorized as A and B.

Table 2 - Commented summary of Table [RD8] Appendix A.

FRM compliancy	Ranking	Sensor and support	Comments
High	A+	Airborne radar altimeter ku-band	Measurand similar to S3 Still needs snow depth information to obtain the sea ice thickness. Thus requires a snow radar or improved waveform retracking adapted for airborne Ku-band sensors
	A+	Upward Looking Sonar moorings	They measure the draft of the ice, i.e. about 90% of the sea ice thickness, which is much more precise than the 10% of the SIT measured with the freeboard.
	A	Airborne lidar	Measures the total freeboard ($FB_{tot} = FB_{ice} + SD$). Needs to be used in combination with snow depth radar. They could provide surface roughness information for satellite altimetry if the flight covers a full footprint.
	A	Airborne EM sensor	Measures the total thickness (SIT+SD). Thus, needs to be combined with a snow radar. Associated uncertainties missing and in particular flags for very thick and deformed ice, where the AEM sensor tends to underestimate the SIT.
High in support of A ranked sensors	B+	Airborne snow radar	Mandatory to convert freeboard to SIT.
	B+	In situ drillings/snow pit etc.	Mandatory to validate other FDR (buoys deployment, airborne and drone campaigns). Currently only methods to better understand the snow layer i.e., snow density, snow stratigraphy, salinity in the snow layer, ice densities.
	B	Airborne geolocated visual (e.g. geotiff)	Mainly to support the lead/floe classification for post-processing of airborne lidar and ku-band radar data. Can be used as validation for the lead/floe surface classification of dedicated satellite along-track underflights.
	B	IMBs from drifting buoys (Ice-T)	The buoys provide information of SIT, FB_{ice}, SD and drift. However, current SD estimates are impacted by excessive uncertainties. Thus, new SD sensors must be investigated.

FRM compliancy	Ranking	Sensor and support	Comments
Similar to B, but with a low TRL or SRL, meaning that they need further R&D in order to be fully operational for S3 FRM provision	Bx	Drone with lidar and/or snow radar	To make this system fully operational for S3 FRM provision, some developments of the drone technology are needed: 1) Drones to be operational in cold conditions (down to -30°C), precise positioning off the coasts, take/off and landings from ships, longer ranges (1km to 5km), 2) Easy to use for non-professional pilots to favour large dissemination on icebreakers and polar stations. 3) As far as possible, integration of the lidar and snow radar on the same drone.
	Bx	Miniature snow radars from drifting buoys	The TRL is high, but the miniature snow radars need further testing in Arctic conditions, as the first test campaign only lasted for 2 weeks.
	Bx	Snow depths from acoustic sounders on drifting buoy	These buoys only provide measurements of snow depths which is good for validation of auxiliary products. For S3 FRM provision, it is of limited use, as we cannot directly validate the FB_{ice} or SIT. As the current snow radar from acoustic sounders primarily measures the accumulation in the current processing, the observations shall not be used if it is passing a melt season.
	Bx	Sea Ice Measurements System (SIMS). EM sensor from icebreakers	The TRL is high as it is already an operational navigation support. Could even be NRT. But the data are rarely made available outside the ship. It tends to bias the SIT distribution due to ships preference of navigating in the thinnest sea ice. This system measures the total SIT (SIT+SD) thus it would need a complementary snow-radar.
	Bx	IR cameras for airborne and drones	IR cameras have not been fully exploited for surface classification and shall be exploited in future. As for the visual cameras the images need to be properly georeferenced.
	Bx	Upward looking sonar from AUV or mammals.	ULS are among the most precise SIT measurement systems as they measure about 90% of the SIT. Sensors on AUV or mammals are undergoing important developments. This is particularly important for Antarctic where moorings cannot be deployed because of the icebergs that carry them away. Nevertheless, they still need further technical developments to act as FRMs. In particular related to the uncertainty on the position depth. Further testing of Ultra-Short BaseLine (USBL) positioning buoy system and in general implementation of ULS on smaller AUVs should be supported.

FRM compliancy	Ranking	Sensor and support	Comments
Low	Bx	airborne radar ka-band altimeter	These measurements are important to validate the KaKu snow depth estimation techniques and prepare for CRISTAL. Unfortunately, the processing and the results remain largely uncertain due to R&D limitation and lack of FRM on SD data.
	C	Upward looking sonar from submarine	Coming from declassified military data: the positions are very approximative (we only have access to the starting and ending positions of the few days trip) and we cannot expect recent data. They remain important for the full exploitation of older satellite missions (ERS1&2, Envisat).
Not compliant	C	Visual SIT observations from ships	Mainly from the ASPECT program. High uncertainties and low traceability on individual measurements, as the observation depends on the observer. In addition, the ships preference thinnest sea ice passages tend to bias low the sea ice thickness distribution. These data are nevertheless important as they are the only data available in Antarctic.
	C	Optical/IR images not fully geolocated	Such images cannot be used in a systematic way for sea ice surface classification. It is of use but cannot be classified as FRM.

