Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)

Roadmap for S3 STM Land FRM operational provision over Land Ice

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4	0	M	ALL	All pages have been modified following the re-organization of the whole document.
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* *I = Inserted* *D = Deleted* *M = Modified*

Acronyms

AD	Applicable Document
AIPo	Agenzia Interregionale del Fiume Po
AOI	Area Of Interest
ALS	Airborne Laser Scanner
ATM	Airborne Topographic Mapper
AUV	Autonomous Underwater Vehicle
AWS	Automatic Weather Stations
BVLoS	Beyond Visible Line of Sight
CEN	Centre d'Etudes de la Neige
CGLS	Copernicus Global Land Service
CO	ESA Contract Officer
CS-2	CryoSat-2 mission
CSV	Comma-Separated Values
DEM	Digital Elevation Model
DMS	Digital Mapping System
EEA	European Environment Agency
EGIG	Expéditions Glaciologiques Internationales au Groenland
EM	Airborne Electromagnetic Induction
EOB	End Of Business
ESA	European Space Agency
EU	European Union
FB	Sea Ice Freeboard
FFP	Firm Fixed Price
FFSAR	Fully Focused SAR
FIR	Flight Information Regions
FM-CW	Frequency-modulated continuous-wave radar
FOEN	Federal Office for the Environment
FR	Final Review
FRM	Fiducial Reference Measurement
GCP	Ground Control Points
GEM	Ground based ElectroMagnetic
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
GPS	Global Positioning System

GRDC	Global Runoff Data Centre
GRP	Ground Reference Point
HDD	Hard Disk Drive
HR	High Resolution
IMB	Ice Mass Balance
INS	Inertial Navigation System
IOCR	In-Orbit Commissioning Review
ISPRA	Instituto Superiore per la Protezione e la Ricerca Ambientale
KO	Kick-Off
KOM	Kick-Off Meeting
L1	Level 1
L2	Level 2
LAM	Low Altitude Mode
LOCSS	Lake Observations by Citizen Scientists & Satellites (OECS in France)
LVIS	Land, Vegetation and Ice Sensor
LRM	Low Resolution Mode
MFF	Multi-annual Financial Framework
MoM	Minutes of Meeting
MPC	S3 Mission Performance Cluster
MSS	Mean Sea Surface
MVP	Minimum Viable Product
N/A	Not Applicable
NMI	National Metrology Institute
NWD	Normal Working Day
OC	Operational Challenges
OCOG	Offset Centre Of Gravity
OIB	Nasa Operation IceBridge
OLTC	Open Loop Tracking Commands table
OS	Operating System
OSSE	Observing System Simulation Experiments
PACF	Permanent Altimeter Calibration Facility
PDF	Portable Document Format
PM	Progress Meeting
PMP	Project Management Plan
POCA	Point Of Closest Approach
PPK	Post Processed Kinematic

PPP	Precise Point Positioning
PRF	Pulse Repetition Frequency
QWG	Quality Working Group
R&D	Research & Development
RD	Reference Document
RO	Routine Operational Phase
RTK	Real-Time Kinematic positioning
RULS	Range Under the Level of the Sonic gauge
S3	Copernicus Sentinel-3 mission
S3VT	Sentinel-3 Validation Team
S4B	Skype For Business
S6	Copernicus Sentinel-6 mission
SAMS	Scottish Association for Marine Sciences
SAR	Synthetic Aperture Radar
SCalSIT	Super CalVal Site Identifier Tool
SI	Système International
SILDAMS	Sea-Ice Lead Detection Algorithm using Minimal Signal
SIMBA	Snow and Ice Mass Balance Array
SLA	Sea Level Anomaly
SMB	Surface Mass Balance
SMP	SnowMicroPen
SR	Sonic Ranger
SRAL	Synthetic Aperture Radar Altimeter
SIRAL	CryoSat's SAR Interferometric Radar Altimeter (SIRAL)
SSH	Sea Surface Height
St3TART	Sentinel-3 Topography mission Assessment through Reference Techniques
STM	Surface Topography Mission
SWOT	Surface Water and Ocean Topography mission
TC	Technological Challenges
TD	Technical Deliverable
TO	ESA Technical Officer
UAV	Unmanned Aerial Vehicle
ULS	Upward Looking Sonar
UWB	Ultra-Wideband
VC	Video-Conference
WP	Work Package

Reference documents

N°	Reference	Title
[RD1]	ESA-EOPG-CSCOP-SOW-29, Issue 1 Rev. 4 – 28/10/2020	Statement of Work - Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)
[RD2]	NOV-FE-0899-PR-002	Technical Proposal
[RD3]	NOV-FE-0899-PR-004	Implementation Proposal
[RD4]	ESA Contract No. 4000135181/21/I-DT	ESA Contract – Copernicus ground segment Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)
[RD5]	NOV-FE-0899-NT-040	Acronyms list
[RD6]	https://sentinel.esa.int/nl/web/sentinel/user-guides/sentinel-3-altimetry	Sentinel-3 Altimetry USer Guide
[RD7]	https://sentinel.esa.int/nl/web/sentinel/technical-guides/sentinel-3-altimetry/	Sentinel-3 Altimetry Technical Guide
[RD8]	S3MPC-STM_RP_0038 (Issue 1.1)	Sentinel-3 SRAL/MWR Land User Handbook
[RD9]	NOV-FE-0899-NT-044	TD-3 FRM Protocols and Procedure for S3 STM Land Ice Products
[RD10]	CLS-ENV-NT-22-035	St3TART WP 3.2.3: Cross-Platform validation with ICESat-2
[RD11]	CLS-ENV-NT-23-0001	St3TART WP 3.2.4: HR-DEM applications for land ice altimetry
[RD12]	https://qa4eo.org/	GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO)
[RD13]	https://promice.org/	Programme for monitoring of the Greenland Ice Sheet & Greeland climate network
[RD14]	https://glacioclim.osug.fr/-Antarctique-	GLACIOCLIM Observatory - Antarctica
[RD15]	https://earth.esa.int/eogateway/campaigns/	ESA Cryovex campaign data and reports
[RD16]	https://icebridge.gsfc.nasa.gov/	Operation IceBridge campaign portal
[RD17]	https://www.scar.org/science/rings/home/	RINGS Action Group in SCAR
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1. Introduction

1.1. Purpose and scope

This document is the Roadmap for S3 STM Land FRM operational provision for the "Sentinel-3 Topography mission Assessment through Reference Techniques (St3TART)" project, [RD1].

As agreed with ESA, this document is specific to the Land-Ice surface type.

An executive summary report covering the three surface types considered in St3TART (Hydrology, Sea ice and Land ice), and identifying the synergies between them, is provided as a scientific paper (see [RD43] for more information).

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:

- Scope of the roadmap
- Surface-specific observational considerations: what are the observational challenges over land ice and how to address them in the design of FRMs, e.g. signal penetration, surface slope/roughness.
- Assessment of existing sensors and observational programs for S3 FRM, including traceability diagrams, uncertainty budgets and compliancy matrices for the selection of suitable FRMs.
- Summary of WP3.2.3 and WP3.2.4 about cross-validation with ICESat-2 and high-resolution DSMs for improved processing and validation, with more details in supplementary technical reports (Annexes 1 and 2).
- Recommendations for future operational FRMs including basic budgets

2. Scope of the roadmap

This roadmap aims to provide a guideline for establishing operational validation of Sentinel-3 SAR altimeter Land data products over land-ice surfaces using Fiducial Reference Measurements (FRMs). It builds upon the accompanying document “FRM Protocols and Procedure for S3 STM Land Ice Products” [RD9], where we have reviewed past satellite altimetry calibration-validation (Cal-Val) activities and defined suitable FRM validation data, including characterization of measurement sites, instruments, traceability, and uncertainty budgets. Here, we focus on the most needed FRM programs for land ice and how they can be designed and maintained in a cost-efficient way. We recommend employing a combination of long-term observational stations and dedicated campaigns with airborne or ground-based surveys.

Although the quality aspects of FRM rank high, we also recognize the inherent difficulty in obtaining stable and representative in situ measurements in the remote and harsh conditions of glaciers and ice sheets. Some level of pragmatism is therefore needed, and we try to account for that in the uncertainty budgets, acknowledging that the ideal conditions of a station mounted on solid ground seldom apply to the changing surfaces of snow and ice, where logistical access for maintenance is often limited to once a year in the spring or summer season. A key question to be considered is also the spatial representativeness of FRM stations, both at the local scale of evolving sastrugi and surface roughness within a S3 footprint, as well as the locational separation between a station and the Point Of Closest Approach (POCA) to the satellite, which can deviate by several kilometres from nadir due to surface topography.

FRM campaigns with airborne or ground-based sensors are needed to achieve actual coverage of validation data over S3 ground tracks, as well as to obtain sufficient statistics for quantifying S3 errors and uncertainties. It is also a way to extend local FRM stations to the scale of S3 footprints and the varying locations of POCAs. Recommendations on these matters are based on sensor characteristics and feasible survey coverages with respect to S3 ground tracks.

