NORCE Norwegian Research Centre AS
www.norceresearch.no

X/L-band SAR on Lufttransport's Dornier DO-228 (LN-LYR)

Mission Requirements Document

Authors:

Tom Rune Lauknes, Line Rouyet, Agnar H. Sivertsen, Temesgen Gebrie Yitayew, Eirik Malnes, Jakob Grahn, Robert Ricker, Jelte van Oostveen

Report 5-2022, NORCE Energy & Technology

Report title	X/L-band SAR on Lufttransport's Dornier DO-228 (LN-LYR) – Mission Requirements Document
Project No	103564
Institution	NORCE Energy and Technology
Client	European Space Agency
Classification	Open
Report No.	5-2022, NORCE Energy & Technology
ISBN	978-82-8408-248-6
No. of pages	61
Date of publ.:	September, 2022
CC-licence	CC BY 4.0
Citation	T. R. Lauknes, et. al. (2022). X/L-band SAR on Lufttransport's Dornier DO-228 (LN-LYR) – Mission Requirements Document, NORCE Report No. 5-2022.
Photo Credit	NORCE
Geographical area	N/A
Keywords	Arctic, Remote Sensing, Synthetic aperture radar, Aircraft, Monitoring

Summary

Current climate changes as well as an increased marine activity in the arctic regions impose a growing need for improved scientific observations and increased situational awareness. This document describes mission requirements for an L- and X-band synthetic aperture radar (SAR), to be installed on the Lufttransport Dornier DO-228 (LN-LYR). An airborne, fully polarimetric, dual frequency, interferometrically capable SAR, would provide a unique platform for regular scientific observations in the Arctic, in synergy with the existing hyperspectral imager, and the existing land-based infrastructure in Svalbard. An airborne imaging radar would furthermore provide all weather capability with unprecedented potential to improve observations of vessels, oil spills, icebergs, sea ice conditions, and floating debris. This will lead to improved safety and emergency response in the Arctic and increase the operational window for collecting situational awareness data.

Rev.	Date	Author	Checked by	Approved by	Reason for rev.
1.0	28.09.2022	T. R. Lauknes, L. Rouyet, A. H. Sivertsen, T. G. Yitayew, E. Malnes, J. Grahn, R. Ricker, J. v. Oostveen, K. A. Høgda, R. Storvold	K. A. Høgda	R. Storvold	

Executive Summary

Current climate changes as well as an increased marine activity in the Arctic impose a growing need for improved scientific observations and increased situational awareness.

The Copernicus Polar Expert Group (PEG), assigned by the European Commission, has investigated Earth Observation (EO) needs for data and value-added services in the polar regions[1]. Availability of in-situ observations from airborne, seaborne and ground based installations, are considered imperative to develop an integrated Polar monitoring system. However, in-situ data and observations are generally very sparse in the polar regions, including in the Arctic. To improve this, the PEG recommends (PEG III report, 2021):

> *"In-situ data is sparse in the polar regions and there is a clear need for Copernicus to make major efforts to increase the number of observation platforms and equipment in particular for the central Arctic region (this is also applicable to Antarctica and Greenland). Development of international cooperation with Arctic countries is essential, but also with the research community and national investments in order to sustain a repository of in-situ data."*

> *"The PEG recommends continuous, stronger international cooperation/coordination (including all EU Member States, WMO and Arctic States) and encouraging national investments/effort to develop and maintain platforms and equipment. In-situ data used for research and operational services, in the polar regions, shall be free and open, following standardised data formats".*

The Norwegian company Lufttransport AS currently operates two Dornier DO-228 aircraft, based in Longyearbyen, Svalbard. The aircraft operate mostly between Longyearbyen and Ny-Ålesund but have also frequent flights to North Greenland and the mainland Norway. One of the aircraft (LN-LYR) has been equipped with a scientific pod containing a state-of-the-art hyperspectral imager. The scientific use is in and around Svalbard is being coordinated by the Svalbard Integrated Arctic Earth Observing System (SIOS).

This document describes the mission requirements for an L- and X-band synthetic aperture radar (SAR), to be installed on LN-LYR. An airborne, fully polarimetric, dual frequency, interferometrically capable SAR, would provide a unique platform for regular scientific observations in the Arctic, in synergy with the existing hyperspectral imager and the land-based infrastructure in Svalbard.

Furthermore, Norway has an important responsibility regarding search and rescue in the Arctic. An available airborne platform, with an imaging radar, would provide all weather capability with unprecedented potential to improve observations of vessels, oil spills, icebergs, sea ice conditions, and floating debris. This will lead to improved safety and emergency response in the Arctic and increase the operational window for collecting situational awareness data.

---

[1] https://www.copernicus.eu/en/news/news/new-copernicus-polar-expert-group-report-published

1. Table of Contents

List of acronyms and applicable documents

List of acronyms

AIS	Automatic Identification System
Cal/Val	Calibration and Validation
CRISTAL	Copernicus polar Ice and Snow Topography Altimeter
DEM	Digital Elevation Model
DO	Dornier
ECV	Essential Climate Variables
EMS	Copernicus Emergency Management Service
EO	Earth Observation
ESA	European Space Agency
FMCW	Frequency-Modulated Continuous-Wave
GCOS	Global Climate Observing System
GNSS	Global Navigation Satellite System
INS	Intertial Navigation System
JRCC	Joint Rescue Coordination Centre
MRD	Mission Requirement Document
MR	Mission Requirements
NASA	National Aeronautics and Space Administration
NESZ	Noise-Equivalent Sigma Zero
NISAR	NASA-ISRO SAR mission (L+S-band SAR)
PEG	Polar Expert Group
ROSE-L	Radar Observing System for Europe at L-band
RX	Receive system
SAR	Synthetic Aperture Radar
SIOS	Svalbard Integrated Arctic Earth Observing System
SLC	Single Look Complex
SWE	Snow Water Equivalent
TX	Transmit system
UR	User Requirements

Applicable documents

User Requirements for a Copernicus Polar Observing System– Phase 1 Report -
User Requirements and Priorities.

> Duchossois G., Strobl P., Toumazou V. (2018)
> https://www.copernicus.eu/sites/default/files/2018.1802_src_polar_expert_group_-_phase_1_-_final_report_20180726final.pdf

User Requirements for a Copernicus Polar Observing System– Phase 2 Report -
High-level mission requirements.

> Duchossois G., Strobl P., Toumazou V. (2018)
> https://www.copernicus.eu/sites/default/files/2018.1802_src_polar_expert_group_-_phase_2_-_final_report_20180726final2.pdf

User Requirements for a Copernicus Polar Observing System– Phase 3 Report -
Towards Operational Products and Services.

> Nordbeck O., Duchossois G., Kohlhammer G., Andersson E., Diehl T., Dinessen F., Eriksson P., Flett D., Garric G., Gros J-C., Jacq F., Molch K., Nagler T., Nicolas J., Strobl P. (2021)
> https://www.copernicus.eu/sites/default/files/DEFIS_Copernicus_Polar_report_210414_HV-NC-29-144-EN-N.pdf

ROSE-L Mission Requirements Document.

> https://esamultimedia.esa.int/docs/EarthObservation/Copernicus_L-band_SAR_mission_ROSE-L_MRD_v2.0_issued.pdf

NISAR Mission Requirements.

> https://nisar.jpl.nasa.gov/mission/mission-requirements/level-1-science-requirements/

2. Introduction

Lufttransport AS operates a Dornier DO-228 aircraft (LN-LYR) stationed in Longyearbyen, Svalbard. The aircraft is currently equipped with a scientific pod consisting of optical instrumentation. The operational use for scientific purposes is coordinated by the Svalbard Integrated Arctic Earth Observing System (SIOS).

This document details the Mission Requirements (MR) for an L- and X-band Synthetic Aperture Radar (SAR) system, that will enhance the observational capacity of the aircraft and contribute to:

- provide high resolution imagery for the monitoring of sea ice, snow, glaciers, ice caps and permafrost in relation with the Global Climate Observing System (GCOS) **Essential Climate Variables**, and addressing the current knowledge gaps (e.g. Snow Water Equivalent (SWE) retrieval, ground ice content);
- improve safety by extending the monitoring of **geohazards** related to ground movement and changes of snow properties, such as landslides, snow avalanches and subsidence, providing complementary service to current Copernicus satellites;
- provide an all-weather sensor for **Search and Rescue and maritime surveillance** including identification of vessels and oil spills, categorization of sea ice types and detection of icebergs critical to safe navigation in Arctic areas, in compliance with the European Arctic policy;
- provide an airborne platform that can collect essential **calibration and validation data for Copernicus satellite missions**, as well as provide capacity for other agencies such as the NASA/ISRO NISAR mission.

The purpose of this Mission Requirements Document (MRD) is to justify the mission objectives by identifying User Requirements (UR) and provide the overall mission requirements at system and operational level .

The document is organized as follows:

- Chapter 1 introduces the scope of the report and briefly outlines the document;
- Chapter 2 provides background and justification for an airborne L-/X-band SAR;
- Chapter 3 presents the user requirements;
- Chapter 4 presents the high-order mission objectives within different thematic fields;
- Chapter 5 contains the observational and system mission requirements that provide a basis for the mission implementation;
- Chapter 6 provides the preliminary system concept and design;
- Chapter 7 contains a description of the data product types at Level-1 and Level-2 to be delivered to end users;
- Chapter 8 provides a list of references.

Please note that the MRD will be evolving with time as the user and mission requirements are matched to the capabilities and technical design of the mission following an iterative process.

3. Background and justification

3.1. Background

Current climate changes as well as an increased marine activity in the arctic regions impose a growing need for improved scientific observations (Box et al., 2019; Jansen et al., 2020) and increased situational awareness (Rainville et al., 2020) in and around Svalbard. In a context of climate change, the Nordic Arctic is especially affected by warming (Arctic Amplification) (Serreze et al., 2009) and Svalbard has an ideal location to study the environmental consequences of these changes. Ongoing research in Svalbard covers all fields involved in the long-term monitoring of Essential Climate Variables (ECVs), to document the Earth's system changes through a set of physical, chemical, and biological variables.

In and around Svalbard Archipelago, the Svalbard Integrated Arctic Earth Observing System (SIOS) has the mission to develop a systematic and long-term environmental monitoring strategy in Svalbard, improve the data access/sharing and enhance the research coordination (SIOS, 2021). SIOS contributors have identified knowledge gaps related to a large range of scientific fields including snow, permafrost, glaciers, oceanic, atmospheric, and biologic research. For most of these fields, the need for medium spatial coverage and frequent high spatial resolution remote sensing data has been identified to complement current measurements and bring the gap between satellite and in-situ observations (Orr et al., 2019; Van den Heuvel et al., 2020; Moreno-Ibáñez, et al., 2021).

Synthetic aperture radar (SAR) systems provide all weather observational capacity. Nowadays, the Copernicus Sentinel-1 C-band satellite has proven to be a key asset for many scientific applications within polar research (e.g. Damman et al., 2019; Park et al., 2020; Lemos et al., 2018; Friedl et al., 2021; Conde et al., 2019; Nagler et al., 2016; Rouyet et al., 2019; Strozzi et al., 2018), as well as for operational maritime surveillance applications (e.g. Hannevik et al., 2017; Santamaria et al., 2017). However, it is well known that SAR sensors with other wavelengths, such as X-band and L-band, are highly complementary due to the backscatter frequency dependence of many ground targets (e.g. Johansson et al., 2017). The longer wavelength of L-band allows for penetration through snow and vegetation, as well as improved capability of detecting fast ground motion using SAR interferometry (InSAR) in areas where traditional C- or X-band systems fail due to signal decorrelation. The shorter wavelength of X-band improves spatial resolution and detection capability of smaller targets, which is of particular importance for maritime surveillance applications (e.g. Iervolino et al., 2017).

Currently, there are no L-band SAR satellite in service providing open-access data like Copernicus. NASA (U.S.A.) and ISRO (India) plans to launch a joint SAR mission (NISAR) in January 2024 (Rosen & Kumar, 2021), but due to its left-looking observational plan there will be no coverage above 77.5° north latitude. The European Space Agency (ESA) is currently developing Sentinel-12 (ROSE-L), with a planned launch in 2028. Sentinel-12 is a new high-priority Copernicus radar observation system for Europe in L-band (Davidson & Furnell, 2021).

The Copernicus Polar Expert Group (PEG), assigned by the European Commission, has investigated Earth Observation (EO) needs for data and value-added services in the polar regions (PEG report I–III, 2018, 2021). The operational Copernicus Polar Observing System is based on a combination of space and in-situ observing systems.