5. Strategy for operational FRM provision over Sea Ice

Based on the requirements described in Section 2.2 the most optimal solution for S3 LAND STM L2 sea ice product validation would be coincident measurements of sea ice freeboard or thickness or draft with snow depth. It is difficult to find a stand-alone solution for such observations over the full sea ice seasons and distribution, and we must look into combinations of different sensors and platforms to meet these requirements.

5.1. Strategies for sensors & platforms

From the overview of all the known sea ice measurement methodologies summarized in Table 2, we have identified some combinations of platforms and sensors that could help to fulfil the gaps listed in Table 1. These combinations are gathered in the Table 3 below.

This table summarizes the solutions that we consider as the most pertinent candidates for FRM measurements.

For each of them we have included the status in terms of maturity of the approach and the remaining challenges to reach a full level of maturity. Most of them are operational or nearly operational and can be supported with a reduce effort.

Only drones need further R&D but they clearly offer new and low-cost opportunities to increase the spatial and temporal coverage in the future.

Table 3 - FRM sensor combinations for operational setup for S3 provision.

Platform	Sensors		Status	Challenges
	Mandatory	Auxiliary		
Airborne	Ku-band radar, laser scanner & snow radar	Camera for surface classification	Operational	There is generally no snow radar due to mechanical and technical limitation in the aircraft which should be analysed (room and flight altitude constraints).
	laser scanner & snow radar	Camera for surface classification	Operational	
	EM & laser scanner & snow radar	Camera for surface classification	Operational	Associated uncertainties missing and in particular flags for very thick ice and deformed ice, where the EM sensor tends to underestimate the SIT. Can potentially provide information of the sea ice density, to be further developed.
Drone	laser scanner, snow radar	Camera for surface classification	R&D for drones. Lidar & snow radar are proved concepts	R&D to fully adapt the drones for Arctic conditions and if possible, combine laser scanner & radar on the same drone.
Moorings	ULS	Sea ice drift	Operational	High costs and specific means (icebreaker with crane). Needs collaborations with involved institutes to access data and to favour the addition of ULS on each mooring, which is not systematic at all as ULS are mainly used to measure oceanic parameters (T°, salinity, currents, …).
Drifting buoys	Sea ice thickness + snow depth	Temperature and salinity	Nearly operational	Need some more experiments to evaluate the snow depth radar performances.
Ship	SIMS & snow radar	Sea ice thickness and snow depth	Nearly operational	Operational for the navigation but about no scientific usage. Could be NRT similarly to the Ferry Box. Need for agreements with ship companies for data gathering and distribution, and to support systematic SIMS installations. Would be worth to combine it with a snow radar as the SIMS measures the total SIT (SIT+SD). Need to investigate the impact of the low SIT bias due to preference of the ships for thinner ice passages.

To provide the final scenarios (see section 5.4), we have further selected sensor & platforms based on different spatial and temporal resolutions as visualized in Figure 3 and Figure 4.