Even with extensive observational campaigns, it is impossible to validate S3 over all surface types and conditions, so we also demonstrate the added value of cross-comparisons with ICESat-2 laser altimetry for this purpose (Annex 1 [RD10]). ICESat-2 performances are reported close to airborne lidar data over land ice. This is valuable for the assessment and evaluation of Sentinel-3 performances, as robust and representative statistics can be derived from the large population of nearly co-located measurements.

In another technical study (Annex 2 [RD10]), we show that the extraction of topography parameters from high resolution digital elevation models (HR-DEM) is valuable to assess the sensitivity of altimetry measurements to surface topography variations within the footprint. HR-DEM can be further used for improving the S3 processing itself through a more precise POCA relocation. It can also be used to compensate for relative topographic differences between FRM stations and S3 ground tracks, as well as between near repeat-tracks when they are to be compared for estimation of surface elevation changes.

3. Theoretical definition of what is needed/missing

In this document we consider land ice as any glacier or ice sheet on Earth's surface, including ice shelves. This means that we have to consider a wide range of surface topographies and properties, ranging from steep mountain glaciers to relatively flat ice sheets, as well as from wet to dry snow conditions imposing variable backscattering conditions for radar altimetry waveforms. Whereas conventional satellite altimeters like ERS and Envisat have mainly been used over the inland ice sheets of Greenland and Antarctica (e.g. Wingham et al., 1998), the invention of higher resolution satellite altimeters using lidar (ICESat/ICESat-2) or interferometric SAR (CryoSat-2) have revolutionized the ability to monitor ice-sheet margins and polar glaciers and ice caps (e.g. Helm et al., 2014; Smith et al., 2020). Glaciological applications of Sentinel-3's SAR altimeter has so far focused on the ice sheets (McMillan et al., 2019), but with the improvements made in the delay-Doppler processing implemented in the ESA Land Ice Thematic processor [RD8], and perspectives brought in the improvement of the level-2 relocation processing, it is expected to be applied more widely over glaciers and ice caps. Therefore, future validation programs should also account for that.

Validation efforts need to cover the same range of environmental variables as the satellite data are planned to be used for, and quality requirements need to be adjusted accordingly. In order to detect ice thickness changes over the interior of ice sheets, the quality of individual altimeter measurements must be extremely high, whereas it is less critical for outlet glaciers and mountain glaciers that change much more rapidly. The measurement environment of coastal and mountainous areas is on the other hand much more challenging with substantial topographic variation within the altimeter footprint. Another challenge is the variable physical properties of snow which causes variation in radar signal penetration and backscatter, making it difficult to track the snow surface or a consistent reference horizon within the snowpack. For these reasons, validation of radar altimetry over land ice is not straightforward and needs to be adapted to a range of different conditions:

- Surface slope and roughness: errors increase with slope and the large-scale roughness (kilometre scale), as it can disrupt the waveform shape and complicate the estimation of POCA location;
- Snow/ice properties: penetration depth and backscatter vary between dry snow, wet snow and ice;
- Mountains: peaks and valley-sides may prevent or degrade glacier signal tracking and relocation.

All these factors are considered in the roadmap. We have to assess the S3 performances over a broad range of conditions, from the ideal to the most challenging ones, and also consider potential improvements in the S3 processing for the different conditions.

As important as the FRM quality is the spatial and temporal comparability with the altimetry data. It is important to plan FRM campaigns well ahead in accordance with satellite acquisitions and ground tracks. Hitting a ground track in near real-time is challenging both in terms of weather/glacier safety (blizzards, white-out, crevasses, etc.) and in the fact that the altimeter-derived surface elevations will typically not be from the nadir ground-track, but rather the point-of-closest-approach (POCA) to the satellite, which coincides with ridges and high-points in the terrain (Figure 1). This presents a two-sided problem; firstly, the altimeter return signal needs to be precisely retracked and relocated to the right POCA spots on the ground by utilizing a digital elevation model, and secondly the ground validation measurements should ideally be collected from the same spots. We propose two ways to overcome the co-location problem:

- Collect track-specific validation data along recently measured or predicted POCA tracks;
- Collect validation data in dense grids to obtain full coverage of POCA tracks.

The first approach is best suited for ground-based and/or UAV surveys where a snow vehicle or drone can be precisely navigated to follow a pre-defined POCA track, whereas the second approach is best suited for airborne surveys where larger areas can be surveyed in a shorter time, but where flight lines need to be relatively straight. In cases of predicted POCA locations, they need to account for typical deviations of ±1 km from the reference orbits (orbital drift), which can result in even larger POCA deviations (several km) depending on local surface topography. This issue can be addressed by looking at the spread of past POCA data from the same reference orbit, or by doing dedicated POCA simulations with a HR-DEM for different orbit scenarios. In areas with complex topography, the width of the survey area along a given reference track might be extended up to ~10-15 km, to cover all POCA variations.

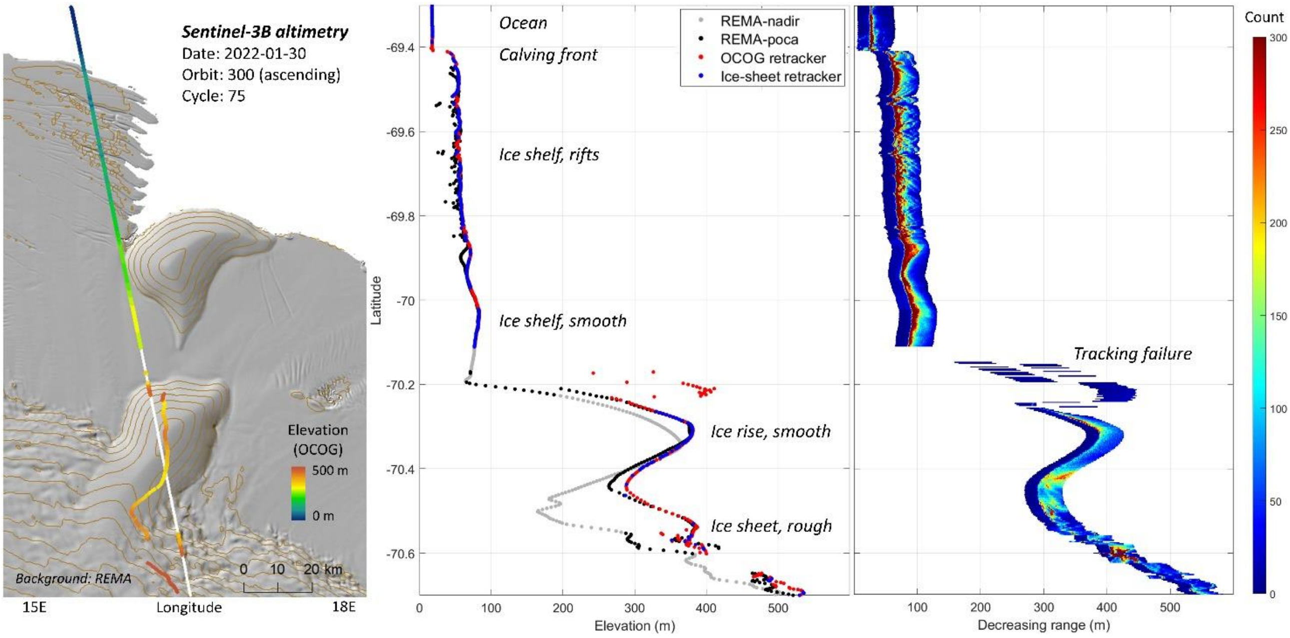

Figure 1 Example of a Sentinel-3 track across the coastal margin of the Antarctic ice sheet showing (left) POCA locations and elevations overlied a hillshade from the Reference Elevation Model of Antarctica (REMA, Howat et al., 2019), (middle) along-track elevation profiles as a function of latitude for ESA retrackers and REMA, and (right) corresponding waveforms shifted relative to their tracked range. Figure from [RD9].

In summary, the key observables that are needed from land-ice FRM programs are:

- Surface elevation, repeated ground-tracks or grids that cover multiple S3 ground-tracks;
- Surface elevation, time series for seasonal evolution and long-term trends at S3 footprint scale;
- Snow/firn properties (stratigraphy, density, temperature), for relation with volume scattering effects on surface-elevation estimates from Ku-band (Ka-band to a lesser extent).

The validation data should be collected from sites that are representative for the larger-scale monitoring of glacier and ice sheet mass balance with S3 altimetry, in particular ice sheet interiors (low-slope, cold conditions), ice sheet margins (medium slopes, seasonal climate) and polar ice caps or icefields (higher slopes, strong seasonality, widespread melting).

The use of S3 data over mountain glaciers and valley glaciers is still limited and explorative due to tracking failures, topographic shadowing and challenging POCA identification. For now, we do not recommend FRM development in mountainous areas, and suggest that efforts here should rather be put into:

- Defining Open Loop Tracking Commands (OLTC) to capture useful signal from selected land ice areas in the footprint, as closed-loop tracking is not suited to follow rapid topography variations of mountainous areas;
- Improving the level-2 relocation processing, by developing new approaches adapted to these complex areas (briefly shown in Annex 2 [RD11]).