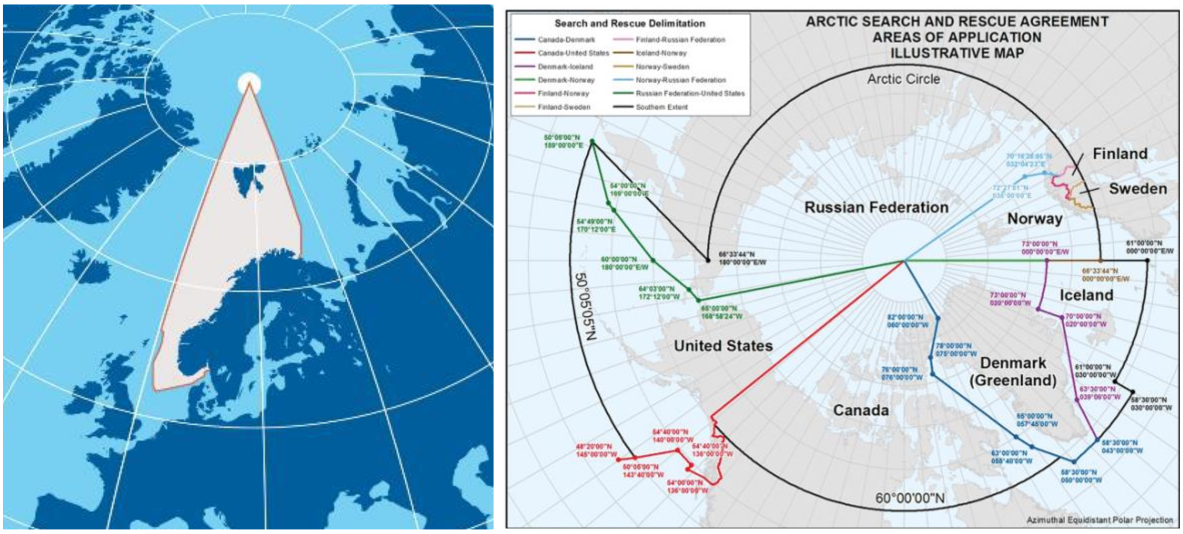


Figure 1. Search and Rescue responsibility area for Norway in the Arctic (Joint Rescue Coordination Centre - JRCC, 2019).

The PEG identified an increased interest in using L-band in combination with C-band Sentinel-1 SAR for improvement of current sea ice monitoring, but also for the development of new products and services. Furthermore, the PEG consider the availability of local observations imperative to develop an integrated Polar monitoring system, by providing:

- Local, high spatial resolution observations with a short revisit period
- Calibration and testing during *development* phase (model constraining)
- Calibration and validation during *operational* phase (product evaluation)
- Geophysical product evaluation and verification (Level-2 data)

Access to in-situ data comprises a central element within the Copernicus regulation (European Regulation 2021/696), where the in-situ component shall ensure coordinated access to observations through **airborne, seaborne, and ground based installations** for the defined service areas (atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security).

An airborne L- and X-band SAR, permanently located in Svalbard, could provide important in-situ local calibration and validation observations for Copernicus and other missions, and help to close the gap between space EO and ground-based in-situ observations.

Norway has an important responsibility regarding Search and Rescue in the Arctic (Figure 1). It is well known that the optical visibility in these regions is often limited by low clouds and fog, especially during the summer with cloud cover up to 75% of the time. Most of the winter, the polar night makes passive optical sensors impossible to use. There is a thus a clear need for an airborne SAR platform that could provide all weather capability and has unprecedented potential to improve observations of vessels, oil spills, icebergs, sea ice conditions, and floating debris (Dyrkoren & Berg, 2014). This will lead to improved safety and emergency response in the Arctic and increased operational window for collecting situational awareness data.

Figure 2 Lufttransport's Dornier DO-228 aircraft (LN-LYR). The optical instrumentation and communication payload are installed in the pod towards the front of the aircraft.

3.2. Lufttransport's Dornier DO-228-202 (LN-LYR)

Lufttransport AS, a Norwegian airline company with head office in Tromsø, Norway, operates a Dornier DO-228 aircraft (Figure 2) based out of Longyearbyen, Svalbard, with regular flights to Ny-Ålesund and around 20 flights per year to Villum Research Station, Station Nord in Greenland. The aircraft has a range of 2400 km which is covered in about 6 hours (Table 1). The aircraft operates regularly on the Norwegian mainland, facilitating potential operations also in Scandinavia or elsewhere in northern Europe.

3.2.1. Current SIOS-Infranor payload description

As part of the SIOS-Infranor project, funded by the Norwegian Research Council and the Norwegian Space Agency, the aircraft LN-LYR has been configured with a permanently mounted pod that contains the following state-of-the-art scientific instrumentation:

- *HySpex VNIR-1800 Hyperspectral imager* providing images with a spectral resolution of 3 nm in the range 400–1000 nm, and a spatial swath width of 600 m and 0.3 m resolution from 1000 m altitude;
- *PhaseOne IXU150, Medium format RGB camera* providing 10 cm resolution images in 800 m swath @1 km altitude;
- *Applanix POS AV 410 Global Navigation Satellite System (GNSS) inertial navigation system (INS) providing precise navigation state for direct georeferencing the hyperspectral and aerial images;*
- *Radionor CRE2-179 Aero 5.8 GHz broadband radio* permitting real-time data relay to other assets;
- *Kongsberg AIS300 Automatic Identification System (AIS) transceiver* for monitoring of ship traffic and capability to serve as an AIS base station, providing extended coverage for all ships in the region.

The current instrument pod is located under the aircraft fuselage in front of the landing gear assembly (Figure 2). An important part of the systems integration is to make sure that all scientific instruments can be operated during regular passenger and cargo flights. This makes it possible to implement a long-term monitoring program, with weekly revisit times throughout the year, for certain areas.

Table 1. General capabilities of the Dornier DO-228 aircraft (LN-LYR).

Normal range	2400 km
Maximal endurance	6:45 hours
Maximal take-off mass	6200 kg
Maximal altitude	10000 feet Typical range 1–3 km
Operating speed	150–180 knots (75–90 m/s)
Seat capacity	2 pilots / 17 passengers

4. User requirements

In order to define mission objectives and user requirements (UR), user involvement is required, both from the scientific community but also from relevant governmental and local stakeholders with activity in or around Svalbard.

4.1. SIOS user survey

To collect feedback on the interest and potential applications of an airborne SAR in Svalbard, a user survey was disseminated to the Svalbard Integrated Arctic Earth Observing System (SIOS) community (sent through SIOS newsletter in December 2021 and advertised during the SIOS polar night week in January 2022) and to other relevant stakeholders at the local, regional and national levels (Norwegian coastal administration, Norwegian Coast Guard, Governor of Svalbard; other governmental agencies, private companies and academic institutions with research or operational activities in and around Svalbard, Fram Center, etc.). Between December 17, 2021, and February 7, 2022, 73 people partially or completely answered the survey. Our analysis of the answers is based on the completed forms (54 people) (Appendix 1).

The user survey provides a starting point for defining the Mission Requirements. We have divided the survey questions into three categories:

- General needs: What kind of specific observations are required?
- Observation requirements: What kind of Level-1/Level-2 products are needed?
- High-level product requirements: What kind of higher-order (Level-4) geophysical products are needed?

The survey was mostly filled by people from academic institutions, private research institutes and governmental agencies (only a few from the industry). The majority has a researcher position (26 out of 54), but the remaining people cover a wide range of positions (professors, engineers, advisers, students, managers, navigators, etc.). All the listed “roles” are represented in the survey. The main represented field was “radar remote sensing” (32 people), “biology” was the least represented field (6 people). Among the other fields, “Optical remote sensing”, “Glaciology”, “Maritime surveillance”, “Geology/Geomorphology”, “Geophysics” had the highest scores (10–20 respondents). The survey participants use (or aim to use) remote sensing for a wide range of applications: snow mapping/characterization (25 people), sea ice mapping/characterization (22), sea ice drift (15), glacier motion (17) and feature characterization (16).

All listed research or operational applications are represented by at least 5 respondents. Considering study areas, the work is mostly focusing in/around Longyearbyen, the main research stations (Ny-Ålesund/Hornsund) and in Spitsbergen fjords and waters around Svalbard (Fram Strait, Arctic Ocean, Barents Sea, Greenland Sea, Norwegian Sea). To the question regarding the appropriate revisit time, a high number of participants answered that weekly revisits or targeted missions (flexible revisit) are valuable to their applications. Subdaily-daily and monthly-annually are slightly less represented. However, the spread both in term of regional focus area and temporal resolution is significant, which is representative of the wide range of application fields covered by the survey participants.

Most of the participants has experience with SAR data (76%) and a third (33%) has used (or is planning to use) optical data from the SIOS Dornier research aircraft (LN-LYR). Most users would use SAR data from Single-Look Complex format or a higher level. Only a few (6) are interested in Level-0 (raw) data. There is a clear interest for a combination of radar frequencies. 31 people think that a combination of both X-/L-band is most appropriate, while 18 do not know. Only 5 people show a special interest towards one single frequency. The main value of the airborne SAR for the users is to complement field/in-situ measurements and calibrate/validate satellite remote sensing. Answers regarding technical specifications (real-time processing, polarization, across/along-track interferometry, left/right wide area mapping) are less clear, with a high percent of participants answering that they don't know. This shows there is a need for further discussing methods with the stakeholders and organizing educational activities about SAR remote sensing, for example a SIOS dedicated webinar and/or course (as also highlighted in the last question of the survey).

In general, the user survey reflects a strong interest for complementing the current remote sensing infrastructure available in Svalbard, with radar sensors. Environmental monitoring in the Arctic relies on a wide variety of complementary sensors, both from satellite and airborne platforms. A combination of optical and multi-frequency radar sensors mounted on an airborne platform, with high availability, would provide a valuable addition to existing and planned satellite systems.

4.2. Summary of user requirements

The main results of the user survey can be summarized in Table 2.

Table 2. Summary of high-level user requirements based on user survey.

User requirement ID	User requirement description
UR-010	Separate L- and X-band synthetic aperture radar systems.
UR-020	Polarimetric capability (surface characterization).
UR-030	Level-1 (single look complex, SLC) and higher order products.
UR-040	Single-pass across-track InSAR in X-band (digital elevation model).
UR-050	Repeat-pass InSAR in L-band (surface deformation).
UR-060	Single-pass along-track InSAR in X-band (surface currents).
UR-070	Support for onboard real-time processing (some applications).

5. Mission objectives

5.1. Selection of mission objectives

The primary objectives of the airborne SAR mission are related to the major scientific observational gaps in the Arctic, to current and future needs for operational Calibration/Validation services specifically related to cryosphere applications, and to improve Norway's capabilities for increased situational awareness in the Arctic.

Criteria for determining primary objectives are:

- **User relevance:** The needs and requirements for the Dornier platform are collected within the SIOS community and in consultations with other Norwegian governmental stakeholders (user survey, see Appendix 1).
- **Maturity:** The scientific community and other stakeholders have different requirements regarding maturity of the products. An agile airborne instrument provides the scientific community the capability of investigating novel operational modes, while for maritime safety and security higher order operational products are desired.
- **Contribution:** We are considering the SAR missions highly complementary to the existing SIOS instrumentation on the Dornier, as well as the current– and planned capabilities of Europe's Copernicus programme.

Based on the above considerations, the four **primary objectives** of the Dornier airborne SAR mission are derived and summarized below.

1. To provide high resolution imagery for the monitoring of sea ice, snow, glaciers, ice caps and permafrost in relation with the Global Climate Observing System (GCOS) **Essential Climate Variables**, and addressing the current knowledge gaps (e.g. Snow Water Equivalent (SWE) retrieval, ground ice content);
2. To improve safety by extending the **monitoring of geohazards** related to ground movement such as landslides and subsidence, and changes of snow properties related to e.g. snow avalanches, providing complimentary service to current Copernicus satellites;
3. To provide an all-weather sensor for **Search and Rescue and maritime surveillance** including localization of vessels and oil spills, categorization of sea ice types and detection of icebergs critical to safe navigation in Arctic areas, in compliance with the European Arctic policy;
4. To provide an airborne platform that can collect essential **calibration and validation data for satellite SAR missions**, such as ROSE-L and NISAR.

These primary objectives are related to four main application fields (Figure 3):

1) monitoring of snow, glaciers and ice caps;

2) monitoring of ground movement;

3) monitoring of sea ice, vessels, icebergs and oil spills;

4) acquisition of calibration and validation data, further described in Section 5.2.

Secondary applications related to ground moisture, freeze/thaw cycles, subsurface mapping, line-of-sight ocean surface currents and vegetation mapping are briefly discussed in Section 5.3. The priority is placed here on applications in and around Svalbard, but potential exploitation in other regions of the European Arctic/Subarctic are also discussed.