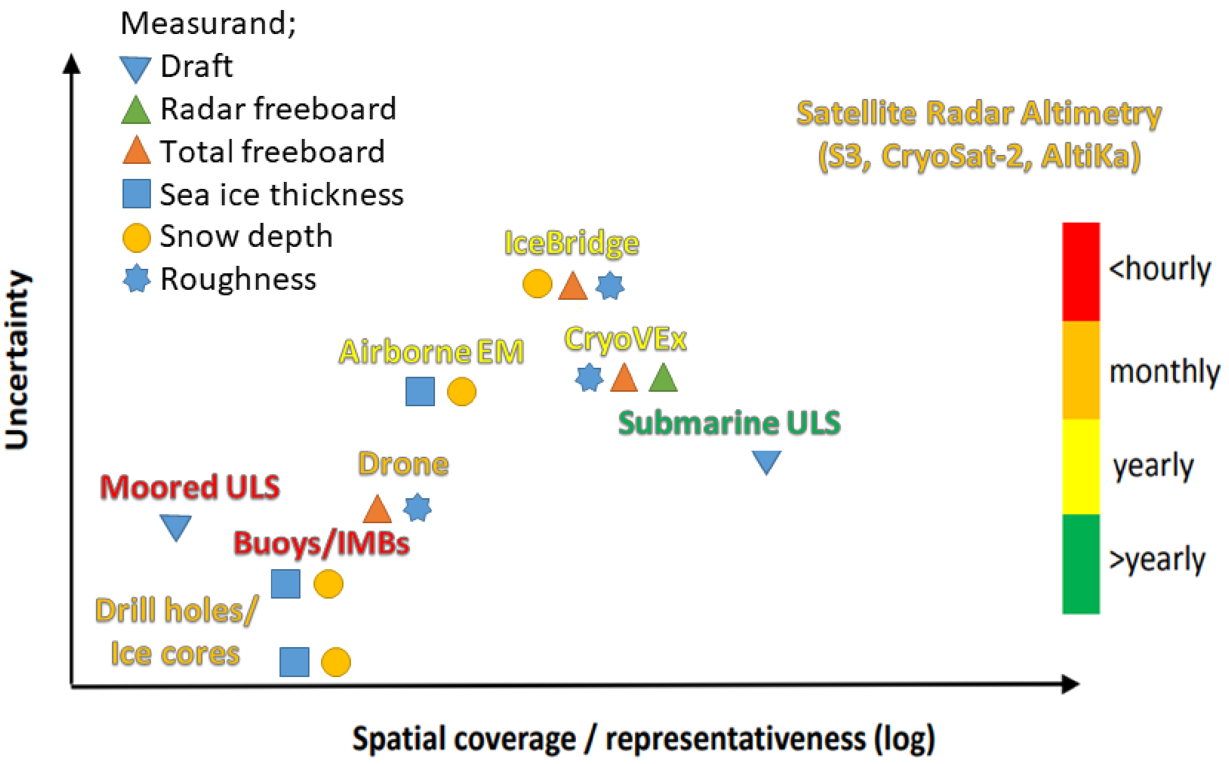

Figure 3 - Sea ice sensors represented according to their representativeness and uncertainty. Adapted from C. Haas.

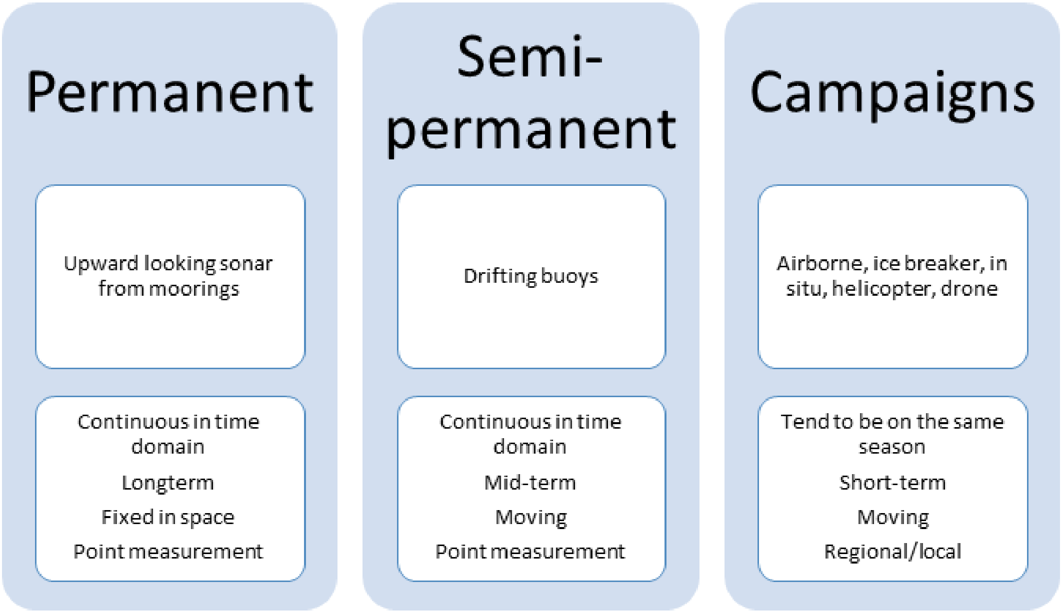

Figure 4 - Definition of permanent, semi-permanent and campaigns

5.2. Actions for operational strategies

From the solutions identified as ranked A in Table 3, we suggest maintaining the following existing methodologies to support operational S3 FRM provision:

- Maintaining the Upward Looking Sonar moorings in Fram Strait, the Beaufort Gyre, and the Russian Arctic, which are all below 81.5N, and adding ULSs to existing moorings without ULSs.
- Continue long-term airborne monitoring programs such as: ESA CryoVEx, NASA Operation IceBridge, AWI IceBird to secure consistent validation data from year-to-year variations as well as cross calibration between successive satellite missions.
- As snow depth is the largest source of uncertainty on the freeboard to thickness conversion and because of the reduced speed of light in snow for Ku-band wave, it is crucial to measure it together with the freeboard or other ice thickness evaluation (draft, SIT, total SIT, total FB).