4. Recommendations for FRM instruments and observations

The principles of FRM derive from guidelines provided by the GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO) [RD12]. ESA has defined FRM as *"the suite of independent ground measurements that provide the maximum science return for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the entire end-to-end duration of a satellite mission"* [RD1]. To assure compliancy with FRM standards, we followed a step-by-step meteorological approach to develop detailed FRM protocols and procedures [RD9], which are here used to develop a roadmap for FRM operations over the next five years on Arctic and Antarctic land ice. We start here by assessing existing infrastructure and sensors suitable for FRM, and then in Section 5 we present a strategy for operational provision.

4.1. Assessment of existing candidate infrastructure for FRM

Establishing FRM instruments on undeveloped glacier sites or new observational platforms is very costly and may take years to develop. Existing observational infrastructure also has the advantage of regular maintenance and additional data from past measurements and complementary sensors. Based on our review of past altimetry Cal-Val activities and relevant observational programs, we have compiled a selected list of candidate infrastructures for operational FRM, including permanent stations/installations (Table 1) and existing observational/logistical transects (Table 2). We have excluded relevant infrastructure/transects in Iceland, western Svalbard and Alaska because of limited S3 data coverage near the relevant glacier monitoring sites due to low latitude (Iceland, Alaska) or mountainous topography that obscures return points from lower-lying glaciers (Alaska and western Svalbard). We have also excluded research stations or monitoring sites in Greenland and Antarctica that do not have a regular maintenance schedule or that do not presently have relevant instrumentation on the ice sheet near S3 ground tracks.

For each of the selected observational infrastructures or transects, we have given ranks from A to C regarding the FRM suitability/readiness of existing instruments and observations (A = FRM suitable, B = partly FRM suitable, C = not FRM suitable) and the suitability of the site for Sentinel-3 validation (A = extensive nearby S3 coverage and low-slope/smooth surface, B = extensive nearby S3 coverage or low-slope/smooth surface, C = flat ice shelf affected by ocean tides). Additional notes of '+' or '-' indicate further positive or negative judgements within each of the ranks. A relatively flat and smooth topography is required for the highest rank here because it makes it easier to locate an S3 target and the S3 signal disturbances will be less. However, it should be noted that FRM data are also needed for higher slopes (e.g. ice cap/sheet margins) and rougher surfaces (e.g. sastrugi, ice streams, ablation areas) where most glacier and ice sheet changes occur and where satellite-based monitoring is actually most important.

Table 1 – Selected infrastructure sites operated by ESA member states and suitable for S3 land-ice FRM development.

Region	Site	Location	Institute / station	Years of data	Instruments*	Surface type	Slope	S3 dist.	Service	Area surveys	Ref.	FRM rank	Site rank
Antarctica	Cap Prud-homme	66.7°S 139.8°E 0-500 m asl.	IGE, IPEV / GlacioClim	2005->	3 sites with AWS, SR, GNSS	Ice sheet margin, snow	Low	A few km	Annual, summer	Annual	RD14	A	B
Svalbard	Austfonna ice cap	79.7°N 22.2°E 200 m asl.	NPI, U. Oslo	2004->	AWS, SR, GNSS	Ice cap margin, snow/ice	Low	800 m, S3A/B crossover	Annua, spring	Annual	RD31	A-	B+
Greenland	Greenland Ice Sheet	Network around ice sheet	PROMICE / GC-NET, GEUS	2007->	AWS, SR, GNSS	Ice sheet margin, snow/ice	Low	Variable for each station	Annual, summer		RD13	B	B
Canadian Arctic	Devon Ice Cap	75.3°N 82.2°W 1800 m asl.	U. Alberta, Nat. Env. Canada	1960->	AWS, SR	Ice cap summit, snow	Medium	At S3A nadir	Annual, spring	Annual	RD21	B	B
Antarctica	Dome C	75.1°S 123.3°E 3200 m asl.	IGE, IPEV / GlacioClim	2005->	1 site with AWS, SR,	Ice sheet plateau, snow	Flat	At S3A nadir	Annual, summer	Occas.	RD14	B	B
Antarctica	Ekström Ice Shelf	70.6°S 8.3°W 20 m asl.	Neumayer Station	1992->	AWS, SR, GNSS	Ice shelf, snow	Flat	5 km from S3A nadir	Cont.	Occas.	RD25	A-	C

Region	Site	Location	Institute / station	Years of data	Instruments*	Surface type	Slope	S3 dist.	Service	Area surveys	Ref.	FRM rank	Site rank
Greenland	Flade Isblink ice cap	81.5°N 16.6°W 700 m asl.	Station Nord, Aarhus U.	2006	No	Ice cap margin, snow/ice	Low	S3 polar limit on ice cap			RD36	C	B+

*AWS = Automatic Weather Station, SR = Sonic ranger

The established infrastructure sites and observational/logistical transects are attractive for FRM development as they are regularly visited and typically have secured maintenance through respective national polar programs. If sufficient competence and capacity exist, additional Cal-Val activities can be carried out at a relatively low cost compared to establishments in new areas. From the infrastructure sites in Table 1, the PROMICE/GC-NET network of Automatic Weather Stations (AWS) stands out for the Greenland Ice Sheet [RD13], and for the Antarctic Ice Sheet, the IGE GlacioClim network between the coastal and inland research stations in Adèlie/Wilkes land [RD14] stands out for having multiple stations in different ice sheet environments. Within these AWS networks, it should be feasible to identify suitable FRM sites that are at or nearby Sentinel-3 POCA tracks, as outlined in Section 5 for GlacioClim sites.

Research stations in polar regions can provide excellent support for Cal-Val activities, but are typically located on solid ground at the coast, or in the case of Antarctica; on floating ice shelves or mountain nunataks in the inland. There are thus few stations with existing instrumentation that can be employed for land-ice FRM purposes, but some of them have nearby land-ice areas that could be suitable for development. It is beyond the scope of this report to address all these cases, so we have only included the German Neumayer Station and the French/Italian Dome Concordia Station in East Antarctica which are located on a flat snow-covered ice shelf and a high inland plateau, respectively. Both stations have long-running climate/snow observational programs, but Dome C is challenged by extremely cold conditions on the plateau and Neumayer by ocean tides which need to be corrected in Cal-Val applications.

Table 2 – Selected observational and/or logistical transects by ESA member states with potential for future S3 FRM use.

Region	Site	Location	Length	Institute	Years of data	Instruments	Surface type	Slope	# of S3 profiles	Freq.	Ref.	FRM rank	Site rank
Antarctica	SAMBA transect	76.1°S 123.3°E 0-157km	157 km	IGE, IPEV / GlacioClim	2004->	AWS, Kin. GNSS, radar, stakes	Ice sheet	0-2 deg.	>5 across	Annual, summer	RD14	A-	A
Antarctica	Cap Prudhomme – Dome C	66.7°S 139.5°E 0.4-3 km	950 km	IGE, IPEV / GlacioClim		AWS, radar	Snow, sastrugi	0-1 deg.	>20 across, >5 along	Annual, summer		A-	A
Svalbard	Austfonna ice cap	79.7°N 22.2°E 0-800 m	>20 km	NPI, U. Oslo	2004->	Kin. GNSS, radar, stakes	Ice cap, snow	0-3 deg.	5-10 across	Annual, spring	RD31	A-	B+
Canadian Arctic	Devon Ice Cap	75.3°N 82.2°W 0-1800 m	>20 km	U. Alberta, Nat. Env. Canada	1961->	Kin. GNSS, radar, stakes	Ice cap, snow	0-5 deg.	5-10 across	Annual, spring	RD21	B+	B
Antarctica	Neumayer - Kohnen Station	75°S 4°E 0-2.9 km	750 km	AWI			Snow, sastrugi	0-2 deg.	>20 across, >5 along	Ocass.		C	A
Greenland	EGIG-line	70°N 45°W 0.5-3 km	<600 km	EGIG*, ESA CryoVEx, and partners	1957->	Ice drill	Ice sheet, snow	0-3 deg.	>20 across	Ocass.	RD33	C	A
Greenland	K-Transect	67°N 48°W 0.5-2 km	140 km	IMAU Univ. Utrecht	1990->	AWS, stakes	Ice and firn	0-3 deg.	>10 across	Annual, summer	RD38	C	A
Antarctica	Coast – Prince Elisabeth Station	72.0°S 23.2°E 0-1400 m	200 km	Int. Polar Foundation, Belgium		stakes	Snow, sastrugi	0-2 deg.	>15 across, 2 along	Annual, summer		C	A-
Antarctica	Coast – Troll Station	72.0°S 2.5°E 0-1300 m	250 km	NPI			Snow, sastrugi	0-2 deg.	>20 across, 2 along	Annual, summer		C	A-

**EGIG = Expéditions Glaciologiques Internationales au Groenland

For glaciers and ice caps, where recent ice mass losses have been comparable to the much larger ice sheets (e.g. Hugonnet et al., 2021), it is natural to focus on the high-latitude polar ice caps where the Sentinel-3 track spacing is dense and where the additional validation aspects of seasonal surface melting and higher surface slopes can be readily assessed. Austfonna Ice Cap on Svalbard and Devon Ice Cap in Arctic Canada stand out for their vast sizes and annual field activities through monitoring programs for surface mass balance. These two sites also have a Cal-Val legacy from past CryoVEx campaigns with coordinated airborne (ASIRAS radar, and ALS lidar) and ground-based (kinematic GNSS and radar) surveys, see e.g. Hawley et al. (2013), Gray et al. (2015) and Morris et al. (2021). Another interesting glacier site we have identified is Flade Isblink Ice Cap in northeastern Greenland which is located near Villum Research Station, Station Nord, where an airstrip and other logistical facilities are in place, but no glacier observational program currently exists. The research station is located near the ice cap edge, 20 km north of the latitudinal limit of Sentinel-3 (81.4°N) where ascending/descending ground-tracks converge and gives the densest possible data sampling. This latitudinal zone is particularly suitable for altimetry Cal-Val activities as demonstrated by Brunt et al. (2019) who carried out a ground-based GNSS transect along the 88°S parallel to validate the ICESat-2 mission at its southern limit in Antarctica.