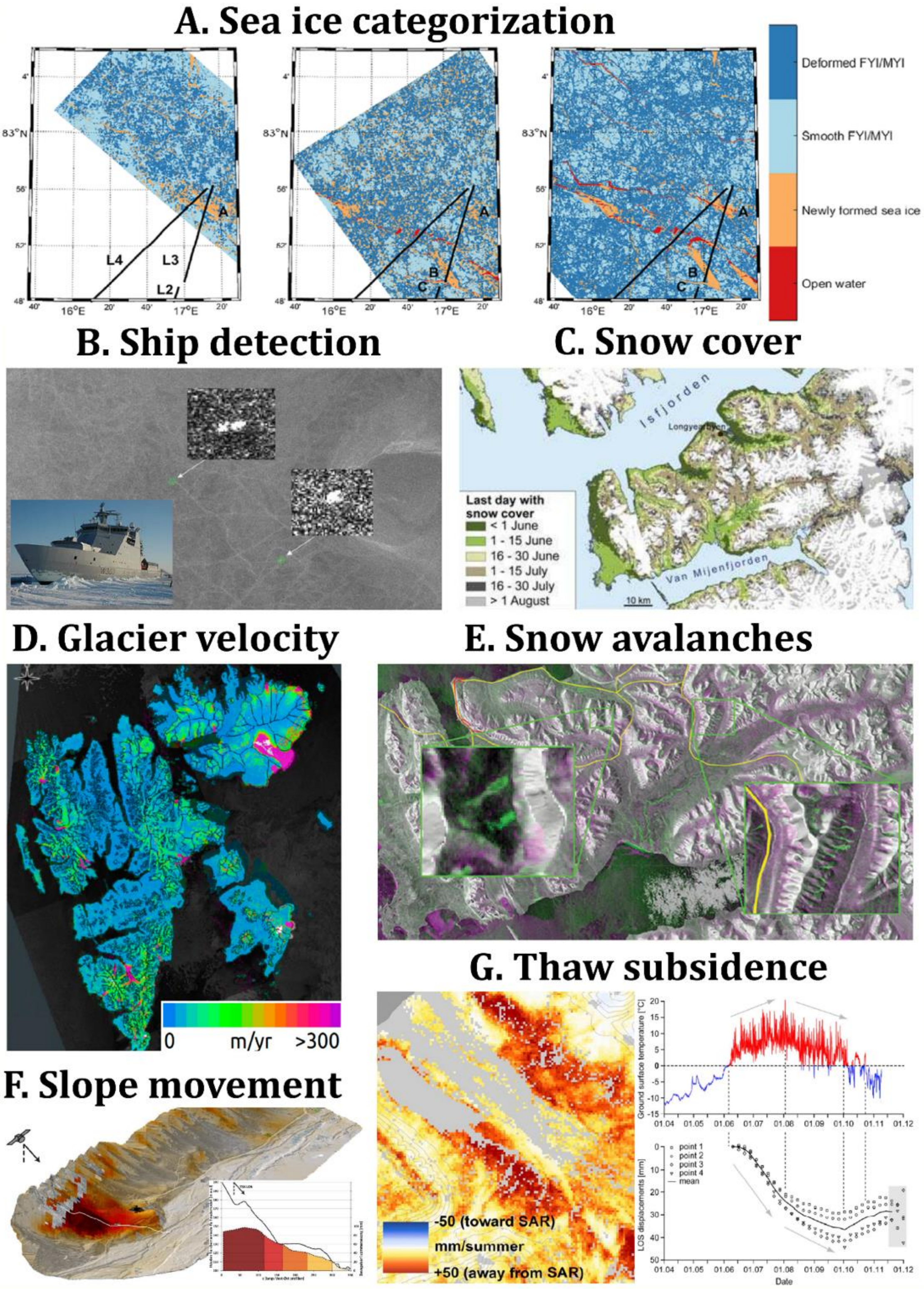


Figure 3: Examples of SAR applications based on satellite imagery that could valuably complemented by airborne measurements. A. Sea ice identification and categorization based on X-, C-, and L-band SAR satellite images (Johansson, et al., 2017); B. Ship detection in ice-infested waters based on Dual-Polarization SAR (Brekke & Anfinsen, 2011); C. Last day of snow cover in Nordenskiöld land based on multi-sensor/multi-temporal satellite observations (Malnes et al., 2010). D. Multi-sensor SAR offset-tracking Ice velocity maps (Strozzi et al., 2017); E. Sentinel-1 backscatter change between a reference image before avalanche activity and image after avalanching (Wesselink et al., 2017); F. Ground velocity map of a creeping landform on Longyear valley side (Rouyet et al., 2017). G. Thaw subsidence map and seasonal displacement time series in Adventdalen (Rouyet et al., 2019).

5.2. Primary objectives

The Copernicus Polar Expert Group (PEG), set up by the European Commission, has published observation priorities including the following critical cryospheric and oceanic variables to be observed in polar areas (PEG report I–III)[2]:

- Floating ice
- Glaciers
- Caps and ice sheets
- Sea level
- Sea surface temperature
- Surface albedo
- Surface fresh water
- Snow and permafrost

The mission objectives of the proposed Dornier L/X-band SAR largely follow the priorities of the PEG.

5.2.1. Monitoring of sea ice, vessels, icebergs, and oil spills

Synthetic Aperture Radar is the most applicable sensor for operational sea ice, vessels, oil spill and iceberg monitoring, mostly because of its all-weather, all-day, and all-season detection capabilities.

Sea ice is a key indicator of climate variability and change in the polar regions and therefore defined as one Essential Climate Variable of the Oceanic domain (GCOS, 2021). Mapping of **sea ice concentration and types** using SAR is a well-established field, exploiting the variable surface and volume scattering from the interaction between the radar wave, the sea ice and free water. Surface scattering depends on the roughness of the ice surface that can result in strong scattering intensity, especially detectable using high radar frequencies (C-, X-, Ku-band). Volume scattering is determined by the penetration depth of a radar wave and decreases with radar frequency, ice salinity and temperature (Dierking et al., 2013). Due to the variable impact of the frequency and polarization on scattering mechanisms and wave penetration, a combination of SAR data using different frequencies is valuable for **sea ice classification** and validation of ice charts (Johansson et al., 2016; Singha et al., 2018; Dierking, 2021). The relation between satellite SAR backscatter at different frequencies and **sea ice surface roughness** (standard deviation of surface height) has been investigated in previous studies (e.g. Johansson et al., 2017) and is still an open field of research, where our proposed airborne SAR system can help fill a knowledge gap. Potential retrieval of sea ice surface roughness may also help to interpret and evaluate radar waveforms from altimetric measurements (e.g. ESA's CryoSat-2). In the future, validation campaigns for the planned Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission scheduled for 2027 (Kern et al., 2020) will require high-resolution information of the sea ice surface properties. High spatial resolution (<10 m) is necessary for detailed ice mapping and therefore high-frequency SAR (e.g. X-band) is usually preferred (Dierking et al., 2013). This requirement emphasizes the value of airborne platforms to complement and validate spaceborne measurements.

Other SAR applications for sea ice characterization include the retrieval of **sea ice thickness**, for example based on an empirical relation between the VV-to-HH backscattering ratio and ice thickness (Wakabayashi et al., 2004). Karvonen et al. (2021) have demonstrated the combined usage of Dual-

[2] https://www.copernicus.eu/en/news/news/new-copernicus-polar-expert-group-report-published

Polarized Sentinel-1 SAR and CryoSat-2 data to estimate sea ice thickness. Using a pair or sequence of SAR images, it is also possible to retrieve **sea ice motion** from drift or deformation using feature tracking or single-pass along-track SAR interferometry (Dammann, 2019; Shokr et al., 2020). Such retrievals can be used to validate high resolution satellite SAR drift products, e.g. from Sentinel-1. Finally, one important driver of sea ice change is snow accumulating over it. The snow influences the retrieval of sea ice properties based on radar remote sensing, e.g. sea ice freeboard and thickness (Ricker et al., 2014, Ricker et al., 2015, Grahn, 2018). Conventionally, the snow is assumed to be dry and homogeneous which is rarely the case on sea ice. Brine wetting greatly changes the dielectric properties of the snow leading to erroneous retrieval results of sea ice properties (Kwok et al., 2011, Nandan et al., 2017). Studies have evidenced that the properties, depth, and distribution of **snow over sea ice** are highly variable in time and space (Webster et al., 2014), highlighting the value of high-resolution airborne systems to validate satellite observation and further understand the impact on snow on sea ice properties (Kwok et al., 2011). After the melt onset, another application is investigating the detection of **melt ponds** using SAR imagery, which is still subject of ongoing research (e.g. Fors et al., 2017).

In Svalbard's fjords, the interannual variability and relations between sea ice and climatic/oceanic variables is studied based on in-situ measurements (Pavlova et al., 2019) or satellite observations (Muckenhuber et al., 2016). In Kongsfjorden for example, sea ice evolution in relation with climatic data has been locally modelled (Wang et al., 2015), but the results have not been coupled with a regional model and the data have limited in temporal and spatial resolution (Gerland et al., 2020), that could benefit from airborne SAR observations with variable spatio-temporal resolutions. At the regional scale, satellite passive microwave instruments are used to document the sea ice coverage and concentration, that have been compared with snow cover trends on land (Killie, et al., 2020; Vickers et al., 2020). The correlation between these variables highlights the importance of interdisciplinary research on climate-related environmental variables in Svalbard, but also the challenge of scale gaps between different data sources. Development of airborne remote sensing at an intermediate level between satellite observations and in-situ instrumentation may contribute to solve this challenge in selected fjords of the archipelago.

For **vessel and iceberg detection**, quad-polarization is considered as the optimal choice allowing for a good discrimination between the floating objects and the surroundings (Hannevik, 2017). However, based on satellite SAR, quad-polarization data has limited swath width, making it difficult to use the data operationally. Alternatively, Brekke & Anfinsen (2011) showed that dual cross-polarization is also suitable for discrimination ships in icy waters. Based on airborne SAR, Liu et al (2005) demonstrated that a fully polarimetric system is superior to single- and multi-polarization configurations. Dual-channel systems with amplitude and phase provide better detection performance than single-channel or amplitude-only systems. For **oil spill detection**, there is a clear need for coordination between satellite overpasses and aerial surveillance flights as aerial evidence is useful to prosecute the polluters (Brekke & Solberg, 2005). Accurate discrimination between water and oil has been performed both using satellite and airborne SAR sensors (Chaudhary & Kumar, 2020).

Norway has a large responsibility with regard to **search and rescue** in the Arctic. It is well known that the optical visibility in these regions is often limited by low clouds and fog, and especially during the summer with cloud cover up to 75% of the time. An airborne SAR system, permanently located in Svalbard, has great potential to valuably complement maritime surveillance in the Arctic Ocean.

For maritime safety applications such as vessel, iceberg, and oil spill detection, timely and coordinated observations are needed, with requirements of rapid delivery of higher-order (detected) products. For the Dornier aircraft, real-time delivery of products could be accomplished by utilizing the onboard Maritime Broadband Radio (MBR), which could provide a direct link with the established network of stations in Svalbard, operated by the Norwegian Coastal Administration, or the observations could be shared using the MBR to other MBR-equipped assets in the area such as coast guard vessels. For vessel detection related to fisheries monitoring, a higher order product where the vessel parameters (ship size, heading) are combined with received AIS information, would be beneficial.

Coincident and collocated polarimetric airborne L- and X-band SAR data will improve the ability to map sea ice, vessels, icebergs and oil spills at high spatial and temporal resolution and support the development and testing of automated sea ice products when used in conjunction with the C, X, or L-band spaceborne SAR systems.

The key SAR-based products that can be generated by the community for the monitoring of sea ice, vessels, icebergs and oil spills and are summarized in Table 3.

Table 3: Summary of potential products based on Dornier SAR images and product requirements associated with the monitoring of sea ice, vessels, oil spills and icebergs.

Product name	Product description	Main targeted areas	Recommended revisit time	General requirements
Sea ice type and concentration	Maps of classified sea ice type / stage of development (mature)	• Svalbard fjords, Arctic Ocean • Prioritized areas: Adventfjorden, Isfjorden, Kongsfjorden, Storfjorden, Hinlopen	• Weekly-monthly in prioritized areas • Dedicated mission for operational support • Yearly in selected areas of the Arctic Ocean	• Fully polarimetric / dual frequency • Low noise floor (-28 dB) at HV polarization • Short latency from observation to product • Latency: From near real-time to days
Sea ice thickness	Ice thickness maps/swath (experimental)	Arctic Ocean	Dedicated experiments/studies	Fully polarimetric L-band (thin ice)
Sea ice surface roughness	(experimental)	Arctic Ocean	Dedicated experiments/studies	Fully polarimetric / dual frequency
Melt-pond fraction	(experimental)	Arctic Ocean	Dedicated experiments/studies	Fully polarimetric / dual frequency
Snow on ice	(experimental)	Arctic Ocean	Dedicated experiments/studies	Fully polarimetric / dual frequency
Sea ice motion	Drift fields maps (experimental)	Arctic Ocean	Dedicated experiments/studies	Single-pass along-track InSAR (X-band)
Vessel detection	Location of detected objects	Svalbard fjords, Arctic Ocean, Barents Sea, Norwegian Sea, Greenland Sea	Dedicated missions	• Left/right looking capability for wide area coverage • Fully polarimetric / dual frequency • Latency: Real-time with visualization in aircraft and dissemination to mainland/Svalbard for operational support.
Iceberg detection	Location of detected objects	Svalbard fjords, Arctic Ocean, Barents Sea, Greenland Sea	Dedicated missions	Latency: Real-time with visualization in aircraft and dissemination to mainland/Svalbard for operational support.
Oil spill detection	Location of detected spills	Svalbard fjords, Arctic Ocean, Barents Sea, Norwegian Sea, Greenland Sea	Dedicated missions	Latency: Real-time with visualization in aircraft and dissemination to mainland/Svalbard for operational support.

5.2.2. Monitoring of snow, glaciers and ice caps/sheets

Synthetic Aperture Radar is widely used for the characterization of snow- and ice-covered land surfaces in polar and mountainous regions, including Svalbard.

Snow is defined as an Essential Climate Variable Snow consisting of the snow cover area, the snow depth or height and the snow water equivalent (GCOS, 2021). The different SAR backscattering properties of wet/dry snow and bare ground can be used to map **the fraction of snow cover** and qualify the snow wetness (Malnes et al., 2010). The **snow depth/height** is a parameter that has been challenging to retrieve from spaceborne remote sensing. In a recent work by Lievens (2019), a potential for measuring snow depth based on Sentinel-1 SAR data in mountains have been demonstrated. Likewise, laser altimeters (Icesat-1 &2) can be used to measure snow depth along in narrow swaths (Treichler & Kääb, 2017). Based on a drone-mounted radar, Jenssen et al. (2019) showed that Ultrawideband UAV-mounted radar with a 5.5 GHz bandwidth (0.95–6 GHz) can be successfully used to characterize the snowpack (snow depth, density and stratigraphy/layering). Based on L-band SAR, microwave penetration into snow may serve the same purpose although this application cannot be considered as fully mature. **Snow water equivalent (SWE)** is also challenging to retrieve from SAR remote sensing. Single polarization X- or C-band SAR backscatter information lacks the sufficient sensitivity to retrieve SWE and snow grain size simultaneously. These snowpack parameters cannot be decoupled in backscatter model (Bradley et al., 2021). Satellite mission concepts proposing high radar frequencies (X/Ku-band) have been suggested (Rott et al., 2010) but never been realized. Co-polar phase difference based on dual polarization SAR data can contribute to mitigate that issue (Patil et al. 2020). Alternatively, the shift in interferometric phase from the refraction of the microwave signal penetrating the snow layer between repeated passes can be isolated and exploited for SWE estimation (Guneriussen et al., 2001; Conde et al., 2019). For this purpose, L-band is more appropriate than high frequency radar, as it decorrelates on longer timescales. The combination of X-band backscatter change and L-band phase difference during snow accumulation could also be utilized to improve the accuracy of the SWE estimates.