As the existing and current reference data in the polar regions are still very sparse, we shall ensure their conservation and continuation. Collaborations across projects must be fully promoted to support the satellite Cal/Val programs. Within each project, a funding for the full cycle of the campaigns including post-processing to the defined FRM measurand shall be secured (see comparison diagram [RD8] Figure 3.1). We shall also expand the observation network and adapt it to future missions such as CRISTAL, CIMR, and ROSE-L, which in particular calls for more snow depth observations, and larger seasons and regions coverage. The Antarctic in general and the polar summers are dramatically limited in observations.

5.2.1. Long-term airborne campaigns

It is crucial to secure future long-term FRM campaigns, as NASA Operation IceBridge has ended in 2019 and soon the ESA CryoSat Validation Experiment (CryoVEx)/Cryo2IceEx will not have further funding. These campaigns together with other long-term campaigns and semi-permanent solutions are important for consistency, long-term monitoring and cross-validation of satellite missions. We encourage the instrument package to include a snow radar. Thus, different aircraft options shall be carefully evaluated for this purpose. As an example, the BAS Dash-7 with a suite of sensors i.e., radar (Ku/Ka/S), swath lidar, radiometer, 3D cameras, GNSS-R, vertical and side looking photography, and gravimetry used for most recent Antarctic ESA Cryo2IceEx/NERC DEFIANT campaign. In particular, the combination of Ku/Ka and S-band radars are important as S-band acts as a snow radar, which can be used to better understand the Ku/Ka penetration into the snow layer. Dedicated CryoSat-2 campaigns beyond 2022 are uncertain, but there could be arranged airborne campaigns in preparation of the CRISTAL mission.

<u>Current status of the different airborne campaigns:</u>

- **NASA ICESat-2 airborne campaign** Operation IceBridge reached their project goals in 2019 by the launch of ICESat-2. There are currently no planned future campaigns, but proposals for ICESat-2 validation campaigns are discussed. Nevertheless, it looks like that the budgets for OIB campaigns have been recently drastically reduced (News from CRISTAL MAG of March 2023).
- **Greenland Integrated Observing System (2021-2026):** Danish national fund for infrastructure has granted 5 million euros to develop and deploy a network of automated observation platforms around Greenland. It is a coordinated effort across the Kingdom of Denmark to improve our understanding of climate change in the Arctic. This includes purchase and implementation of an airborne snow sensor as an add on to the proposed airborne campaign setup.
- **CRISTALair and CIMREX/CIMRair** will make the future baselines for CRISTAL and CIMR. For now, there is no plan for including a snow radar in the CRISTALair setup, however discussions have begun to certify the AWI IceBird aircraft for CRISTALair which has its own snow radar set-up available.
- **CryoBridge** Airborne campaign to bridge CryoSat-2 and CRISTAL – not confirmed

Copernicus Expansion Mission Sea Ice Experiment (CEMSIE) proposed for spring 2026 which plan to collect relevant sea ice and snow geophysical properties in situ while coordinate overflights of relevant airborne campaigns to support algorithm development in support of the future CEMs.

- **AWI IceBird.** Collaboration with AWI IceBird, which since the addition of a snow radar in the instrument package in 2019, is a very strong FRM. Future planned campaigns:
    - 2023: IceBird Winter in March/April with the standard EM-Bird/ALS/Snow Radar configuration. Inuvik -> Eureka -> Station Nord -> LYR. CFS Alert is not accessible to us. The campaign is done by Thomas (Krumpen) and Arttu.
    - 2023: IceBird Summer: Station Nord. ALS + EM-Bird
    - 2024: There will be an "IceBird Canada" by Christian. No exact plans yet
    - 2025: Submitted proposal für IceBird Winter and Summer. No exact plans yet
    - 2026+ No plans yet and unclear situation of available personnel. E.g. we do not have a dedicated person for snow radar work after 2023.

  The use of AWI research aircraft requires a proposal. Each year there is a proposal phase for a period covering approximately 3 years. The next deadline (for spring 2026) is End of November 2023. External parties are encouraged to apply, though the process is not well advertised by AWI logistics.
- Some projects also plan campaigns in Antarctic, such as the **Antarctic Rings** project, led by the Scientific Committee on Antarctic Research (SCAR) or **DEFIANT** project, funded by the Natural Environment Research Council (NERC) and led by the British Antarctic Survey (BAS)

Also, existing campaigns are important for the continuity of the S3 STM validation over sea ice, and it is important to prepare them at a proper level.
Coincident campaigns with land ice validation, which has already been done for ESA CryoVEx, ESA Cryo2IceEx and OIB, is encouraged and will lower the cost.