The selected list of observational/logistical transects that have FRM potential (Table 2) are dominated by established transects for surface mass balance or satellite Cal-Val in the Arctic and by logistical supply routes from the coast to inland research stations in Antarctica. The Expéditions Glaciologiques Internationales au Groenland (EGIG) line across the western side of the Greenland Ice Sheet has a long history of glaciological observations, particularly ice coring and airborne radar through the CryoVEx program, e.g. Morris et al. (2017), Overly et al. (2019), and Otosaka et al. (2020). However, there is no fixed monitoring program on the EGIG-line as opposed to the K-transect further south on the ice sheet where stakes and weather stations are maintained every summer for monitoring of surface mass balance and climate (Smeets et al. 2018). At either location, longer ground-based survey transects are typically not carried out.

Table 3 – Selected airborne or ground-based campaign data of surface elevation relevant for S3 validation since 2016.

Region	Name	Site	Location	Type	Length or area	Institute	Years of data	Type of data	Surface type	Slope	# of S3 profiles	Ref
Svalbard	CryoVEx IceBridge SMB*	Austfonna ice cap	79.7°N 22.2°E 0-800 m	Grid Profiles	2500 km2 1000 km2 200 km 500 km	ESA/DTU NASA NPI/UofO	2016-> 2017 2017 2016->	Lidar/radar Lidar/radar GNSS/radar	Ice cap, snow	0-3 deg.	>10 >20 >10 >10	RD15 RD16 RD31
Canadian Arctic	IceBridge SMB*	Devon Ice Cap	75.4°N 83.2°W 0-1800 m	Profiles Profiles	400 km 2000 km Variable	NASA NRC/UA	2017 2019 2016->	Lidar/radar GNSS/radar	Ice cap snow	0-5 deg.	>10 >20	RD16 RD21
Canadian Arctic	IceBridge	Other ice caps	Various	Profiles	5000 km 1000 km	NASA	2017 2019	Lidar/radar	Ice cap snow	0-5 deg.	>50 >20	RD16
Greenland	IceBridge	Flade Isblink ice cap	81.5°N 16.6°W 0-700 m	Profiles	100 km 200 km	NASA	2018 2019	Lidar/radar	Ice cap snow	0-3 deg.	>10 >20	RD16
Greenland	CryoVEx IceBridge	EGIG-line	70°N 45°W 0.5-3 km	Profiles Profiles	600 km	ESA/DTU NASA	2016 2017 2019 2022 2017 2018 2019	Lidar/radar Lidar/radar	Ice sheet, snow	0-1 deg.	>20	RD15 RD16
Greenland	IceBridge	Ice sheet	Various	Profiles	10000s km	NASA	2016-2019	Lidar/radar	Snow and ice	0-3 deg.	>500	RD16
Antarctica	IceBridge	Ice sheet	Various	Profiles	10000s km	NASA	2016-2019	Lidar/radar	Snow	0-1 deg.	>500	RD16
Antarctica	CryoVEx	West Ant Adelaide Isl.	Various	Profiles	1000s km	ESA/DTU	2018 2022	Lidar/radar	Snow	0-1 deg.	>100	RD15
Antarctica	EAIIST-traverse	Dome C – South Pole	75-90°S 123E 3000 m	Transect	1700 km	France, Italy, US	2019	Kin. GNSS, radar, cores	Snow, flat	0-1 deg.	>20	RD28
Antarctica	ASUMA-traverse	Dome C region	75°S 123E 3000 m	Transect	>500 km	France	2016	Kin. GNSS, radar, cores	Snow, flat	0-1 deg.	>20	RD28
Antarctica	Vostok station	Lake Vostok	78.5°S 106.8°E	Profiles	Variable	Russia	Annual	Ice sheet, snow	Snow, flat	0 deg.	>20	RD37

			3200 m									
Antarctica	CHINARE	Traverse to Taishan Station	70-74°S 75°E 0-3km	Transect	150 km	China	2020	Ice sheet, snow	Snow, flat	0-1 deg.	>50	RD27
Antarctica	Oldest Ice	Dome Fuji survey	78°S 39°E 3800 m	Profiles	1100 km	Japan, Norway, US	2018	Ice sheet, snow	Snow, flat	0-1 deg.	>20	RD41

*SMB = Surface Mass Balance, annual field programs

Surface mass balance measurements on Austfonna and Devon ice caps are typically carried out as annual snow vehicle traverses equipped with GNSS and snow radar, with good potential for additional Cal-Val surveys under nearby Sentinel-3 ground tracks. This has been shown to be useful for validation of CryoSat-2 (Gray et al., 2015; Morris et al., 2020) and is expected to apply similarly for Sentinel-3. Similar types of observations are also done regularly along the GlacioClim stake transect from Cap Prudhomme to the inland ice sheet in East Antarctica and occasionally elsewhere as a part of logistical supply traverses (e.g. Li et al., 2021) or dedicated science traverses (e.g. Kohler et al., 2013; Larue et al., 2021). This could also be done for other fixed logistical traverse routes at a relatively low extra cost, for example to the inland French/Italian Dome Concordia Station, Norwegian Troll Station, and Belgian Prince Elisabeth Station (Table 2).

Existing campaign data of surface elevation and snow/firn properties can also be highly useful for Sentinel-3 validation (Table 3). There has been three springtime CryoVEx campaigns over land ice in the Arctic (2016, 2017 and 2019) and one campaign in West Antarctica (2017-2018) since the launch of Sentinel-3 in February 2016 [RD15]. Operation IceBridge campaigns have been even more extensive with annual campaigns during 2016-2019 for both the Arctic and Antarctica [RD16]. These airborne campaigns carried lidar and radar instruments in various configurations, mainly aimed at comparisons with CryoSat-2 and ICESat-2, but equally relevant for Sentinel-3. Some of the campaigns were also coordinated with field activities along the EGIG-line in Greenland and various transects on Austfonna and Devon Ice Caps. There has also been a number of relevant field-transects in Antarctica during the Sentinel-3 period, and we have listed surveys with published or known data in Table 3.

The RINGS project within the Scientific Committee on Antarctic Research is worth to mention as a near-future ambition for internationally coordinated airborne surveys around coastal Antarctica [RD17]. The primary aim is radar/gravity mapping of subglacial bed topography along the Antarctic grounding line for improved estimates of ice discharge and sea level contribution, but it is also desired to measure precise surface elevations with lidar and snow accumulation with radar (Matsuoka et al., 2022). A first survey is intended for Enderby Land, East Antarctica, in austral summer 2023-2024, and more regions will likely follow in the years to come.

4.2. Assessment of existing and new FRM platforms and sensors

Sensors are described in TD-3 [RD9] and are summarized below (Table 4) for selected types, commonly used in ESA CryoVEx campaigns and at in-situ sites on land ice. The airborne sensors are common to those used over sea ice and described in more detail in the associated St3TART deliverables for sea ice (TD-2 and TD-6).