In addition, snow observations have an operational significance to assess avalanche hazards, especially important in and around settlements. In Longyearbyen, two inhabitants died in the 2015 snow avalanche that additionally destroyed 11 houses (NGI, 2017). The observations of past and present snow avalanche activity are important to understand the spatio-temporal distribution of the events according to environmental variables and therefore improve warning and forecasting systems (McClung, 2002). Comparison of SAR backscatter images before and after event can be used for the regional **detection of snow avalanche**, as backscatter on avalanche deposits are usually higher due to increased scattering at the air–snow interface from the rough snow surface (Eckerstorfer & Malnes, 2015). Spaceborne SAR remote sensing has been based on X- and C-band SAR remote sensing for avalanche detection and mapping based on manual or automated procedure has been applied in Norway (Eckerstorfer et al., 2017a; Müller et al., 2021) and Svalbard (Wesselink et al., 2017). For targeted missions, spaceborne systems could valuably be complemented by airborne acquisitions (for high-resolution mapping and validation). In addition, using L-band SAR providing a better penetration in snow, applications for search and rescue could be further studied (Jenssen et al., 2019).

Monitoring the evolution of terrestrial ice bodies and estimating their mass balances is a significant scientific field in geosciences due to their major contribution to sea level change (Meredith et al., 2019). In Svalbard, about 57% of the land areal is covered by glaciers and ice caps (Nuth et al., 2013), correspond to volumes estimates of ca 6,200 km^3 (Schuler et al., 2020a). Based on SAR backscatter images, the detection of variable snow and ice conditions can be used to map and track the **glacial**

transient snow line assumed to relate with the equilibrium line altitude (ELA) (Winsvold et al., 2018). SAR remote sensing is used to map **glacial surface topography** (Digital elevation model (DEM) generation) from single-pass SAR interferometry (InSAR). Elevation changes can be documented by subtracting DEMs acquired at different times (Neckel et al., 2013), while **glacier velocity** can be measured using repeat-pass differential InSAR or SAR offset-tracking when the loss of coherence from rapid and incoherent flow limits the use of InSAR (Strozzi et al., 2008). The 6-days[3] temporal sampling of the Sentinel-1 constellation has revealed new insights in glacier dynamics, especially interesting for understanding processes on surging glaciers (Strozzi et al., 2017) and points towards a clear potential of airborne platforms with frequent repeat-pass capability. Based on L-band, airborne SAR has for example been successful applied for velocity mapping in Greenland and Iceland (Hensley et al., 2010; Minchew et al., 2015). Along-track component by estimating the azimuth coregistration offsets can be exploited together with the line-of-sight displacement form differential interferometry in order to obtain the 3D surface velocity fields (Prats et al., 2008). For ice bodies terminating in the sea, change in position of the boundary between grounded and floating ice, called the **grounding line**, is critical for assessing the stability of the ice mass (Friedl et al., 2020). Double-different differential InSAR can be used to isolate the vertical (i.e. tidal) displacement on a tidewater glacier or ice cap/sheet (Rignot et al., 2011). Finally, the study of the **internal structure and thickness of glaciers** is traditionally measured using ground penetrating radar operating with lower frequencies than SAR, but recent applications showed the potential of airborne L-band SAR tomography for this purpose (Tebaldini et al., 2016). It is expected that airborne SAR systems has a great potential for **mapping of glacier crevasses**, also the ones covered with snow bridges (Marsh et al., 2021), in particular by combining L- and X-band.

In Svalbard, there is extensive research on snow and increasing effort to coordinate activities related to modelling, in-situ and remote sensing measurements, as well as to relate the findings to other fields such as sea ice and vegetation characterization (Malnes et al., 2021; Karlsen et al., 2020; Vickers et al., 2020; 2021). Recent contributions show the need to bridge the spatial-temporal gaps between in-situ and satellite observations. For glaciers and ice caps in Svalbard, the scientific community has identified knowledge gaps to further understand unstable glacier flow (surging) and to couple glacier mass balance and glacier dynamics model that can be applied to investigate the effects of different climate scenarios (Schuler et al., 2020a; 2020b). A better understanding of frontal ablation and its drivers is also highlighted, which require high spatial and temporal resolution data and for which airborne SAR imagery can valuably complement existing field and satellite observations. The exploitation of an airborne SAR system has also obvious potential for applications on the **Greenland glaciers and ice-shelves**, in combination with regular flights to Station Nord as well as for additional targeted missions.

In Svalbard, an L/X-band SAR capacity on the Dornier will add an important dimension to the current plans of establishing cryosphere supersites in Ny Ålesund, Longyearbyen and Hornsund, where systematic in situ measurements will start up in 2022 (Salzano, 2020). The area around southern Spitsbergen and Hornsund is particularly interesting since this will also be covered by the NISAR L-band mission, scheduled for 2024, covering up to 77.5 north latitude.

The key SAR-based products that can be generated by the community for the monitoring of snow, glacier, ice caps/sheets are summarized in Table 4.

[3] In December 2021 the mission ended for Sentinel-1B due to a failure of the instrument electronics power supply. After this the repeat cycle is 12 days using Sentinel-1A.

Table 4: Summary of potential products based on Dornier SAR images and product requirements associated with the monitoring of snow, glaciers, and ice caps in Svalbard.

Product name	Product description	Main targeted areas	Recommended revisit time	General requirements/comments
Snow-covered area	Snow cover maps (mature)	Land areas with seasonal or perennial snow. Prioritized snow supersites (Ny-Ålesund, Adventdalen, Hornsund)	Weekly (prioritized areas) Monthly in selected areas of the archipelago	Combination L/X-band polarimetry
Snow depth or height	Snow depth maps (experimental)	Prioritized snow supersites (Ny-Ålesund, Adventdalen, Hornsund)	Dedicated experiments/studies	• Snow depth can be measured with Laser scanner (LIDAR) or laser altimeter or Ground penetrating radar (GPR) • Most works on L/X band SAR focus on retrieving SWE. Snow depth can be derived with independent snow density assumptions/ measurements.
Snow water equivalent	SWE maps (experimental)	Prioritized snow supersites (Ny-Ålesund, Adventdalen, Hornsund)	Dedicated experiments/studies	• Repeat-pass InSAR (L-band) • Systematic acquisitions from before first snowfall • Some sensitivity to SWE in X-band backscatter could also be utilized.
Snow avalanche detection	Detected avalanches (mature)	Prioritized areas around settlements	On demand, after heavy snow fall or after conditions with increased risk. Short temporal baseline desirable to detect the avalanche timing	• Combination L/X-band to be investigated • High spatial resolution beneficial • Backscatter change detection.
Glacier and ice cap topography	DEM (mature)	Glaciers and ice caps Prioritized selected glaciers close to Ny-Ålesund	Weekly (prioritized glaciers) Monthly-yearly in selected areas of the archipelago	Single pass across-track interferometry (X-band)
Glacier and ice cap surface velocity	Velocity field maps (offset tracking / InSAR) (mature)	Glaciers and ice caps Prioritized selected glaciers close to Ny-Ålesund	Weekly (prioritized glaciers) Monthly-yearly in selected areas of the archipelago	• Repeat-pass InSAR (L-band) • Systematic observations in same mode • Observations from multiple geometries to retrieve displacement direction and magnitude
Glacier grounding line	Grounding line delineation based on interferograms (mature)			
Glacier crevasse detection	Crevasses covered with snow bridges (experimental)	Svalbard archipelago, selected glaciers with significant snow mobile traffic	Yearly, pre snow mobile season	• High spatial resolution, X-band • L-band for increased penetration • Tomography for internal structures
Glacier internal structure	Glacier cross-section (experimental)	Selected glaciers (experimental)	Dedicated experiments/studies	Tomography

5.2.3. Monitoring of ground surface deformation

The ground of cold-climate environments is seasonally or perennial frozen (permafrost). Permafrost is an important component of the terrestrial cryosphere, defined as an Essential Climate Variable. Melting of ground ice from permafrost thawing may have direct impacts on population safety and infrastructure stability (e.g. thaw subsidence, slope hazards) (Harris, et al., 2009; Kääb et al., 2005; Deline et al., 2021). Permafrost degradation also contributes to global warming by releasing greenhouse gases previously trapped in the frozen ground (Schuur et al., 2015) and it is therefore paramount to design monitoring strategies that can cover extensive polar areas. The thermal state of the permafrost and the thickness of the seasonally thawed active layer are the two current components of the Permafrost ECV (GCOS, 2021).

Although permafrost is a subground phenomenon, surface changes documented by SAR sensors allow us to indirectly investigate permafrost dynamics (Philipp et al., 2021). Repeat-pass InSAR can detect ground surface deformation related to the **seasonal subsidence and heave** from active layer thawing and freezing (Strozzi et al., 2018). Based on subsidence maps it is also possible infer the active layer thickness (Liu, et al., 2012; Wang et al., 2018) or the ground ice content (Zwieback & Meyer, 2021). These applications have been primarily performed based on SAR satellites, but some studies have also shown the potential of airborne L-band SAR for this purpose (Chen et al., 2021; Michaelides et al., 2021). Comparison between airborne and satellite InSAR over permafrost areas have shown consistent results in similar environments as Svalbard (Xu et al., 2021). Interannually, deepening of the active layer corresponding to a vertical degradation of the permafrost may lead to irreversible subsidence, that can have major consequences on **infrastructure stability**. With this objective, InSAR has been applied for the detection of subsidence on settlements located in permafrost areas (Short et al., 2014; Wolfe et al., 2014), with the objective of identifying building or roads currently affected by destabilization, but also in a long-term perspective, to plan urban developments. In areas with mountainous topography, InSAR has been also widely used for the detection, mapping and monitoring of **line-of-sight ground displacement on unstable slopes** (e.g. landslides, rock glaciers) that can represent a hazard for population and infrastructure (Barboux et al., 2015; Carlà et al., 2019; Lauknes et al., 2010; Strozzi et al., 2020).

In permafrost environment, the use of satellite InSAR may be challenging due to highly dynamic ground, complex seasonal patterns, sudden changes, as well as moist and snow-covered surfaces. High radar frequency (e.g. C-/L-band) and frequent data sampling (e.g. 6. or 12. days for Sentinel-1) are generally more suitable, providing better data coverage and performance compared to X-band and longer repeat-pass (Antonova et al., 2016; Strozzi et al., 2018; Rouyet et al., 2019). Another issue of the polar-orbit satellite sensors is their fixed line-of-sight that leads to very low sensitivity to displacements in the N-S directions (Eriksen et al., 2017). This limitation can be overcome with airborne sensors, for which the **3D velocity fields of unstable slopes** can be comprehensively retrieved by exploiting complementary line-of-sight (Delbridge et al., 2016).

In Svalbard, measurements of seasonal InSAR displacement progression related to the active layer thawing/freezing show that SAR remote sensing can be used to infer the thermal state of the ground (Rouyet et al., 2019; 2021), in complement with traditional measurements of the ECV products (Christiansen et al., 2019, 2021). The identification of large unstable rock slopes in coastal areas and close to settlements (Kuhn et al., 2021) also shows that there is a need for further slope hazard assessment on Spitsbergen. Retrogressive thaw slumps and their impact on the cultural heritage of Nordenskiöld Land has also been the subject of recent research focus (Nicu et al., 2021). In and around

Longyearbyen, satellite InSAR has been used to map unstable areas, potentially posing a hazard for the population and infrastructure (Rouyet et al., 2017).

An airborne L-band SAR system, with high availability, would valuably complement C-band Copernicus Sentinel-1 observations by providing high spatial resolution imagery, targeted mission with flexible and targeted repeat-pass, complementary line-of-sight, and L-band would improve coherence for most targets. Such as system would also benefit the Copernicus Emergency Management Service (EMS) by providing capacity to provide geospatial information to aid in risk assessment for ongoing disasters such as landslides, earthquakes, or volcanic eruptions. The aircraft has long range and could potentially assist for crisis in large parts of Europe. For emergency response, high-resolution mapping using X-band would be useful, in addition to multisensory change detection capability.

The key SAR-based products that can be generated by the community for the monitoring of ground surface deformation are summarized in Table 5.

Table 5: Summary of potential products based on Dornier SAR images and product requirements associated with the monitoring of ground surface deformation.

Product name	Product description	Main targeted areas	Recommended revisit time	General requirements/comments
Infrastructure deformation	Line-of-sight surface displacement on key infrastructure (mature)	Land areas with infrastructure (Longyearbyen, Ny-Ålesund, Barentsburg, Hornsund, Svea)	Weekly-monthly over critical infrastructure	• Repeat-pass InSAR (L-band) • Systematic observations in same mode • Observations from multiple geometries to retrieve displacement direction and magnitude
Slope deformation	Line-of-sight surface displacement on slopes (mature)	Prioritized areas with slope hazards	Monthly over prioritized areas with slope hazards	
Slope deformation	3D velocity fields from complementary line-of-sight measurements (experimental)	Prioritized areas with slope hazards		Dedicated experiments/studies
Active layer displacement progression	Line-of-sight surface displacement associated with active layer freeze/thaw (mature)	Valley bottoms and strandflats Prioritized permafrost observation sites from GTN-P and CALM network	Monthly (Prioritized permafrost observation sites from GTN-P and CALM network)	Dedicated experiments/studies
Active layer parameters	Inferred active layer thickness, freeze/thaw onset times and ground ice content (experimental)	Prioritized permafrost observation sites (GTN-P and CALM network)		Dedicated experiments/studies

5.2.4. Acquisition of calibration and validation data

There are several satellite L-band SAR missions planned (ROSE-L, NISAR) for which the collection of calibration and validation data will be important (Davidson & Furnell, 2021; Rosen & Kumar, 2021).