Contacts:

- IceBird, Christian Haas, AWI; for potential collaboration and dedicated underflights of S3, chaas@awi.de
- NASA, Sinead Farrell, UMD, sineadf@umd.edu
- ESA CryoVEx/Cryo2IceEx: Henriette Skourup, DTU, hsk@space.dtu.dk
- GIOS: Henriette Skourup, DTU, hsk@space.dtu.dk
- CRISTALair: Valeria Gracheva, Valeria.Gracheva@esa.int
- Antarctic Rings: Rene Forsberg, DTU Space, rf@space.dtu.dk

Budget:

- ESA CryoVEx Campaign in the order of 20-30 flight hours 250 k€ including some in situ measurements using TO. The cost will increase by using a larger aircraft e.g., a Basler or Dash-7.
- Instruments: see FRM compliancy matrix
- Antarctic airborne campaign 300-400 k€ depending on aircraft and location

5.2.2. Permanent solutions, ULS

Currently, there are no specific FRM sea ice data sites, but permanent solutions such as the upward looking moorings in the Beaufort Gyre Experiment (BGEP), the Norwegian Polar Institute moorings in Fram Strait and the ULSs in the Russian Arctic, shall be considered as potential S3 FRM data sites. The operational ULSs are all located south of 81.5°N and shall act as potential FRMs for S3 validation, once the uncertainty budget and SI traceability has been defined by using the approach presented in [RD8] Section 7.3. The individual measurements are point measurements, but due to the sea ice drift, it provides a mean of the sea ice draft in the area when integrated over time. In addition, it provides continuous measurements over the full yearly sea ice cycle. The existing ULSs are located at strategically important sites, representing different sea ice types and conditions. That is why all these moorings shall be maintained, as they also represent a long time-series to validate ECV. Additionally, deployed ULSs within future S3 FRM could support further information to secure S3 validation at specific S3A and S3B crossover points.

Beside the already existing moorings with an IPS with public available sea ice draft observations, the access to data from other existing moorings shall be explored. First of all, the data can be classified or just not public available. Additionally, existing ocean moorings with no IPS shall be explored in terms of the value in adding IPS.

Existing moorings with IPS, publicly available draft data can be found in Section 4.1. No publicly available data from moorings and oceanographic moorings are listed below:

- BGEP The data are freely available and maintained by US Healy
- NPI have a few mooring deployments with ULS on the shelf east of Svalbard as part of the Nansen Legacy project: https://arvenetternansen.com/nansen-legacy-oceanographic-moorings/,
- Some of the A-TWAIN/SIOS-Infranor moorings have been located south of 81.5: https://septentrio.uit.no/index.php/nansenlegacy/article/view/6461/6495
- NPI/UiT: Central Arctic IPSs at 86° 30' and 83° 56' IPS (Norteks)
- Berings Sea moorings Canadian Fisheries and Oceans
- Nansen and Amundsen Basins Observational System (NABOS)

AWI has moorings in Antarctica, but as the IPS cannot be deployed below 150 m below the surface the larger and more frequent incidents with icebergs possess a potential danger to the mooring system.