Table 4 – Overview of instruments and platforms relevant for FRM

Instrument	Model	Platform	Coverage	Scale	Measurement
Airborne Laser Scanner	ALS (Riegel)	Fixed winged	Regional	S3 underflights and grids, 10-100 km scales	Surface elevation
Ku-band radar (13.5 Ghz)	ASIRAS (MetaSensing)	Fixed Winged	Regional	S3 underflights and grids, 10-100 km scales	Ku-band backscatter and retracked surface elevation at a frequency similar to S3. Snow penetration to be considered in comparison with coincident ALS.
Ka-band radar (34.5 Ghz)	KAREN (MetaSensing)	Fixed Winged	Regional	S3 underflights and grids, 10-100 km scales	Ka-band backscatter and surface elevation, expecting minimal snow penetration.
Lidar	Various	UAV/drone	Local	S3 footprint scales	Surface elevation, gridded as DSM, derived slope and roughness
Camera	Various	UAV/drone	Local	S3 footprint scales	Surface elevation, gridded as DSM, derived slope and roughness
GNSS	Trimble, Leica	Station (static) and snowmobile (kinematic)	Local and regional	Point (station) and regional (10-50 km)	Surface elevation, absolute (PPP) or differential vs. base station
Snow radar	Various	Snowmobile	Local and regional	10-50 km	Backscatter and snow properties/depth
Ultrasonic surface ranger	Campbell Scientific SR50A	Station	Local	Point measurement	Surface level
Multipoint Scanning Snowfall Sensor	MSSS – SDMS40	Station	Local	Multipoint measurement	Surface level

4.3. Cross-platform validation with ICESat-2

As a part of the St3TART project activities for land ice, CLS investigated how cross-platform validation with ICESat-2 laser altimetry can aid the validation of Sentinel-3 in Antarctica and Greenland. Since the analysis has the form of a technical study rather than a review or roadmap, it is provided as a supplementary report, Annex 1 [RD10]. Current performances reported in the scientific literature show that ICESat-2 is a stable reference for Sentinel-3, with insignificant surface penetration and low sensitivity to surface slope and roughness. The study shows that there are vast amounts of overlapping of Sentinel-3/ICESat-2 measurements over the Antarctic and Greenland ice sheets. Over the ideal surface of Lake Vostok (flat, smooth and stable) there is a 13 cm standard deviation between surface topography estimated by Sentinel-3A and ICESat-2. The performance of Sentinel-3 gradually degrades with increasing surface slope and large-scale roughness. Elevation biases due to signal penetration can be kept at a minimum if retracking thresholds are carefully chosen. But a constant retracking threshold will not estimate a constant backscattering horizon, depending on snow conditions and surface topography variations within the footprint (affecting the Ku-band waveform shape).

4.4. High-resolution DEMs for S3 processing and validation

In addition to the cross-comparison with ICESat-2, CLS and LEGOS have also carried out a technical study of how high-resolution satellite DSMs can be used to improve processing and validation of Sentinel-3 in sloping or rough land-ice terrain such as ice-sheet outlets and mountain glaciers. This work is presented in another report, Annex 2 [RD11]. It reviews available high-resolution DEMs over land ice (REMA, ArcticDEM, HMA, etc.) and demonstrates how they can help to assess Sentinel-3 performance over complex topographies such as megadunes, ice-sheet margins, and valley glaciers. High-resolution DEMs are particularly useful for precise relocation of the retracked surface elevation which can be several kilometres across-track from nadir for Sentinel-3. CLS is currently developing a new level-2 relocation algorithm, based on numerical facet-based simulations achieved with such HR-DEMs. With this innovative approach, first results show that the mission performances are significantly improved compared to the other state-of-the-art relocation algorithms.

5. Strategy for operational FRM provision over Land Ice

As described in TD-3 [RD9], there are two fundamental approaches to provide FRM over land ice. The first approach is to install a fixed ground station that takes pseudo-continuous measurements at a frequency greater than the time between satellite overpasses. Secondly, there are airborne or in-situ survey campaigns that provide profiles of absolute height along tracks that cross the satellite observations. Such absolute survey campaigns can be performed by moving instruments on the ground (e.g. GNSS on a snow vehicle), or from aircraft (crewed or drone, equipped with lidar, radar or photogrammetry). For either approach, the FRM should be optimized with regards to S3 data coverage and overpasses, and auxiliary data on snow properties should be collected to address impacts of signal penetration and volume scattering. FRMs over flat and smooth surfaces will provide the most precise validation, but it is also important to assess Sentinel-3 performance over sloping and rough surfaces found over the ice sheet margins and polar ice caps. This is critical, as some of these areas are experiencing the most rapid changes in context of global warming, and therefore must be carefully monitored..

This section provides recommendations for how an operational FRM program can be designed and maintained, including a budget break-down for different instrumentational setups at a selected location in East Antarctica. The strategy is applicable to other locations as well, but cost levels might vary for logistical reasons. As for TD-3 [RD9], we have chosen to focus mainly on a fixed-station setup with associated local field surveys. Regional-scale observational campaigns are highly scalable and dependent on logistical costs associated with ground-traverses or airplane overflights. Airborne campaigns are discussed in more detail in the associated sea ice reports (TD-2 and TD-5) and it is advisable to combine campaigns between the two surfaces for efficiency and cost saving.

5.1. FRM stations

5.1.1. FRM station setup

One of the proposed ways to get FRM is to install fixed ground stations at selected S3 POCA locations. A GNSS receiver would be placed near the other instruments to act as an absolute positioning reference. The GNSS would be fixed at the ice surface, but then moving with the ice. The antenna's ellipsoidal height is directly measured by the GNSS, whereas its height above the real surface continuously changes with snow accumulation and erosion. GNSS positions would be retrieved using the PPP technique. The relative height of the antenna above the surface would be retrieved using laser scanning or ultrasonic rangers. To account for small scale spatial and temporal surface height fluctuations and minimize the impact of small-scale surface roughness variations (e.g. sastrugi) and make the FRM surface-elevation time series more robust, the fixed station should ideally consist of several surface-measuring instruments spaced a few metres apart, whose data are cross-compared for errors and averaged into a time series.

A Multipoint Scanning Snowfall Sensors (MSSS) and several sonic gauges (or rangers) would allow to monitor, and average the variations in height of the antenna above the surface in a small area of a few m^2. The MSSS samples at 36 positions an area of the size of a few m^2. When using sonic gauges, it is necessary to employ 7 to 10 instruments within a confined area for a comparable coverage to MSSS (see schematic of either setup in Figure 2). In Antarctica where small-scale roughness in form of sastrugi is widespread, we recommend multiple surface level measurements. Surface level should be measured on an hourly time step and assessed with a MSSS (multi-point scanning snowfall sensor – called SDSM40 in Figure 2) or 7-10 sonic rangers. This will provide an averaged local reference elevation over a 5x5 m^2 area.

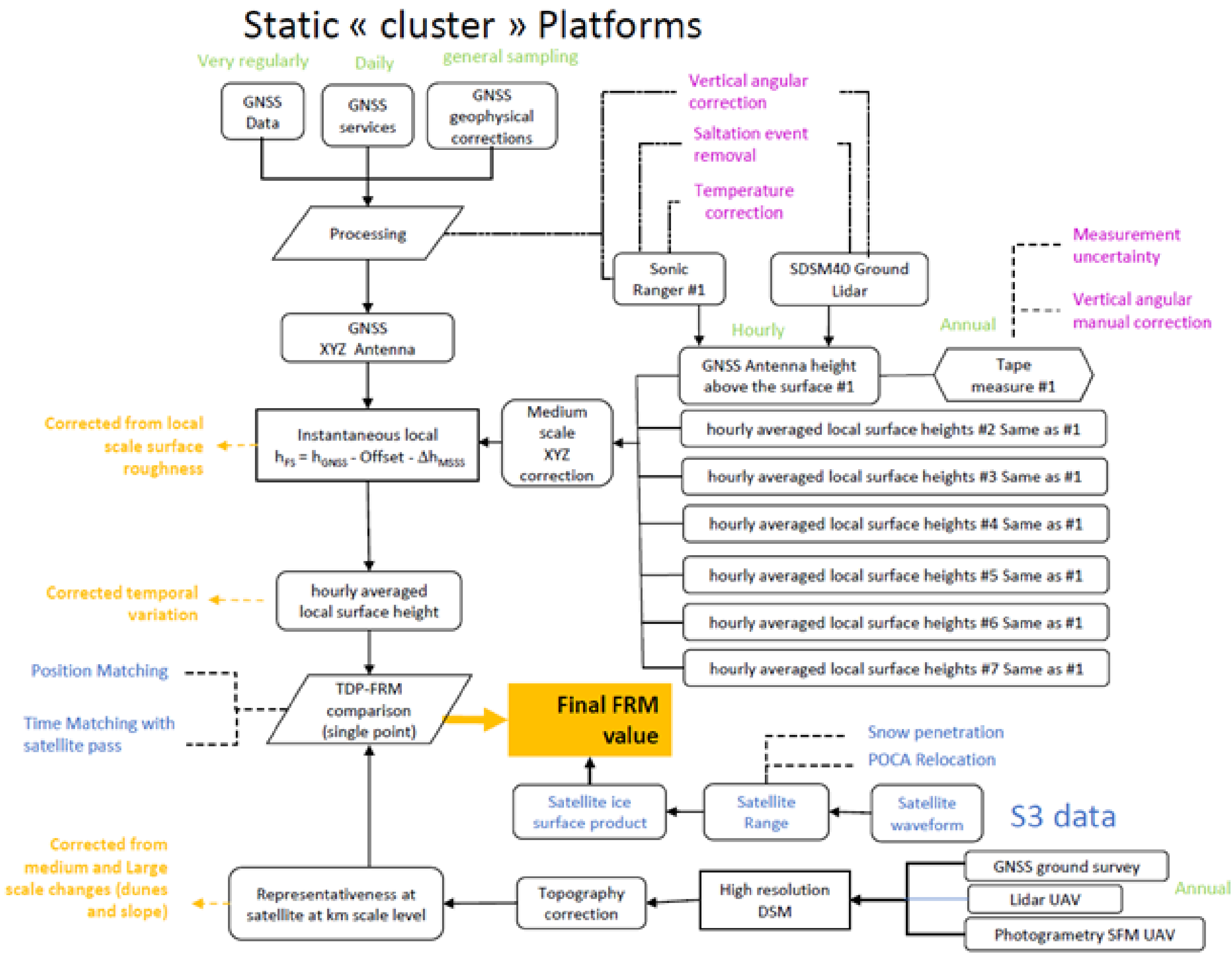

Figure 2 Schematic of a static platform for FRM. Figure from TD-3 [RD9].