Cal/Val is a necessary part of Earth Observation satellite development and operations and can be divided into pre- and post-launch activities (Sterckx et al., 2020). Pre-launch activities focus on instrument calibration, algorithm development and evaluation. Post-launch Cal/Val activities focus on evaluating the accuracy of the satellite-derived products. Airborne campaigns usually play an important role in Cal/Val activities. However, the cost of bringing airborne instruments to the Arctic is significant, and unpredictable weather often complicates such campaigns.

An airborne dual frequency L/X-band SAR on Svalbard has the potential to significantly contribute to both pre- and post-launch activities for ROSE-L and other missions. The system would permit coordinated, fully polarimetric observations of the same area on the ground using both frequencies, allowing studies of the frequency dependence of polarized and depolarized backscatter with respect to frequency that can be related to backscatter models of snow and ice.

An airborne platform in Svalbard with both optical and SAR (L- and X-band) will, in addition to the existing SIOS infrastructure, be an important asset for calibration and validation (Cal/Val) activities for all cryosphere applications described in previous sections (e.g. sea-ice, snow, glaciers/ice-sheets, permafrost).

Mapping of sea ice as well as glacier motion are among the envisaged applications of the upcoming L-band space-borne SAR missions of ROSE-L and NISAR with the technique of repeat-pass interferometry. The L-band system on the Dornier SAR will feature repeated acquisitions with the objective of mapping movement of sea ice and glaciers and hence offer a great potential for collecting Cal/Val datasets to validate products of those missions.

Two examples related to cryospheric applications are:

- **Sea ice:** Studies have demonstrated the complementarity of C- and L-band SAR for operational sea ice monitoring. In order to investigate this complementarity, the data needs to be recorded within seconds of each other due to ice drift. By conducting coordinated observations between satellite missions and the airborne SAR, we can provide simultaneous X-, C- and L-band SAR images for improving sea ice classification.
- **Snow/Glaciers:** Low frequency SAR systems will in dry condition penetrate deeper into the snow/ice layer than X- and C-band systems and they accordingly will be sensitive to features in deeper layers. The penetration capability and the properties that can be extracted (e.g. snow water equivalent) is important for L-band satellite product validation.

5.3. Secondary objectives

In addition to the primary objectives, we define secondary objectives linked to applications for which there is a documented potential for X-/L-band airborne SAR observations but for which the maturity and/or user demand is not yet fully established. The applications can also take place elsewhere than Svalbard, considering that the aircraft can operate in Greenland or European mainland.

5.3.1. Soil moisture and freeze/thaw cycles

Soil moisture retrieval from satellite is currently performed with passive microwave sensors such as SMOS (Kerr et al., 2012). They provide daily global coverage, but with poor spatial resolution (20 km). Soil moisture investigation based on SAR backscatter and/or phase (Antonova et al., 2016; Zwieback et al., 2017; 2019) has also been studied. Active L-band sensors are highly desired to improve the resolution down to 50–100m. The ESA mission ROSE-L and NASA's NISAR has the retrieval of soil moisture as a primary objective. In order to validate and calibrate data from those sensors, an airborne L-band platform is highly desirable. The main advantage of L-band is the deeper penetration into the upper ground. Current SAR sensors like Sentinel-1 with shorter wavelengths are very sensitive to surface changes due to vegetation.

Based on multiple sensors with different frequencies, improved understanding of the distributed soil moisture in Svalbard could be a valuable contribution to multi-disciplinary sciences such as ecology, geophysics and permafrost science. Documenting ground moisture is for example highly relevant in combination with InSAR measurements documenting the frost heave and thaw subsidence due to ice formation/melting in the active layer (Chen et al., 2021), but discrimination phase shifts from ground displacements and moisture is a complex task that is the object of ongoing research (Zwieback et al., 2017). Cold-climate freeze-thaw cycles of the ground can also be studied using SAR backscatter (Bergstedt et al., 2018; Eckerstorfer et al., 2017b) and related to the active layer thickness (Widhalm et al., 2017).

As for sea ice, SAR may provide interesting additional information over lake ice that can be utilized to extract additional lake ice features and supplement the monitoring of freeze/thaw cycles (Atwood et al., 2015; Murfitt & Duguay, 2021; Pointner & Bartsch, 2021). Lake parameters such as lake area extent, ice extent and water level are essential climate parameters that needs additional attention in the arctic where nominal optical sensors have significant problems with overcast and polar night. Vickers et al. (2019) demonstrated how C-band SAR can be used to acquire long term lake extent datasets over an arctic lake. However, several problems with lake classification could be alleviated using multiple frequencies (e.g. L- and C-band).

5.3.2. Line-of-sight ocean surface currents

High resolution mapping and monitoring of ocean currents has scientific and operational relevance especially in coastal areas where the understanding of complex circulation patterns if important for many applications such as river runoff observations, pollution monitoring, tide-driven electric power plant development or ship traffic advisory (Gens, 2008). The exploitation of airborne SAR images for ocean current measurements have been shown in the 1980s (Goldstein & Zebker, 1987), and have been later applied based on spaceborne SAR systems (Chapron et al., 2005).

SAR remote sensing of ocean surface currents requires the use of along-track interferometry (ATI) based on two SAR antennas mounted on the same platform and separated by some distance in the flying direction to acquires two images of the same target with a very short time lag (milliseconds) (Romeiser et al., 2005). Phase difference between the two along-track interferometry SAR images is a measure of the Doppler shift of the backscattered signal documenting the line-of-sight (LOS) velocity of the scatterers. In maritime environments, the detected velocities are related to surface ocean currents and wind-wave motions (Romeiser & Thompson, 2000). To reliable estimate the ocean surface current, the wave-induced contribution must be corrected, which is especially challenging in highly heterogenous coastal areas. The exploitation of recent spaceborne SAR sensors, such as Sentinel 1, shows the value of exploiting high-resolution imagery to accurately model wind field (speed and direction) and retrieve ocean surface current (Moiseev et al., 2020). Airborne ATI (e.g. Wavewill airborne system operating at X-band) has also shown great potential for validating theoretical or empirical models for separating phase shift contributions from various sources (Martin et al., 2016).

Surface wind-wave patterns and ocean currents variably interact over a wide range of spatio-temporal scales, ranging from centimetres to global scales and from seconds to year-decades (Villas Bôas et al., 2019). Therefore, a comprehensive understanding of the interaction between ocean, ice and atmosphere requires a set of measurements with variable resolutions. An airborne SAR system enabling ATI and designed for mission in the Arctic Ocean would be of great value to validate and complement satellite-based empirical models of ocean currents.

5.3.3. Vegetation mapping and phenology

Climate changes have significant consequences on vegetation distribution, type, distribution, and phenology all around the World, including in the Arctic. However, changes of vegetation patterns in high-latitude environments are relatively neglected compared to other biomes due to access difficult, high costs and process complexity (Diepstraten et al., 2018). Remote sensing techniques are therefore highly relevant to overcome this unbalance (Beck et al., 2006).

The sensitivity of SAR backscattering signal to vegetation density and height can be used to map and monitor vegetation changes, even in cold-climate areas above the treeline (Duguay et al., 2015; Bartsch et al., 2020). The use of multiple SAR frequencies, polarizations and complementary sensors provides cross-validation potential in areas where ground-based validation is often lacking (Diepstraten et al., 2018). A SAR mounted on an airborne platform would typically contribute to that objective for Svalbard vegetation monitoring (Karlsen et al., 2020; Pedersen et al., 2020).

An airborne SAR is also highly relevant for vegetation applications in the Scandinavian mainland. Targeted missions can for example be designed for forest mapping and monitoring in Norway, Sweden or Finland. In densely vegetated regions, the use of long wavelengths (L-, P-band) is typically recommended to penetrate the vegetation structure, sense the entire canopy volume and estimate woody density (Rincon et al., 2014).

6. Mission requirements

This chapter presents mission requirements (MR) related to system (MR-SYS) and observational (MR-OBS) requirements, which constitutes a basis for the implementation phase where the MR will be translated into specific system design.

6.1. Mission requirements at system level

6.1.1. Radar system requirements

MR-SYS-010	**The payload shall include a L-band imaging synthetic aperture radar that is optimized for the mission objectives.**
	The User Survey has identified that an airborne L-band SAR system will fulfil a spectrum of applications, fill known observational gaps, and provide complementary observations to existing and planned Copernicus missions.

MR-SYS-020	**The payload shall include a X-band imaging synthetic aperture radar that is optimized for the mission objectives.**
	The User Survey has identified that an airborne X-band SAR system will fulfil a spectrum of applications, fill known observational gaps, and provide complementary observations to existing and planned Copernicus missions.

MR-SYS-030	**The mission shall support single-pass across-track interferometry on X-band**
	This satisfies the need to collect interferometric observations relevant to producing topographic terrain maps. The validity of this requirement is depending on the achievable baseline between the antennas. This will be defined in the detailed implementation phase.

MR-SYS-040	**The mission shall support single-pass along-track interferometry on X-band**
	This satisfies the need to collect interferometric observations relevant to estimating ocean currents and ice drift. The validity of this requirement is depending on the achievable baseline between the antennas. This will be defined in the detailed implementation phase.

MR-SYS-050	**The mission shall support repeat-pass interferometry at L-band**
	Repeat-pass InSAR is an important objective of the mission. This requirement satisfies the objective for monitoring surface motion including glacier, landslides, permafrost, and other geohazards. Other potential repeat-pass interferometric SAR products includes mapping of grounding lines and estimating SWE. Compared to the planned satellite L-band SAR missions such as NISAR (NASA/ISRO) and ROSE-L/Sentinel-12, an airborne system has high flexibility regarding temporal baselines, hence easily meets the performance requirement of upcoming SAR missions.

MR-SYS-060	**The mission shall support polarimetric observations on at least one of the frequencies**
	The User Survey has identified that a flexible system with capacity for polarimetric observations are necessary for certain applications. The detailed design phase will discuss the implementation of e.g. dual polarization or implementation of near-full polarization via compact polarization to satisfy this requirement.

MR-SYS-070	**The mission shall support operations at both frequencies simultaneously**
	Some applications such as sea ice and maritime surveillance could benefit from having simultaneous observations at both L and X-band.

MR-SYS-080	**Noise Equivalent Sigma Zero (NESZ) shall be < -28 dB for full-swath SAR image products at both frequencies**
	NESZ specifies the allowable noise for the system and is an important mission design driver. A low level NESZ is required for applications such as sea ice mapping, oil spill detection, ship detection and mapping of smooth surfaces.

MR-SYS-090	**The individual or combined data rates should support multiple receive channels**
	Specific modes of operation require the use of several receive channels. Possible redundancy and flexibility using two independent radar systems should be investigated.

MR-SYS-100	**Sufficient storage capacity to support extended missions and onboard processing**
	Depending on the mission chrematistics, long data takes could be expected. The system should have sufficient capacity to store raw data, as well as capacity to store onboard processed Level-1 data.

MR-SYS-110	**The radar systems and antennas shall have a design minimizing power consumption and weight**
	Overall weight and size must be kept to a minimum to minimize impact of cargo capacity on the aircraft.

MR-SYS-120	**The SAR systems should be integrated with the Inertial Navigation System**
	Precise knowledge of position and attitude of the aircraft is important for optimal focusing, and essential for repeat pass InSAR measurements. There is already an IMU installed in the pod on the aircraft, but there could be a need for another INU collocated with the antennas in the tail part of the aircraft.

MR-SYS-130	Need for GNSS correction signals
	In order to satisfy requirements for navigation for repeated flights, there is a need to employ GNSS correction signals. Different sources should be considered.

6.2. Mission requirements at observational level

MR-OBS-010	The mission shall support data acquisition during regular operations
	The SAR systems should allow planning of flight paths. The planned flight patterns shall be accessible to the pilots, with a user interface allowing them to operate the SAR and other payload, also during regular passenger or cargo flights, with no requirement of a dedicated payload operator.

MR-OBS-020	A short data latency is required to support maritime surveillance
	Maritime surveillance missions require strong coordination between observing aircraft and different stakeholders such as coast guard and JRCC. It is therefore imperative that the onboard SAR payload system can produce a timely Level-1 product. Onboard processing is therefore required.

MR-OBS-030	The mission shall support data acquisition simultaneous with optical payload
	The opportunity of conducting joint experiments combining optical and radar sensors provides a novel opportunity.

MR-OBS-040	The mission shall support data relay via Maritime Broadband Radio
	For maritime surveillance and search and rescue operations, sharing of near real-time observations between stakeholders is needed. If the aircraft is within radio coverage of the MBR network in Svalbard, operated by the Norwegian Coastal Administration, radar imagery and higher order detected products could be shared with JRCC in real time, facilitating detailed control of all stages of the operation.

MR-OBS-050	The mission shall support AIS observations simultaneous to SAR acquisitions
	For maritime surveillance and vessel detection, synergistic use of SAR and AIS is useful. The aircraft has an AIS receiver that provides information about vessels, and this should be used together with the SAR systems to increase situational awareness.

7. Preliminary system concept and design

In this Chapter, we briefly present the main system concept and design, that are to be completed and harmonized as part of mission requirement consolidation process.