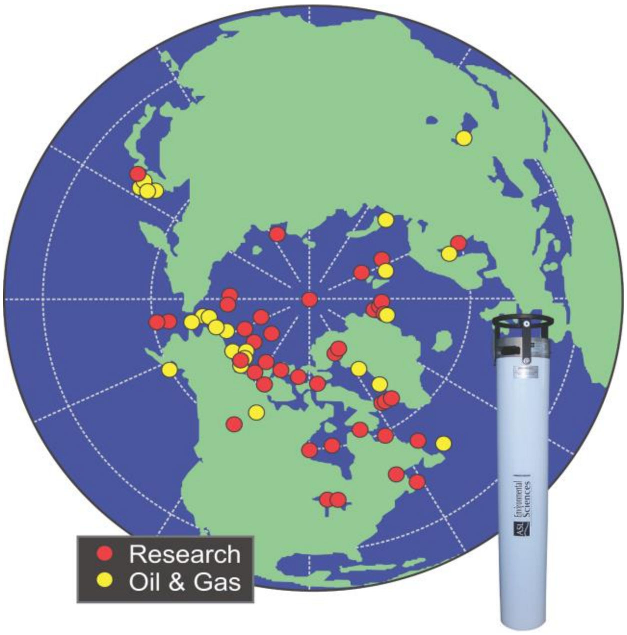

Figure 5 - Positions of IPS deployed by ASL all around the world

5.2.3. Contacts

- Fram Strait Arctic Outflow Observatory: Norwegian Polar Institute; Dmitry Divine Dmitry.Divine@npolar.no, Laura De Steur laura.de.steur@npolar.no;
  NPI's IPS program has recently been expanded to include moorings in the northern Barents Sea and over the adjacent shelf slope, and in the western Nansen and Amundsen Basins of the interior Arctic Ocean since this last summer. **Moorings NE and E of Svalbard, at 81.4 and 79.6 N, but unconfirmed if the last 2 have IPSs**
- NPI/UiT: Central Arctic IPSs at 86° 30' and 83° 56'? IPS (Norteks)
- BGEP: Woods Hole Oceanographic Institution (WHOI)
- NPEO: Applied Physics Laboratory (APL)
- Nansen and Amundsen Basins Observational System (NABOS), University of Alaska, Fairbanks, US. NABOS is part of the Arctic Observing Network. NABOS research is funded by the National Science Foundation, and the National Oceanic and Atmospheric Administration: https://uaf-iarc.org/nabos/;
- AWI moorings in Laptev Sea; (AWI)
- IPS and mooring manufacturer, ASL Environment, James Barltett, jbartlett@aslenv.com.

5.2.4. Budget

The manufacturer ASL Environmental Sciences based in Victoria, British Columbia, Canada, has been contacted followed by an online meeting to define needs to prepare a quote for a full mooring and for the addition of the Ice Profiling System (IPS) to an existing mooring. The costs are detailed below. In addition to the draft of the sea ice measured by IPS, adding an ADCP to a mooring system will also allow measuring the sea ice drift. As there is not very much drift validation data, beside drifting buoys, this would possibly be a pro bonus for a small extra cost.

On top of the cost for a new mooring, there are costs related to deployment, recollection of data, maintenance, but also large costs related to the post-processing.

We are currently working on developing in-house ice draft processing routines, and will also work with comparing new data from a new instrument which has an ice draft measurement mode as well (from Nortek) and which would be a cost reducing investment on the long run in the observing system, if the data delivers the same quality as the IPS.

Numbers kindly provided by Laura De Steur from NPI. These numbers are estimates and might change depending on the location of mooring:

- New mooring: 100 k€ with an IPS, an ADCP (for drift speed) and a Microcat CTD (for sound speed in water) as well as a release, wire, and floats, required consumables.
- Ship deployment and recovery: 25 - 30 k€ /day, but depends heavily on the cruise. This is an estimate for using ships to support Fram Strait moorings and might be on the cheap end.
- Post-processing of data by experts, as the ULS system does not come with a software kit. This has been a huge cost too: about 14 - 24 k€ per dataset of 1 year (depending on incl or excl ice speed from ADCP).

5.3. Actions for new technics and R&D

Based on the solutions that still required R&D, i.e., ranked as Ax or Bx in Table 3 we propose below some R&D activities to support future operational S3 FRM provision. Here we list new innovative technologies which have potential for becoming excellent FRMs, and activities needing further investigation and support:

- Drones
- Snow depth measurements
- Ship observations
- Surface classification
- Sea ice density and salinity measurements
- Snow density and salinity
- More R&D into extracting data (Sea ice concentration, albedo, sea ice drift, roughness, snow depths)

5.3.1. Drones

Drones offer a huge potential to increase the spatial and temporal coverage of FRMs and can provide repeat measurements at a given location and thus expand the airborne campaigns throughout the year. However, currently they are not at a high enough TRL/SRL level to be used as an FRM. Below are identified some of the developments needed to further develop drones towards FRM compliancy:

- Development of a polar drone which can operate in polar conditions (down to -30°C).
- Expand interface and communication with drones above 80°N
- Large range drone with option of Vertical Take-off and Landing (VToL) for deployment from ships, sea ice and other locations where a runway is not available
- Support development of a combined system including snow radar (NORCE) together with Lidar and camera
- Further test of drone from moving platform e.g., ship, drifting sea ice.
- Explore the drone observations to support validation of existing sea ice ECVs (Sea ice concentration, sea ice drift) and new ECVs (snow depths, albedo and surface temperatures)

Test opportunities with “Commandant Charcot” and from coastal polar stations as suggested in Section 5.3.2.

Contact:

- Snow radar, NORCE; Robert Ricker Robert Ricker, rori@norceresearch.no
- Lidar, VorteX.io: Jean-Christophe Poisson, jeanchristophe@vortex-io.fr
- Ship-based drone observations, LEGOS: Sara Fleury, sara.fleury@legos.obs-mip.fr
- Arctic drone technology, DTU: Henriette Skourup, hsk@space.dtu.dk, Daniel Haugaard Olesen, danole@space.dtu.dk

Budget:

The expected budget for these developments has not been evaluated yet.