The in-situ observations should be taken at a selected location near the theoretical nadir track orbit, or where POCA tracks are known to cluster due to surface topography. The satellite nadir point is meant to repeat on a 'theoretical orbit' ground track, however, in practice, due to orbit fluctuations, the actual orbit may differ from this theoretical ground track and may vary from orbit to orbit over scales of hundreds of metres. Hence, a digital surface model (DSM) would be also needed over the area that covers the possible POCA positions for multiple overpasses along the reference orbit, or orbits – if more than one orbit crosses near the in-situ instruments. This DSM can come from a local measurement campaign (by air or on the surface) and should cover a sufficiently large area to capture deviations in POCA trajectories from the fixed station. For a reasonably flat surface, the area needed can be defined by the potential variability of the nadir ground track, and an area of approximately 2 km diameter is suitable. For sites with significant topographic variability or slope, much larger areas may be needed. A priori analyses of the POCA locations along the S3 tracks would be valuable to precisely quantify the area extension needed. The DSM can then be used to transfer POCA heights to the height at the in-situ station or vice versa.

The DSM needs to connect the fixed station to the POCA sampling locations, for example with a survey that covers a few kilometres to either side, e.g. a circle with a diameter larger than 2 km. The reference DSM can be obtained with a drone/UAV, preferably updated annually. This DSM needs to be retrieved in summer when field campaigns are possible in Antarctica. The station-to-POCA height difference given by the DSM will be assumed to be valid for any time of measurement. The assumption is made that any changes between the time of the production of the DSM and the time of the satellite overpass of interest is either due to the windswept layer that is rapidly changing (and therefore reduced by averaging), or due the intermediate layer and averaging out for multiple POCAs.

5.1.2. Instrument costs

Sonic rangers are robust and have been tested over more than 25 years. They are currently the most appropriate sensor for FRM in Antarctica but to associate with temperature measurements. The MSSS, however, has not been tested over long time periods. For safety reasons, the use of sonic rangers will be the first choice before validation in the field of the MSSS. However, if the latter is robust in the field, then it will allow to easily scan a larger number of points over the surface and would thus be preferred for FRM setup. The local variations of elevation around the fixed station are then translated over a larger area using a DSM, obtained from UAV photogrammetry, UAV lidar or ground-based GNSS survey. Table 5 shows approximate costs for one FRM station with GNSS and AWS including surface rangers and a UAV for surveying the surface topography in the area between the station and S3 ground tracks.

Table 5 – Estimated cost of one station and of the UAV equipment

Item	Price* (1 unit)
AWS (with 7 sonic rangers) (option 1)	24.5k€
AWS with MSSS (option 2)	22.5k€
AWS with sonic rangers and MSSS (option 3)	33k€
GNSS + independent energy suplly	12k€
UAV** + camera	27k€

*estimated according to present price of sensors and electronics

**adapted to fly near the geomagnetic pole

5.1.3. Strategy and costs for deployment in Antarctica, case of Adélie Land

We consider Antarctica to be the most stable reference surface for Sentinel-3 land-ice validation due to its cold climate (minimal or no surface melting), gentle surface slopes (typically less than 1 degree) and relatively small ice thickness changes compared to the Arctic.

From the overview and ranks of suitable infrastructure and ground transects in Table 1 and Table 2, we can see that the logistical supply routes to inland stations are attractive locations as they are regularly visited. Observational mass-balance transects from the coast to the inland have already been done along some of these routes. For more than 20 years, IGE has contributed to the implementation of a continuous GPS and AWS network associated with long-term continuous measurements of surface mass balance with annual maintenance along a 157 km transect (called the SAMBA transect) in Terre Adélie (e.g. Agosta et al., 2012). This transect (approximately until Station 2 in Figure 3) is located along the French-Italian logistic traverse to Dome C and is visited every year. Measurements done as part of the French national glacier observatory (SNO-GLACIOCLIM) are expected to continue at least during the next decade. Several stations have already been installed under S3 orbits (ASUMA and EAIIST science traverses in 2016 and 2019, respectively). However, there are some improvements that need to be made:

1) the measurements along SAMBA transect are rarely made under the S3 orbit and do not cover areas as large as the S3 footprint,
2) they do not always meet the accuracy requirements for satellite validation,
3) the data are not yet delivered through a data portal and should become a part of a FRM data hub for S3 validation.

This would take advantage of the SNO-GLACIOCLIM logistics (Figure 3), which is already funded and done every year. A dedicated FRM station would be installed close to the intersection between ascending and descending S3 tracks, accounting for calculated POCA relocation.

Table 6 – Potential location of four FRM stations in Adélie Land, Antarctica

Location	Longitude (°)	Latitude (°)
Station 1	138.9505	-67.1456
Station 2	138.0505	-67.5483
Station 3	135.9875	-68.1200
Station 4	134.3516	-69.2972

We propose here two different scenarios with different consolidated costs related to the number of stations to be deployed in the field. We propose to install two stations along the Concordia Station supply route (Franco-Italian logistics). However, the installation and the annual maintenance of the stations will require the realization of a specific traverse because the time constraints of the logistic traverse are not adapted to the realization of additional science activities. In the case of the installation of two stations in the first 157 km from Cape Prud'homme (Stations 1 and 2 in Figure 3), the activities could be carried out in collaboration with the GLACIOCLIM-SAMBA program, and during the SAMBA traverse. However, if the installation of four stations (Stations 1-4 in Table 6 and Figure 3) up to 380 km from Cape Prud'homme is preferred, then a larger traverse would have to be organized.

The logistic means for this type of longer traverse can be carried out by IPEV in principle. However, IPE' capacities are limited and this is subject to the pressure of other implemented projects by IPEV. Investment and maintenance of a network would require to estimate and spread the cost of a logistical supply (more particularly an additional caravan, estimated total cost ~200k€) over the entire duration of long-term project of FRM. This would mean considering amortization of very expensive equipment, which cost would need to be discussed with the French Polar Institute (IPEV).