7.1. Systems integration

A major design criterion for any modifications on the Dornier aircraft is to minimize impact on passenger or cargo capacity. Another criterion is support SAR data acquisitions during regular operations. This requires permanently mounted antennas and radar hardware, not occupying space inside the cabin or in the cargo area of the aircraft. The aircraft already has a payload pod which includes the optical instrumentation, inertial navigation unit and communication systems. The radar systems can utilize free space in the pod for X-band antennas, while the main radar antennas must be installed towards the rear part of the aircraft.

In addition to the requirements listed in Section 6, the following opportunities will be investigated in the technical implementation phase:

- Simultaneous left/right imaging (important for search & rescue and wide area mapping)
- Electric antenna beam steering to compensate for squint and desired look angle

7.2. Antenna considerations

In an effort to provide SAR processing capability to the Dornier SAR development project, a number of studies have been conducted through a parallel project. Among the relevant studies is a simulation experiment investigating potential antenna configurations for the purpose of meeting the interferometric SAR requirements listed in Section 6.1.1 (Yitayew et al., 2021). Motivated by a number of advantages such as low and constant transmit output power, and relatively less complex hardware, a Frequency-Modulated Continuous-Wave (FMCW) radar system with separate transmit and receive antennas has been considered for the Dornier SAR system, hence has been assumed in the simulation study. By using a typical FMCW radar and antenna configuration, we aim to achieve performance similar to the values presented in Table 6.

Table 6. Preliminary radar frequencies, bandwidth, resolution, and swath widths assuming a nominal flight altitude between 1–3 km, with a nominal cruise speed over ground between 60–92 m/s.

Operating band	Frequency	Bandwidth	Range resolution	Azimuth resolution	Swath width at 1000–3000 m altitude
L-band	1307.5 MHz	100–185 MHz	1.5–0.8 m	0.6 m	1.8–5.3 km
X-band	9600 MHz	100–300 MHz	1.5–0.5 m	0.6 m	1.2–3.6 km

7.2.1. X-band across- and along-track interferometry (XTI/ATI)

To be able to achieve topographic mapping capability of different surfaces such as glaciers, ice ridges and land surfaces, the system is required to support across-track interferometry (**MR-SYS-030**). This technique also commonly abbreviated as XTI requires two SAR measurements acquired from two different locations that are laterally displaced from each other. Details about different antenna configurations for this mode of operation with respect to the Dornier aircraft can be found in (Yitayew et al., 2021). The single-pass along-track interferometry (ATI) technique (**MR-SYS-030**) on the other hand is a requirement for fulfilling the objective of mapping motion vectors such as ocean currents and sea ice drift. In this case, the two SAR images are acquired at two different locations with a certain along-track separation. A number of antenna configurations that are feasible to achieve with the Dornier aircraft have been investigated for this application in (Yitayew et al., 2021).

As it is stated in the system requirements above, X-band antennas are intended for single pass interferometry whereas L-band antennas are for repeat-pass interferometric measurements. We have identified two potential locations on the aircraft for mounting the antennas. The first one is at the rear part of the aircraft where the antennas will be flash mounted to the fuselage of the aircraft (Figure 4) and the second one is inside the pod where at the rear part of the pod, there is about 0.77 m x 1.27 m space available (Figure 2).

Among the different antenna configurations investigated in the simulation study, two potential candidates are identified for implementation. In the following, a very short summary of these two candidate configurations and the corresponding performances are provided.

The first candidate is to flash-mount all the antennas on the fuselage at the rear part of the aircraft. This configuration is shown in Figure 5.

Figure 4 : An approximately 1 m x 1 m space is available for mounting the antennas at the rear part of the aircraft.

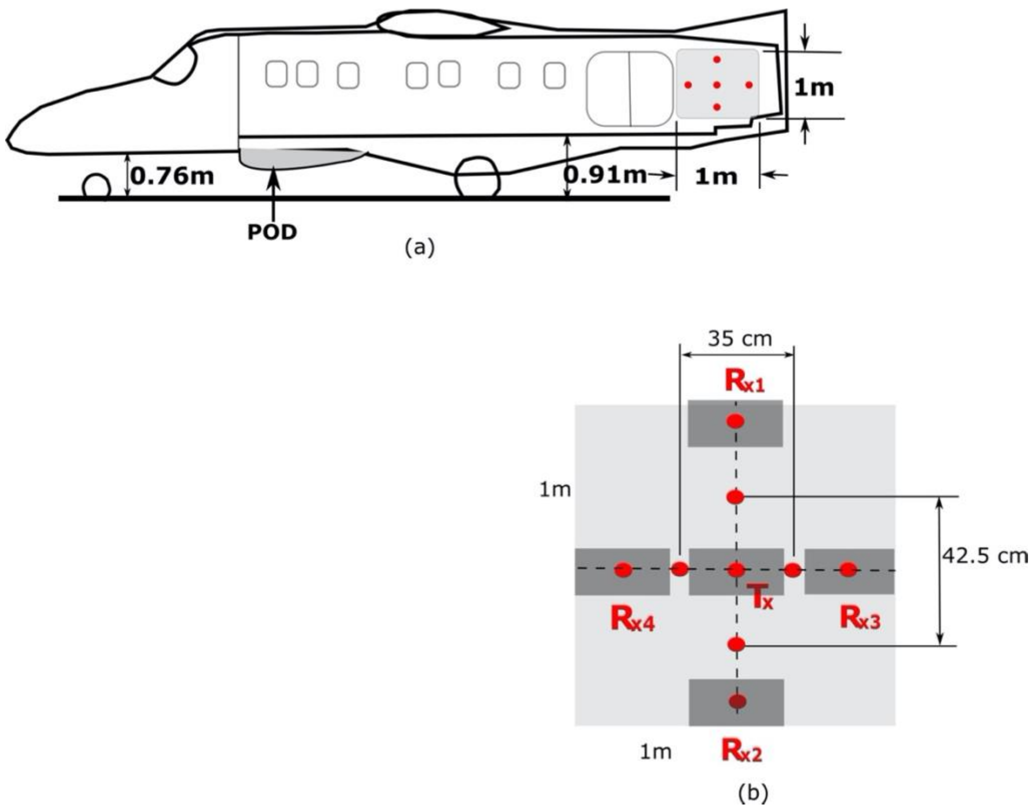


Figure 5 : Candidate X-band antenna configuration on the Dornier. All the antennas are flush-mounted on the fuselage of the aircraft. (a) Potential locations of effective phase centres of the different TX/RX combinations. (b) Location of the transmitter and receiver antennas and the corresponding effective phase centres. Note that the dark shaded rectangles represent the antennas, but not drawn to scale. XTI is performed by combining TX/RX1 and TX/RX2 whereas ATI is performed by combining TX/RX3 and TX/RX4.

For line-of-sight velocity mapping, the maximum achievable along-track baseline with this configuration is about 0.35 m, which can be translated to a sensitivity of 5 cm/s. In other words, this configuration is sensitive to motion vectors greater than 5 cm/s hence can be applicable to both ocean surface current and sea ice drift measurements.

For topographic mapping using the technique of XTI, the achievable performance with single-look processing is about 1.5 m, i.e., this configuration can only be used to reliably retrieve topographic features that are bigger than 1.5 m high. The performance can be improved to 0.75 m with multi-look processing (4-looks), however, as it is discussed in (Yitayew et al., 2021) at the cost of vertical resolution.

The second candidate configuration is similar to the first one, with the exception that one of the X-band receivers is mounted inside the pod (Figure 6). This configuration provides an improved performance in terms of topographic mapping with XTI. The achievable performance with single look processing is 0.75 m and can be improved to 0.3 m with multi-look processing (4-looks). The along-track interferometric performance is the same as the first candidate.

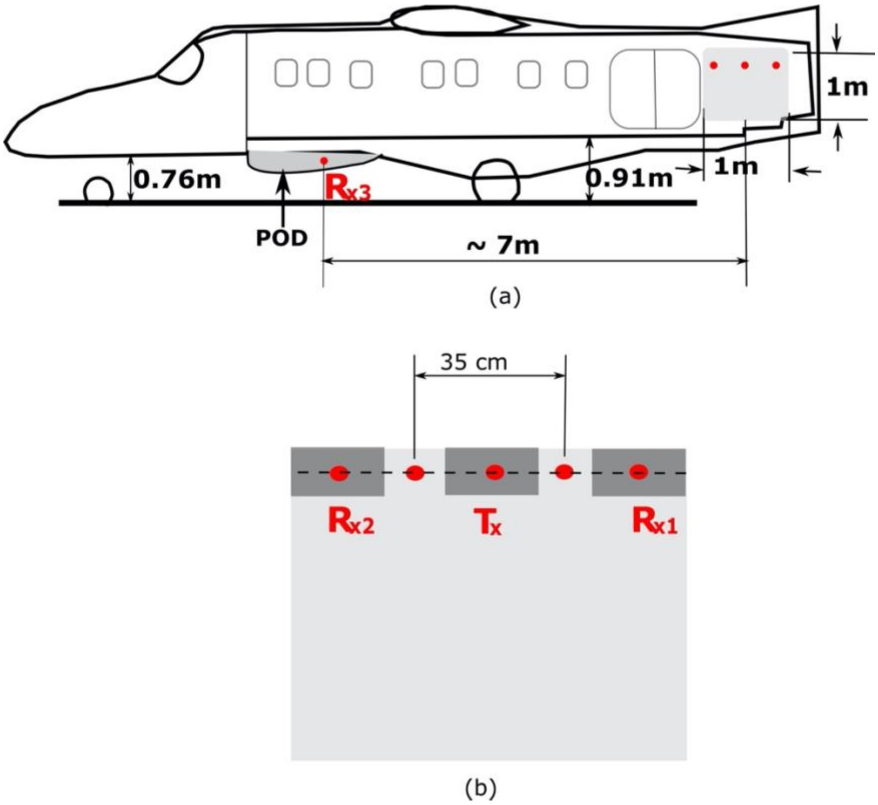


Figure 6. Candidate X-band antenna configuration on the Dornier. A receiver antenna is mounted inside the pod, labelled as RX3 and the remaining antennas are flush-mounted on the fuselage at the rear part of the aircraft. (b) Location of the transmitter and receiver antennas and their corresponding effective phase canters. ATI is performed by combining TX/RX1 and TX/RX2. XTI is performed by combining the dataset acquired by the TX/RX3 system inside the pod and the one acquired by either TX/RX1 or TX/RX2.

For mapping motion of slowly moving targets such as glaciers or sea ice with repeat-pass SAR interferometric technique (**MR-SYS-050**), the L-band antenna can be mounted in-between the X-band antennas. One possible configuration is shown in Figure 7. Note that, with the second candidate discussed above, RX2 would move into the POD.

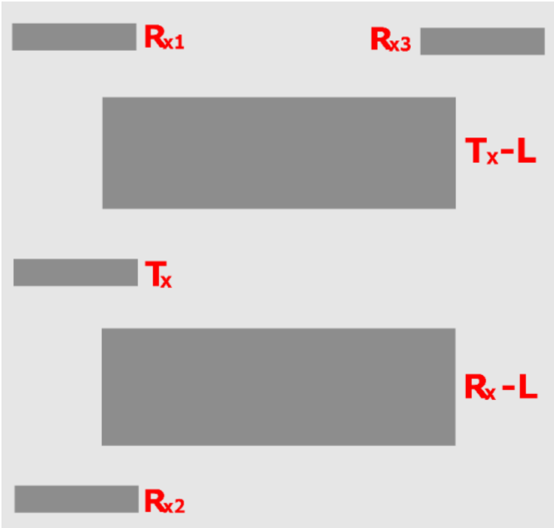


Figure 7 : Candidate X-, and L-band antenna configuration on the Dornier at the rear part of the aircraft.

In summary, the two candidate configurations are feasible in terms of availability of space on the aircraft as well as the desired interferometric performances. The Second candidate configuration provides a better across-track interferometric performance and would be the ideal choice. However, a final decision will be made during the implementation phase taking into account factors other than interferometric performances.

8. Product family (L0/L1/L2)

To be completed and harmonised as a function of mission requirement consolidation process.

9. References

Antonova, S., Kääb, A., Heim, B., Langer, M., & Boike, J. (2016). Spatio-temporal variability of X-band radar backscatter and coherence over the Lena River Delta, Siberia. *Remote sensing of Environment*, *182*, 169-191.

Atwood, D. K., Gunn, G. E., Roussi, C., Wu, J., Duguay, C., & Sarabandi, K. (2015). Microwave backscatter from Arctic lake ice and polarimetric implications. *IEEE Transactions on Geoscience and Remote Sensing*, *53*(11), 5972-5982.

Barboux, C., Strozzi, T., Delaloye, R., Wegmüller, U., & Collet, C. (2015). Mapping slope movements in Alpine environments using TerraSAR-X interferometric methods. *ISPRS journal of photogrammetry and remote sensing*, *109*, 178-192.

Bartsch, A., Widhalm, B., Leibman, M., Ermokhina, K., Kumpula, T., Skarin, A., ... & Pointner, G. (2020). Feasibility of tundra vegetation height retrieval from Sentinel-1 and Sentinel-2 data. *Remote Sensing of Environment*, *237*, 111515.

Beck, P. S., Atzberger, C., Høgda, K. A., Johansen, B., & Skidmore, A. K. (2006). Improved monitoring of vegetation dynamics at very high latitudes: A new method using MODIS NDVI. *Remote sensing of Environment*, *100*(3), 321-334.

Bergstedt, H., Zwieback, S., Bartsch, A., & Leibman, M. (2018). Dependence of C-band backscatter on ground temperature, air temperature and snow depth in arctic permafrost regions. *Remote Sensing*, *10*(1), 142.

Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F. J. W., ... & Olsen, M. S. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, *14*(4), 045010.

Bradley et al. (2021). An agenda for the future of snow research in Svalbard - a multidomain approach. DRAFT Version 05 March 2021. SIOS.

Brekke, C., & Anfinsen, S. N. (2010). Ship detection in ice-infested waters based on dual-polarization SAR imagery. *IEEE Geoscience and Remote Sensing Letters*, *8*(3), 391-395.

Brekke, C., & Solberg, A. H. (2005). Oil spill detection by satellite remote sensing. *Remote sensing of environment*, *95*(1), 1-13.

Carlà, T., Intrieri, E., Raspini, F., Bardi, F., Farina, P., Ferretti, A., ... & Casagli, N. (2019). Perspectives on the prediction of catastrophic slope failures from satellite InSAR. *Scientific reports*, *9*(1), 1-9.

Chapron, B., Collard, F., & Ardhuin, F. (2005). Direct measurements of ocean surface velocity from space: Interpretation and validation. *Journal of Geophysical Research: Oceans*, *110*(C7).

Chaudhary, V., & Kumar, S. (2020). Marine oil slicks detection using spaceborne and airborne SAR data. *Advances in Space Research*, *66*(4), 854-872.

Chen, R. H., Michaelides, R. J., Zhao, Y., Huang, L., Wig, E., Sullivan, T. D., ... & Schaefer, K. M. (2021, July). Permafrost Dynamics Observatory: Retrieval of Active Layer Thickness and Soil Moisture from Airborne Insar and Polsar Data. In *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS* (pp. 1444-1447). IEEE.

Christiansen, H. H., Gilbert, G. L., Demidov, N., Guglielmin, M., Isaksen, K., Osuch, M., & Boike, J. (2019). Permafrost thermal snapshot and active-layer thickness in Svalbard 2016–2017. In *SESS Report 2018*. Svalbard Integrated Arctic Earth Observing System.

Christiansen, H. H., Gilbert, G. L., Neumann, U., Demidov, N., Guglielmin, M., Isaksen, K., ... & Boike, J. (2021). Ground ice content, drilling methods and equipment and permafrost dynamics in Svalbard 2016–2019 (PermaSval). In *SESS report 2020.* Svalbard Integrated Arctic Earth Observing System.

Conde, V., Nico, G., Mateus, P., Catalão, J., Kontu, A., & Gritsevich, M. (2019). On the estimation of temporal changes of snow water equivalent by spaceborne SAR interferometry: a new application for the Sentinel-1 mission. *Journal of Hydrology and Hydromechanics*.

Dammann, D. O., Eriksson, L. E., Jones, J. M., Mahoney, A. R., Romeiser, R., Meyer, F. J., ... & Fukamachi, Y. (2019). Instantaneous sea ice drift speed from TanDEM-X interferometry. *The Cryosphere*, *13*(4), 1395-1408.

Davidson, M. W., & Furnell, R. (2021, July). ROSE-L: Copernicus L-Band Sar Mission. In *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS* (pp. 872-873). IEEE.

Delbridge, B. G., Bürgmann, R., Fielding, E., Hensley, S., & Schulz, W. H. (2016). Three-dimensional surface deformation derived from airborne interferometric UAVSAR: Application to the Slumgullion Landslide. *Journal of geophysical research: solid earth*, *121*(5), 3951-3977.

Deline, P., Gruber, S., Amann, F., Bodin, X., Delaloye, R., Failletaz, J., ... & Weber, S. (2021). Ice loss from glaciers and permafrost and related slope instability in high-mountain regions. In *Snow and Ice-Related Hazards, Risks, and Disasters* (pp. 501-540). Elsevier.

Diepstraten, R. A., Jessen, T. D., Fauvelle, C. M., & Musiani, M. M. (2018). Does climate change and plant phenology research neglect the Arctic tundra?. *Ecosphere*, *9*(9), e02362.

Dierking, W. (2013). Sea ice monitoring by synthetic aperture radar. *Oceanography*, *26*(2), 100-111.

Dierking, W. (2021). Synergistic Use of L-and C-Band SAR Satellites for Sea Ice Monitoring. In *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS* (pp. 877-880). IEEE.

Duguay, Y., Bernier, M., Lévesque, E., & Tremblay, B. (2015). Potential of C and X band SAR for shrub growth monitoring in sub-arctic environments. *Remote Sensing*, *7*(7), 9410-9430.

Dyrkoren, E., & Berg, T. E. (2014). Norwegian work on search and rescue in Barents Sea. In *International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 45561, p. V010T07A050). American Society of Mechanical Engineers.

Eckerstorfer, M., & Malnes, E. (2015). Manual detection of snow avalanche debris using high-resolution Radarsat-2 SAR images. *Cold Regions Science and Technology*, *120*, 205-218.

Eckerstorfer, M., Malnes, E., & Müller, K. (2017a). A complete snow avalanche activity record from a Norwegian forecasting region using Sentinel-1 satellite-radar data. *Cold regions science and technology*, *144*, 39-51.

Eckerstorfer, M., Malnes, E., & Christiansen, H. H. (2017b). Freeze/thaw conditions at periglacial landforms in Kapp Linné, Svalbard, investigated using field observations, in situ, and radar satellite monitoring. *Geomorphology*, *293*, 433-447.

Eriksen, H. Ø., Lauknes, T. R., Larsen, Y., Corner, G. D., Bergh, S. G., Dehls, J., & Kierulf, H. P. (2017). Visualizing and interpreting surface displacement patterns on unstable slopes using multi-geometry satellite SAR interferometry (2D InSAR). *Remote Sensing of Environment*, *191*, 297-312.

Fors, A. S., Divine, D. V., Doulgeris, A. P., Renner, A. H. H., & Gerland, S. (2017). Signature of Arctic first-year ice melt pond fraction in X-band SAR imagery, *The Cryosphere*, 11, 755–771, https://doi.org/10.5194/tc-11-755-2017.

Friedl, P., Seehaus, T., & Braun, M. (2021). Global time series and temporal mosaics of glacier surface velocities, derived from Sentinel-1 data. *Earth System Science Data Discussions*, 1-33.

Friedl, P., Weiser, F., Fluhrer, A., & Braun, M. H. (2020). Remote sensing of glacier and ice sheet grounding lines: A review. *Earth-Science Reviews*, *201*, 102948.

GCOS (2021). The Global Climate Observing System 2021: The GCOS Status Report – GCOS-240. https://gcos.wmo.int/en/gcos-status-report-2021

Gens, R. (2008). Oceanographic applications of SAR remote sensing. *GIScience & Remote Sensing*, *45*(3), 275-305.

Gerland, S., Pavlova, O., Divine, D., Negrel, J., Dahlke, S., Johansson, A. M., ... & Semmling, M. (2020). Long-term monitoring of landfast sea ice extent and thickness in Kongsfjorden, and related applications (FastIce). In *SESS report 2019*. Svalbard Integrated Arctic Earth Observing System.

Goldstein, R. M., & Zebker, H. A. (1987). Interferometric radar measurement of ocean surface currents. *Nature*, *328*(6132), 707-709.

Grahn, J. (2018). Multi-frequency radar remote sensing of sea ice. Modelling and interpretation of polarimetric multi-frequency radar signatures of sea ice. PhD Thesis.

Guneriussen, T., Hogda, K. A., Johnsen, H., & Lauknes, I. (2001). InSAR for estimation of changes in snow water equivalent of dry snow. *IEEE Transactions on Geoscience and Remote Sensing*, *39*(10), 2101-2108.

Hannevik, T. N. A., Viken, K. O., Olsen, R. B., & Lensj, Ø. K. (2017). Arctic maritime surveillance with sentinel-1 data using a norwegian collaborative ground segment. In *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (pp. 4052-4055).

Harris, C., Arenson, L. U., Christiansen, H. H., Etzelmüller, B., Frauenfelder, R., Gruber, S., ... & Muehll, D. V. (2009). Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. *Earth-Science Reviews*, *92*(3-4), 117-171.

Hensley, S., Jones, C., Moller, D., Chapman, B., Michel, T., Simard, M., ... & Simons, M. (2010). Ice studies using UAVSAR L-band and Ka-band data. In *8th European Conference on Synthetic Aperture Radar* (pp. 1-4). VDE.

Prats, P., Scheiber, R., Reigber, A., Andres, C., & Horn, R. (2008). Estimation of the surface velocity field of the Aletsch glacier using multibaseline airborne SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, *47*(2), 419-430.

Iervolino, P., Guida, R., Lumsdon, P., Janoth, J., Clift, M., Minchella, A., & Bianco, P. (2017, July). Ship detection in SAR imagery: A comparison study. In *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (pp. 2050-2053).

Jansen, E., Christensen, J. H., Dokken, T., Nisancioglu, K. H., Vinther, B. M., Capron, E., ... & Stendel, M. (2020). Past perspectives on the present era of abrupt Arctic climate change. *Nature Climate Change*, *10*(8), 714-721.

Jenssen, R. O. R., Eckerstorfer, M., & Jacobsen, S. (2019). Drone-mounted ultrawideband radar for retrieval of snowpack properties. *IEEE Transactions on Instrumentation and Measurement*, *69*(1), 221-230.

Johansson, A. M., & Berg, A. (2016). Agreement and complementarity of sea ice drift products. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *9*(1), 369-380.

Johansson, A. M., Brekke, C., Spreen, G., & King, J. A. (2018). X-, C-, and L-band SAR signatures of newly formed sea ice in Arctic leads during winter and spring. *Remote Sensing of Environment*, *204*, 162-180.

Johansson, A. M., King, J. A., Doulgeris, A. P., Gerland, S., Singha, S., Spreen, G., & Busche, T. (2017). Combined observations of Arctic sea ice with near-coincident colocated X-band, C-band, and L-band SAR satellite remote sensing and helicopter-borne measurements. Journal of Geophysical Research: Oceans, 122(1), 669-691.

JRCC (2019). SAR Cooperation Plan. Plan for co-operation between SAR-services and passenger ships in an emergency. https://www.hovedredningssentralen.no/wp-content/uploads/2019/08/SAR-Cooperation-Plan_2019.pdf

Karlsen, S. R., Stendardi, L., Nilsen, L., Malnes, E., Eklundh, L., Julitta, T., ... & Tømmervik, H. (2020). Sentinel satellite-based mapping of plant productivity in relation to snow duration and time of green-up (GROWTH). *SESS REPORT 2019*.

Karvonen, J., Rinne, E., Sallila, H., Uotila, P., & Mäkynen, M. (2021). Arctic Sea Ice Thickness Estimation Based on CryoSat-2 Radar Altimeter and Sentinel-1 Dual-Polarized SAR. *The Cryosphere Discussions*, 1-33.

Kern, M., Cullen, R., Berruti, B., Bouffard, J., Casal, T., Drinkwater, M. R., Gabriele, A., Lecuyot, A., Ludwig, M., Midthassel, R., Navas Traver, I., Parrinello, T., Ressler, G., Andersson, E., Martin-Puig, C., Andersen, O., Bartsch, A., Farrell, S., Fleury, S., Gascoin, S., Guillot, A., Humbert, A., Rinne, E., Shepherd, A., van den Broeke, M. R., & Yackel, J. (2020). The Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) high-priority candidate mission, *The Cryosphere*, 14, 2235-2251.

Kerr, Y. H., Waldteufel, P., Richaume, P., Wigneron, J. P., Ferrazzoli, P., Mahmoodi, A., ... & Delwart, S. (2012). The SMOS soil moisture retrieval algorithm. *IEEE transactions on geoscience and remote sensing*, *50*(5), 1384-1403.

Killie, M. A., Aaboe, S., Isaksen, K., Van Pelt, W., Pedersen, Å. Ø., & Luks, B. (2021). Svalbard snow and sea-ice cover: comparing satellite data, on-site measurements, and modelling results (SvalSCESIA). *In* SESS report 2020: The State of Environmental Science in Svalbard.

Kuhn, D., Torizin, J., Fuchs, M., Hermanns, R. L., Redfield, T. F., & Balzer, D. (2021). Back analysis of a coastal cliff failure along the Forkastningsfjellet coastline, Svalbard: Implications for controlling and triggering factors. *Geomorphology*, *389*, 107850.

Kwok, R., Panzer, B., Leuschen, C., Pang, S., Markus, T., Holt, B., & Gogineni, S. (2011). Airborne surveys of snow depth over Arctic sea ice. *Journal of Geophysical Research: Oceans*, *116*(C11).

Kääb, A., Huggel, C., Fischer, L., Guex, S., Paul, F., Roer, I., ... & Weidmann, Y. (2005). Remote sensing of glacier-and permafrost-related hazards in high mountains: an overview. *Natural Hazards and Earth System Sciences*, *5*(4), 527-554.

Lauknes, T. R., Shanker, A. P., Dehls, J. F., Zebker, H. A., Henderson, I. H. C., & Larsen, Y. (2010). Detailed rockslide mapping in northern Norway with small baseline and persistent scatterer interferometric SAR time series methods. *Remote Sensing of Environment*, *114*(9), 2097-2109.

Lemos, A., Shepherd, A., McMillan, M., Hogg, A. E., Hatton, E., & Joughin, I. (2018). Ice velocity of Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjerdsfjorden, and Zachariæ Isstrøm, 2015–2017, from Sentinel 1-a/b SAR imagery. *The Cryosphere*, *12*(6), 2087-2097.

Lievens, H., Demuzere, M., Marshall, H. P., Reichle, R. H., Brucker, L., Brangers, I., & De Lannoy, G. J. (2019). Snow depth variability in the Northern Hemisphere mountains observed from space. *Nature communications*, *10*(1), 1-12.