5.3.2. Ship observations

Visual ship observations rely on human interpretation, and are related with relatively high uncertainties. Further development of more systematic observations from ships is needed. Recent initiatives as described in [RD10] need further development:

- NRT Ship-based observations using an EM system in front of the boat (SIMS). In order to fulfil the FRM protocols and procedures as described in [RD8], this system, mainly used for navigation purposes, needs further scientific evaluation. The adding of a snow radar seems feasible and would allow to access the SIT and the FB as the SIMS measures the total SIT, *i.e.,* the sum SIT+SD.
- Camera stereographic images taken of the broken ice floes along the ship.

For all approaches, ships moving in sea ice tend to choose a route with thinner sea ice, thus having a larger representation of thin ice in the sea ice thickness distribution. Analyses are needed to estimate this bias.

A dozen of icebreakers are already equipped with a SIMS: *Commandant Charcot, Polarstern, Lance, Kronprins Hakon, MV Arctic, Kapitan Dranitsyn, Aurora Australis, Shirase, Nuyina, Oden*, and others.

Upcoming ice-breaker cruises:

- ▲ Future identified campaigns:
  - Polarstern (PolarStern/MOSAiC (10kEUR/Day))
  - Commandant Charcot scientific (3-4 times a year) commercial but allows scientists on board.
  - Antarctica: AstroLab, French ice breaker, 4 times a year.

  - David Attenborough, UK

Contact:

- ▲ SIMS; Christian Haas, AWI
- ▲ Automized image; Frederic Vivier, LOCEAN

Budget:

The cost of an EM31 sensor (the main SIMS component) is about 30k€ but the full budget for the deployment and the new developments, such as the addon of a snow radar, have not been evaluated yet.

5.3.3. Snow depth

- ▲ Development of a state-of-the art snow depth as input for future baselines of S3 (currently no snow depth parameter is provided). This could be a combination of SARAL/S3 and/or ICESat-2/S3
- ▲ Inclusion of snow radars for airborne campaigns
- ▲ Valorisation of drone-born snow radar
- ▲ Adding snow radar to SIMS
- ▲ Validation data for snow depths including further development of Ice-T buoy snow radar system ([RD10] Section 4.1.4)

5.3.4. Surface classification

Methods using OIB visible cameras exist. These should be further developed and include Colour-infrared (CIR) surface classification. There is still progressed to be made to use it as direct FRMs: the data shall be geo-referenced as e.g. Geotiff format.

- ▲ wide angle cameras to secure overlap between tracks
- ▲ Support studies using NIR/IR options for sea ice classification

5.4. Proposed S3 FRM scenarios (2023-2028):

Following the needs and conclusions discussed so far, we suggest as a first iteration, a FRM observation network for S3 Cal/Val.

Platforms and temporal coverage:

- Deployment of ULS moorings in areas not already covered to provide continuous measurements of the sea ice at e.g. a S3A and S3B cross-over point.
- Yearly (or bi-yearly) airborne campaigns to tie regional studies of regional to larger scales. The airborne campaigns should prioritize to overfly ULSs to fully exploit the freeboard to draft conversion. This has been done in Fram Strait for NPI moorings, but so far, no conclusions have been drawn. The most optimal site for airborne campaigns will be to reach the Beaufort Gyre from either Inuvik and/or Barrow, and to overfly the BGEP ULS. The repeat airborne campaigns shall be obtained at the same time a year, i.e. in March.
- In situ observations of sea ice and snow properties at ULS and drifting buoy deployment sites.
- Extended usage of SIMS measurements.

Future (see R&D focus areas in Section 5.3):

- Monthly repeat drone surveys at selected sites to observe the seasonal variations, which are not captured by airborne campaigns, thus providing a link to larger-scale airborne campaigns. This setup could be located at remote places, i.e. smaller communities, weather stations, or at military stations or by ship.
- Yearly deployments of drifting buoys, at selected sites to obtain continuous observations of ice thicknesses, snow depth and sea ice drift e.g. the Ice-T buoy, preferable deployment site in Beaufort Gyre.
- Summer airborne campaigns to support development of S3 summer algorithms.
- Systematic measurements with drones from scientific and commercial icebreakers.
- Systematic measurements with SIMS and snow radar combination from icebreakers.

Sensors and measurements:

The lidar equipped drone used in the dedicated St3TART campaign has relatively short range (< 5km) but is relatively easy to operate and to deploy from different platforms such as the ice or from ship. If longer baselines are wanted i.e., if the study area is further away from the launch site the operation of the drone gets more complex and would currently need take-off and landing sites. For the future it would be worth to consider VTOL drones (fixed wings drones with Vertical Take-off and Landing).