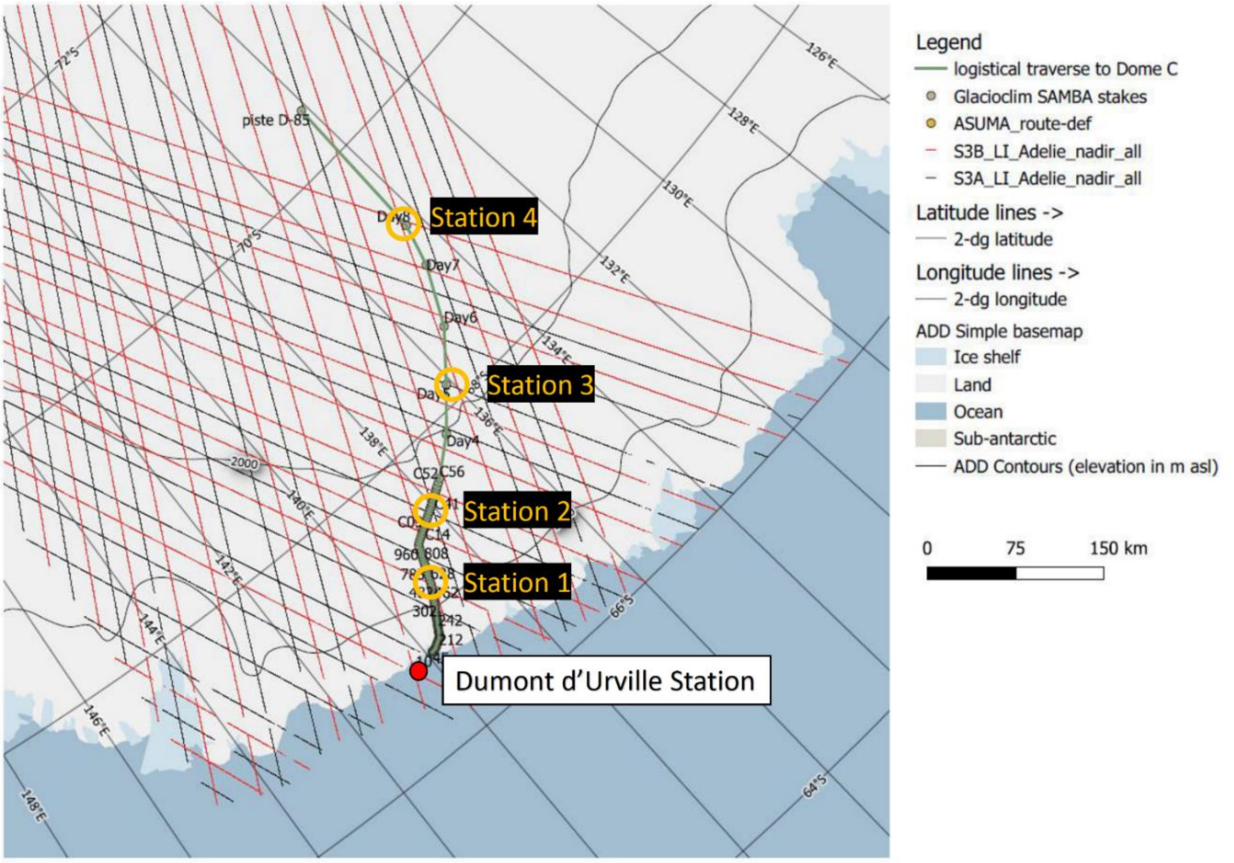

Figure 3 Map of Adélie Land, East Antarctica, showing potential station locations of static FRM platforms (orange circles). Green dots show the location of surface mass balance stakes along the logistical traverse route to Dome C (green line). Black and red lines are S3 nadir orbits.

If one or more fixed FRM stations would be installed along the route to Dome C (Figure 3), installing them at S3 POCA locations would require longer side trips to get away from the original route (Figure 4). This would induce extra costs. The four locations should be in relatively flat areas, and with moderate surface roughness (sastrugi height).

For the first year, additional costs would be associated with the development and installation of the stations. We consider here the salary of an engineer who would develop and build the stations, the price of each station (Table 5), and the cost of each field campaign (for installation, year 1). Three options are proposed for the stations based on the type of sensors that would be installed (Table 5). If MSSS is robust in the field, option 3 will be best suited. If funds are limited, an option with only a MSSS is possible. However, if it turns out that the MSSS is not robust in the field, the station would only be installed with sonic rangers. During following several years, the cost would be associated only with maintenance (Table 7).

Table 7 – Estimated cost of one station and of the UAV equipment

Year 1	**2 stations (130km inland)**	**4 stations (380 km inland)**
Equipment	116 k€	206 k€
Salary*	22 k€	32 k€
Logistics **	28 k€	73 k€
Total **	***167 k€***	***311*** k€
Other years		
Sensor rejuvenation***	20 k€	27 k€
Logistics**	23 k€	68 k€
Total**	***43 k€***	***95 k€***

*including salary during the installation in the field

**not considering amortization of very expensive equipment, whose cost would need to be discussed with the French Polar Institute (IPEV). Considering a 10-y amortization, this would mean additional cost of about 20k€ per year

***part of the sensors may break every year due to harsh weather conditions (mainly due to very high wind speeds >150-200km/h). In the absence of sensor breaks, a lifetime of 5 years is expected.

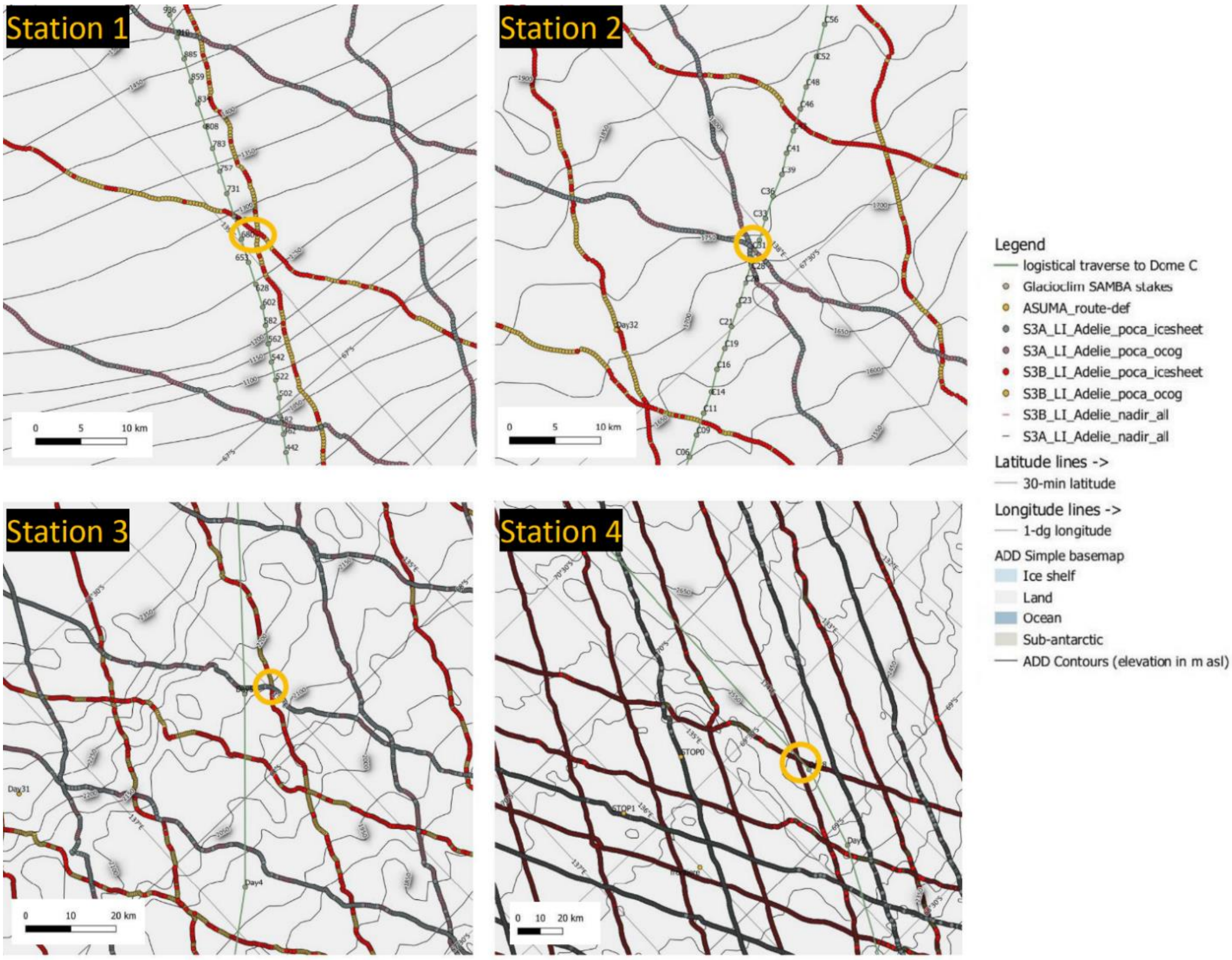

Figure 4 Close-up of the potential station locations of static FRM platforms (orange circles) in Adélie Land. Green dots show surface mass balance stakes along the logistical traverse route to Dome C (green line). Coloured dotes show POCA locations from the S3A/B land-ice product.

The FRM procedures and comparison with the Sentinel-3 thematic data product (TDP) are described in detail in the TD-3 report [RD-9] and will in this study case include the following steps and approaches:

1. The GNSS antenna position will be evaluated daily for X hours and corrected according to the PPP approach.

2. After elimination of suspect data, the average height of the antenna relative to the snow surface will be estimated using 7-10 sonic gauges or a multi-point scanning snowfall sensor performing 36 scans over a 10x10 m^2 area including the GNSS. If the multi-point snowfall sensor fails, the sonic gauges will provide a second-order quality correction of the mean surface level. The separation between the GNSS and other sensors will be determined with a tape measure.

3. Each summer, the station elevation will be recalibrated to the km^2 scale using a drone equipped with Lidar or a camera for a photogrammetric approach. In this case, the average elevation of the 10x10 m^2 area comprising the GNSS will be accurately scanned by the drone, and a digital surface model (DSM) over a 2 km circle minimum will be processed to evaluate the elevation difference between the GNSS location and the average elevation over 1 km^2. The DSM will be accurately georeferenced with spheres clearly visible in the photos.

4. Comparison between the FRM and TDP will then be performed according to two potential approaches:

Approach 1: We assume that all measurements of the fixed station have been resampled to the same timestamp as the TDP, e.g., the 20 Hz timestamp. In this case, we can define an FRM measurement that can be compared to a single TDP measurement at the POCA. In fact, we need to take the height measurement of the fixed station at time of overflight *j*, and transfer it to the POCA location using the DSM model. Here, the FRM height is specific to each altimetry sample in terms of its spatial properties. However, we directly compare the TDP to the generated FRM at each sampling point. Then to get a more reliable understanding of the difference of the Sentinel-3 height estimates to the FRM, we can then average all such residuals within the confined area and for as long as corresponding measurements of satellite and the fixed station are available.

Approach 2: If the variation of topography in time is not significant, we may decide to compare the average of TDP estimates to the average of FRM estimates, as opposed to approach 1, where we average the differences of TDP and FRM samples. As depicted in Fig. 7.5 from TD-3 [RD9], it is required that every single height estimate at the fixed station is first transferred to the POCA location and then the transferred heights are averaged to represent a single FRM height. The assumption is that both measured heights are representative of the confined area (2km circle minimum) during the period.

5.1.4. Additional Arctic deployments

In addition to one or more super-sites in Antarctica, we also propose to establish station FRMs in the Arctic to cover different climate and environmental conditions that impact the quality of Sentinel-3 products. Most of the candidate infrastructure sites and observational transects in the Arctic (Table 1 and Table 2) are within zones with significant surface melting during summer, resulting in meltwater percolation and refreezing into ice layers in the snow. This strongly impacts radar backscatter and can cause a seasonal transition from dominant volume scattering in the winter (with potential penetration bias) to dominant near-surface backscattering during the summer melt season. This aspect can be addressed with similar types of FRM stations, including temperature sensors in the air and upper snow-layer (thermistor string) as a part of the AWS to detect melt (or rain) events and associated refreezing.

Suitable existing infrastructure on Arctic land ice are the annually maintained automatic weather stations (AWS) of Austfonna and Devon Ice Caps or the PROMICE/GC-NET network of AWS stations on the Greenland Ice Sheet. In cases where sastrugi and small-scale roughness is less of an issue than in Antarctica or where the impact is exceeded by more complex surface topography or rapid glacier changes, a simplified setup with fewer surface ranging measurements can be considered. Multiple stations at different locations can in some cases be more efficient than an individual super-site as it allows comparison with more satellite data and over different surface types and conditions.

Deployment costs in the Arctic are highly dependent on location and to which extent air support is needed. Most installations on the Greenland Ice Sheet (e.g. PROMICE/GC-NET network) relies on helicopter usage in the field, whereas on Arctic ice caps (e.g. Austfonna and Devon) the work is typically conducted by snowmobiles from a field depot after initial transportation by air. Joining forces with ongoing field programs is essential for cost-saving. We have not made a detailed cost break-down for these cases, but the general logic and structure follows from the Antarctic case (Section 5.1.3).

5.2. FRM campaigns

Airborne or in-situ survey campaigns at a regional scale are important for absolute validation of multiple altimetry tracks at given times. This has been demonstrated for CryoSat-2 over sea ice and land ice through the series of validation campaigns carried out by the ESA CryoVEx program (e.g. Sørensen et al., 2018; Morris et al., 2022). A unique feature with the CryoVEx campaigns were the coordinated airborne and in-situ activities that made it possible to connect coarser airborne data with finer in-situ data (e.g. Hawley et al., 2013; Otosaka et al., 2020). Follow-on activities from that, including the proposed CryoBridge airborne program, would be suitable for Sentinel-3 also, e.g. EGIG-line on Greenland, Austfonna Ice Cap on Svalbard and Devon Ice Cap in Arctic Canada. In such cases, airborne radar (e.g. ASIRAS Ku-band, KAREN Ka-band, or the future CRISTALair with dual Ku/Ka-band) should be combined with in-situ ground penetrating radar (GPR) and/or shallow firn coring for glaciological interpretations of reflection horizons.

Some of the existing campaign data (Table 3) can potentially be used in a FRM context for past Sentinel-3 data if quality requirements are fulfilled. However, it is advisable to carry out new campaigns for better targeting to S3 ground-track coverage, including POCA relocation, and to validate the stability of the S3 altimeter over time. Concerning POCA relocation, survey designs should not only consider current thematic data products, but also alternative processing strategies for POCA relocation that have been shown to give very different results (see Annex 2 [RD11]) and will be a subject for future research and improvements that need similar validation from FRMs. It is also important for campaigns to cover different types of ice-sheet/glacier terrain in order to characterise S3 performance in relation to surface slope and roughness, as demonstrated by the cross-comparison with ICESat-2 in Annex 1 [RD10]. In that respect, the coastal zones of the ice sheets and the Arctic ice caps are essential as this is where most land-ice changes occur and where the monitoring capability of S3 needs to be demonstrated.

Regional-scale in-situ campaigns can be carried out in a cost-efficient way in combination with fieldwork for FRM stations or other relevant field programs (Table 2) if resources allow to do further ground-transects with kinematic GNSS/GPR or larger-scale UAV surveys. The spatial coverage of snow vehicles on the ground is limited compared to airplanes, but they have the advantage of more flexible navigation like for example using a pre-defined S3 POCA-track as waypoints for a kinematic GNSS transect or a narrow grid survey along the track. Snowmobiles are most efficient for this purpose and can cover hundreds of kilometres in one day. Ice divides and ridges are particularly good locations for such surveys as POCA-tracks tend to cluster along these local topographic highs. The timing of such campaigns is typically late winter in the Arctic (April/May), after the polar night period and before the summer melt season prevents surface travel. The latter is less of a problem in Antarctica where the main field period is the austral summer (Nov-Jan).

Airborne campaigns with lidar and radar are needed for covering larger areas and obtaining a robust statistical sample for absolute validation. Since POCA locations in sloping terrain can deviate substantially from nadir and vary between different processing techniques, it is recommended to carry out grid-based surveys rather than to attempt following individual ground-tracks directly (Sørensen et al. 2018). Grid lines should be dense enough that interpolation between tracks introduces minimal errors, ideally with overlapping lidar swaths. This must be weighted against the area coverage of the grid which should at least be wide enough to capture the spread of POCA locations for a given track and long enough to obtain robust validation statistics. Covering a few POCA tracks within one month of temporal spacing would give a good basis for statistical validation. The timing of airborne campaigns has typically been the same as for in-situ campaigns, hence surveying over cold and dry snow, but it would also be useful to carry out one or more summer campaigns in the Arctic in order to determine the impact of surface melting and refreezing in the snowpack on the backscattered radar signal and retracked elevations.

Instruments and cost levels for airborne campaigns are similar to those for sea ice, as described in associated sea-ice reports (TD-2 and TD-6). Lidar should be the key sensor for absolute validation of surface elevation (FRM), whereas radar altimeters and optical cameras are valuable for investigating impacts of signal penetration and snow/surface conditions. Costs in Antarctica are substantially higher than in the Arctic due to the remote deployment of aircrafts and higher fuel/logistics costs. Typical intervals between airborne campaigns in different regions of Antarctica are 3-5 years. Potential airborne FRM campaigns in Antarctica should be coordinated with other airborne projects as an add-on or side activity, for example through the SCAR initiative RINGS [RD17], as discussed earlier.

In summary, we recommend the following for in-situ campaigns:

- Annual or biannual campaigns of 1-2 weeks in the Arctic (Greenland and/or Arctic ice caps) and Antarctica (coastal region) in conjunction with FRM station servicing or established in-situ monitoring programs (Table 2);
- Ice divides at high latitudes are particularly suitable sites due to their high density of S3 POCA tracks;
- Snow vehicle surveys with kinematic GNSS along targeted S3 tracks within one month time separation;
- Auxiliary data on snow properties (stratigraphy/layers, grain size, density and temperature) from GPR, probing, snow pits or shallow cores should ideally be collected for investigating volume scattering effects;
- Surveys should consider S3 processing outputs from different relocation and retracking methods;
- Surveys should ideally cover a range of surface conditions (smooth, rough, sastrugi etc.) and slopes;
- Coordination with coincident airborne surveys, if possible.

And similarly, recommendations for airborne campaigns are:

- Airborne campaigns every 2-3 years in the Arctic and every 3-5 years in Antarctica, balancing benefits and costs;
- Flights from one or more airports in Greenland, Svalbard or Arctic Canada (station airstrips in Antarctica);
- Primarily grid-based surveys with lidar and preferably radar altimeter (ASIRAS/KAREN) and optical camera;
- Survey duration of a few days per 2-5 target areas, 2-3 weeks in total, including weather days;
- Coverage of POCA variations for a few selected tracks within a month time separation in each target area;
- Surveys should ideally cover a range of surface conditions (smooth, rough, sastrugi etc.) and slopes;
- One summer campaign over melt-affected areas in the Arctic, otherwise winter conditions as reference;
- Coordination with sea ice campaigns and in-situ land-ice surveys, if possible;

Supplementary material – Annexes 1 and 2

Two technical reports from the land-ice work are provided as supplementary material:

- Annex 1: Technical report "St3TART WP 3.2.3: Cross-Platform validation with ICESat-2" with detailed assessment of the added benefit of using ICESat-2 laser altimetry for larger scale evaluation of Sentinel-3 performance
- Annex 2: Technical report "St3TART WP 3.2.4: High-resolution DEMs for S3 processing and validation" with detailed assessment of the added benefit of using high-resolution DEMs in Sentinel-3 processing and validation.

The main findings of these studies are briefly summarized in Section 4.4.