Deployment of buoys should be supported by in situ measurements to know the initial conditions. Here we recommend including:

- Sea ice thickness
- Sea ice freeboard
- Snow depth
- Snow properties such as grain size
- Snow and ice density
- Snow salinity
- Temperature of the air and snow gradient in the snow layer

5.5. Proposition for new calibration sites

For S3 STM Sea ice FRM, the sites must be below 81.5° of latitude. This is a strong limit for the Arctic and in particular for Multi Year Ice (MYI) observations. However, First Year Ice (FYI) becomes more and more relevant to validate as this ice type is currently covering more than half of the Arctic Ocean even during winter and keeps on expanding on the coast of multiyear ice-covered areas. Predictions from IPCC show that MYI can disappeared as soon as 2030, which means that the Arctic Ocean will be only covered by seasonal ice i.e., first year ice. FYI is more challenging to measure from satellite altimetry because it presents lower freeboards which are more difficult to measure, and because its snow layer is more saline which limits radar penetration into the snow and increases the uncertainty of the freeboard to sea ice thickness uncertainties.

On the other hand, the relatively low S3 polar orbits offer very high densities of flyovers not far from the Arctic coasts, even more considering both S3A and S3B. A site situated not far from the higher latitude and at a S3A/S3B cross-over would be frequently revisited. Potential moorings should be located in such cross-over points. It would be possible to use already existing ULS for validation, as the currents ones are located south of 81.5N in the Beaufort Sea, the Fram Strait and the Russian Arctic. However, they are not aligned with specific S3A and S3B cross-over points.

These new calibration sites shall not be closer than 25 km from the coast in order to avoid effects from land in the satellite measurements. This challenges drone measurements from settlements along the Arctic coast and even deployment of dedicated buoys from helicopters, which are limited in range depending on the type of helicopter and the weather and ice conditions.

5.6. Collaboration with international institutes and projects

In Section 5.2 and 5.3 we mention several projects and future campaigns. **For S3 operational provision, we shall ensure to support these projects.** An extended reflexion shall be led to define to which extent, and by which means we could benefit/contribute/collaborate to them.

In addition, several ESA projects have been identified as interesting to create synergies with, such as:

- S3 LAND MPC Validation Team https://s3mpc-stm.groupcls.com/project,
- FRM4Alt https://www.frm4alt.eu,
- FRD4Alt https://www.fdr4alt.org,
- QA4EO https://qa4eo.org,
- SIN'XS https://sinxs.noveltis.fr
- EU/ESA Copernicus Services, mainly CMEMS https://marine.copernicus.eu and C3S, https://climate.copernicus.eu
- CCI Sea Ice, http://esa-cci.nersc.no
- CRISTAL IN-PROVA, TBD

6. Conclusions

During this project, we have identified the FRM data that we believe are essential and we have compared them with what is currently available and being used. We have also established a description as exhaustive as possible of the methodologies of measurement of the various essential parameters identified. This description, developed in [RD8], covers all past, present operational and future techniques being developed in laboratories. It also includes analyses of the uncertainties related to these different techniques according to a metrological approach formalized in the framework of QA4EO. We also conducted several field campaigns to evaluate new methods (drones, snow radar buoys) in conjunction with proven airborne methods [RD9]. The results of these missions are presented in the [RD10] report.

These different analyses and field measurements have finally allowed us to establish in this last report the methods that seem the most relevant to maintain or develop with an analysis of their maturity level. A sub-section is dedicated to each of these solutions in section 5 to identify the actors of these solutions and their work, and above all to specify the actions that could be taken in the future to promote the production of FRM in operational mode and their potential deployment sites.

The main measurement methods identified are the following:

- recurrent maintenance of airborne measurements
- development and operation of polar drones
- adaptation of buoys to space needs
- reinforcement of the deployment and exploitation of ULS
- exploitation of the SIMS

We have also identified an essential parameter that is currently very rarely observed: snow depth. Whatever the support considered (aircraft, drone, buoy, SIMS) it is essential to associate as frequently as possible a snow radar to reconstitute the measurements necessary for the validation of the radar freeboard measured by space altimeters.

Whatever the method implemented, the transition to operational requires upstream planning of the post-processing and distribution chains. Indeed, this step is often underestimated and results in considerable delays in the production of FRM. These delays, which can exceed one year, necessarily have an impact on the validation of spatial data and their evolution.

Finally, we underline the fact that validation data of the ice pack are currently extremely rare, even almost non-existent in Antarctica and during polar summers. Thus, it is necessary to support, gather, process and distribute acquired data or on-going time-series whether they meet all the criteria to be qualified as FRM.