Liu, C., Vachon, P. W., & Geling, G. W. (2005). Improved ship detection with airborne polarimetric SAR data. *Canadian Journal of Remote Sensing*, *31*(1), 122-131.

Liu, L., Schaefer, K., Zhang, T., & Wahr, J. (2012). Estimating 1992–2000 average active layer thickness on the Alaskan North Slope from remotely sensed surface subsidence. *Journal of Geophysical Research: Earth Surface*, *117*(F1).

Malnes, E., Karlsen, S. R., Johansen, B., Haarpaintner, J., & Hogda, K. A. (2010). Monitoring of the snow coverage and its relation to vegetation and growing seasons on Svalbard using ENVISAT ASAR and TERRA MODIS data. In *ESA Living Planet Symposium* (Vol. 686, p. 265).

Malnes, E., Vickers, H., Karlsen, S. R., Saloranta, T., Killie, M. A., Van Pelt, W., ... & Notarnicola, C. (2021). Satellite and modelling based snow season time series for Svalbard: Inter-comparisons and assessment of accuracy (SATMODSNOW). In *SESS report 2020*. Svalbard Integrated Arctic Earth Observing System.

Marsh, O. J., Price, D., Courville, Z. R., & Floricioiu, D. (2021). Crevasse and rift detection in Antarctica from TerraSAR-X satellite imagery. *Cold Regions Science and Technology*, https://doi.org/10.1016/j.coldregions.2021.103284.

Martin, A. C., Gommenginger, C., Marquez, J., Doody, S., Navarro, V., & Buck, C. (2016). Wind-wave-induced velocity in ATI SAR ocean surface currents: First experimental evidence from an airborne campaign. *Journal of Geophysical Research: Oceans*, *121*(3), 1640-1653.

McClung, D. M. (2002). The elements of applied avalanche forecasting, Part I: The human issues. *Natural Hazards*, *26*(2), 111-129.

Meredith, M., Sommerkorn, M., Cassotta, S., Derksen, C., Ekaykin, A., Hollowed, A., ... & Schuur, E. A. (2019). Polar Regions. Chapter 3, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Michaelides, R. J., Chen, R. H., Zhao, Y., Schaefer, K., Parsekian, A. D., Sullivan, T., ... & Chen, J. (2021). Permafrost Dynamics Observatory—part I: Postprocessing and calibration methods of UAVSAR L-band InSAR data for seasonal subsidence estimation. *Earth and Space Science*, *8*(7), e2020EA001630.

Minchew, B., Simons, M., Hensley, S., Björnsson, H., & Pálsson, F. (2015). Early melt season velocity fields of Langjökull and Hofsjökull, central Iceland. *Journal of Glaciology*, *61*(226), 253-266.

Moiseev, A., Johnsen, H., Johannessen, J. A., Collard, F., & Guitton, G. (2020). On removal of sea state contribution to Sentinel-1 Doppler shift for retrieving Reliable Ocean surface current. *Journal of Geophysical Research: Oceans*, *125*(9), e2020JC016288.

Moreno-Ibáñez M., Hagen J.O., Hübner C., Lihavainen H., & Zaborska A. (eds) (2021). SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen.

Muckenhuber, S., Nilsen, F., Korosov, A., & Sandven, S. (2016). Sea ice cover in Isfjorden and Hornsund, Svalbard (2000–2014) from remote sensing data. *The Cryosphere*, *10*(1), 149-158.

Murfitt, J., & Duguay, C. R. (2021). 50 years of lake ice research from active microwave remote sensing: Progress and prospects. *Remote Sensing of Environment*, *264*, 112616.

Müller, K., Eckerstorfer, M., Grahn, J., Malnes, E., Engeset, R., Humstad, T., & Widforss, A. (2021). Norway's Operational Avalanche Activity Monitoring System Using Sentinel-1. In *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS* (pp. 236-238).

Nagler, T., Rott, H., Ripper, E., Bippus, G., & Hetzenecker, M. (2016). Advancements for snowmelt monitoring by means of Sentinel-1 SAR. *Remote Sensing*, *8*(4), 348.

Nandan, V., Geldsetzer, T., Yackel, J., Mahmud, M., Scharien, R., Howell, S., King, J., Ricker, R., & Else, B. (2017). Effect of snow salinity on CryoSat-2 Arctic first-year sea ice freeboard measurements. *Geophysical Research Letters, 44*(20), 10419-10426.

Neckel, N., Braun, A., Kropáček, J., & Hochschild, V. (2013). Recent mass balance of the Purogangri Ice Cap, central Tibetan Plateau, by means of differential X-band SAR interferometry. *The Cryosphere*, *7*(5), 1623-1633.

NGI (2017). Oppdatert ulykkesstatistikk. (Updated accident statistics.)
https://www.ngi.no/Tjenester/Fagekspertise/Snoeskred/snoskred.no2/Snoeskredulykker-med-doed.

Nicu, I. C., Lombardo, L., & Rubensdotter, L. (2021). Preliminary assessment of thaw slump hazard to Arctic cultural heritage in Nordenskiöld Land, Svalbard. *Landslides*, 1-13.

Nuth, C., Kohler, J., König, M., Von Deschwanden, A., Hagen, J. O., Kääb, A., ... & Pettersson, R. (2013). Decadal changes from a multi-temporal glacier inventory of Svalbard. *The Cryosphere*, *7*(5), 1603-1621.

Orr et al. (eds) (2019). SESS report 2018. Svalbard Integrated Arctic Earth Observing System, Longyearbyen.

Park, J. W., Korosov, A. A., Babiker, M., Won, J. S., Hansen, M. W., & Kim, H. C. (2020). Classification of sea ice types in Sentinel-1 synthetic aperture radar images. *The Cryosphere*, *14*(8), 2629-2645.

Pavlova, O., Gerland, S., & Hop, H. (2019). Changes in sea-ice extent and thickness in Kongsfjorden, Svalbard (2003–2016). In *The ecosystem of Kongsfjorden, Svalbard* (pp. 105-136). Springer, Cham.

Pedersen, Å. Ø., Stien, J., Albon, S., Fuglei, E., Isaksen, K., Liston, G., ... & Ims, R. A. (2020). Climate-ecological observatory for Arctic Tundra (COAT). In *SESS report 2019*. Svalbard Integrated Arctic Earth Observing System.

Philipp, M., Dietz, A., Buchelt, S., & Kuenzer, C. (2021). Trends in Satellite Earth Observation for Permafrost Related Analyses—A Review. *Remote Sensing*, *13*(6), 1217.

Pointner, G., & Bartsch, A. (2021). Mapping Arctic Lake Ice Backscatter Anomalies Using Sentinel-1 Time Series on Google Earth Engine. *Remote Sensing*, *13*(9), 1626.

Rainville, L., Wilkinson, J., Durley, M. E. J., Harper, S., DiLeo, J., Doble, M. J., ... & Woods, J. (2020). Improving situational awareness in the Arctic Ocean. *Frontiers in Marine Science*, *7*, 1024.

Ricker, R., Hendricks, S., Helm, V., Skourup, H., & Davidson, M. (2014). Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation. *The Cryosphere*, 8(4), 1607-1622.

Ricker, R., Hendricks, S., Perovich, D. K., Helm, V., & Gerdes, R. (2015). Impact of snow accumulation on CryoSat-2 range retrievals over Arctic sea ice: An observational approach with buoy data. *Geophysical Research Letters*, 42(11), 4447-4455.

Rignot, E., Mouginot, J., & Scheuchl, B. (2011). Antarctic grounding line mapping from differential satellite radar interferometry. *Geophysical Research Letters*, *38*(10).

Rincon, R. F., Fatoyinbo, T., Ranson, K. J., Osmanoglu, B., Sun, G., Deshpande, M., ... & Lu, D. (2014, May). The ecosystems SAR (EcoSAR) an airborne P-band polarimetric InSAR for the measurement of vegetation structure, biomass and permafrost. In *2014 IEEE Radar Conference* (pp. 1443-1445).

Romeiser, R., & Thompson, D. R. (2000). Numerical study on the along-track interferometric radar imaging mechanism of oceanic surface currents. *IEEE transactions on geoscience and remote sensing*, *38*(1), 446-458.

Romeiser, R., Breit, H., Eineder, M., Runge, H., Flament, P., De Jong, K., & Vogelzang, J. (2005). Current measurements by SAR along-track interferometry from a space shuttle. *IEEE Transactions on Geoscience and Remote Sensing*, *43*(10), 2315-2324.

Rosen, P. A., & Kumar, R. (2021). NASA-ISRO SAR (NISAR) Mission Status. In *2021 IEEE Radar Conference (RadarConf21)* (pp. 1-6).

Rott, H., Yueh, S. H., Cline, D. W., Duguay, C., Essery, R., Haas, C., ... & Thompson, A. (2010). Cold regions hydrology high-resolution observatory for snow and cold land processes. *Proceedings of the IEEE*, *98*(5), 752-765.

Rouyet, L., Eckerstorfer, M., Lauknes, T. R., & Riise, T. (2017). Deformasjonskartlegging rundt Longyearbyen ved bruk av satellittbasert radarinterferometri. Norut rapport (13/2017).

Rouyet, L., Lauknes, T. R., Christiansen, H. H., Strand, S. M., & Larsen, Y. (2019). Seasonal dynamics of a permafrost landscape, Adventdalen, Svalbard, investigated by InSAR. *Remote Sensing of Environment*, *231*, 111236.

Rouyet, L., Liu, L., Strand, S. M., Christiansen, H. H., Lauknes, T. R., & Larsen, Y. (2021). Seasonal InSAR Displacements Documenting the Active Layer Freeze and Thaw Progression in Central-Western Spitsbergen, Svalbard. *Remote Sensing*, *13*(15), 2977.

Salzano, R., Aalstad, K., Boldrini, E., Gallet, J. C., Kępski, D., Luks, B., ... & Westermann, S. (2020). Terrestrial photography applications on snow cover in Svalbard (PASSES). *SESS report 2019*. Svalbard Integrated Arctic Earth Observing System.

Santamaria, C., Alvarez, M., Greidanus, H., Syrris, V., Soille, P., & Argentieri, P. (2017). Mass processing of Sentinel-1 images for maritime surveillance. *Remote Sensing*, *9*(7), 678.

Schuler, T. V., Glazovsky, A., Hagen, J. O., Hodson, A., Jania, J., Kääb, A., ... & Van Pelt, W. (2020a). New data, new techniques and new challenges for updating the state of Svalbard glaciers (SvalGlac). *SESS report 2019*. Svalbard Integrated Arctic Earth Observing System.

Schuler, T. V., Kohler, J., Elagina, N., Hagen, J. O. M., Hodson, A. J., Jania, J. A., ... & Van Pelt, W. J. (2020b). Reconciling Svalbard glacier mass balance. *Frontiers in Earth Science*, *8*, 156.

Schuur, E. A., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., ... & Vonk, J. E. (2015). Climate change and the permafrost carbon feedback. *Nature*, *520*(7546), 171-179.

Serreze, M. C., & Barry, R. G. (2011). Processes and impacts of Arctic amplification: A research synthesis. *Global and planetary change*, *77*(1-2), 85-96.

Shokr, M. E., Wang, Z., & Liu, T. (2020). Sea ice drift and arch evolution in the Robeson Channel using the daily coverage of Sentinel-1 SAR data for the 2016–2017 freezing season. *The Cryosphere*, *14*(11), 3611-3627.

Short, N., LeBlanc, A. M., Sladen, W., Oldenborger, G., Mathon-Dufour, V., & Brisco, B. (2014). RADARSAT-2 D-InSAR for ground displacement in permafrost terrain, validation from Iqaluit Airport, Baffin Island, Canada. *Remote Sensing of Environment*, *141*, 40-51.

Singha, S., Johansson, M., Hughes, N., Hvidegaard, S., & Skourup, H. (2018). Arctic Sea ice characterization using spaceborne fully polarimetric L-, C-and X-band SAR with validation by airborne measurements. *IEEE Transactions on Geoscience and Remote Sensing, 56*(7), 3715-3734.

SIOS (2021). Svalbard Integrated Arctic Earth Observing System – The current state. 18 November 2021. https://sios-svalbard.org/system/files/common/Documents/SIOS_CurrentState.pdf.

Sterckx, S., Brown, I., Kääb, A., Krol, M., Morrow, R., Veefkind, P., ... & Thorne, P. (2020). Towards a European Cal/Val service for earth observation. *International Journal of Remote Sensing*, *41*(12), 4496-4511.

Strozzi, T., Kouraev, A., Wiesmann, A., Wegmüller, U., Sharov, A., & Werner, C. (2008). Estimation of Arctic glacier motion with satellite L-band SAR data. *Remote Sensing of Environment*, *112*(3), 636-645.

Strozzi, T., Paul, F., Wiesmann, A., Schellenberger, T., & Kääb, A. (2017). Circum-Arctic changes in the flow of glaciers and ice caps from satellite SAR data between the 1990s and 2017. *Remote Sensing*, *9*(9), 947.

Strozzi, T., Antonova, S., Günther, F., Mätzler, E., Vieira, G., Wegmüller, U., ... & Bartsch, A. (2018). Sentinel-1 SAR interferometry for surface deformation monitoring in low-land permafrost areas. *Remote Sensing*, *10*(9), 1360.

Strozzi, T., Caduff, R., Jones, N., Barboux, C., Delaloye, R., Bodin, X., ... & Schrott, L. (2020). Monitoring rock glacier kinematics with satellite synthetic aperture radar. *Remote Sensing*, *12*(3), 559.

Tebaldini, S., Nagler, T., Rott, H., & Heilig, A. (2016). Imaging the internal structure of an alpine glacier via L-band airborne SAR tomography. *IEEE Transactions on Geoscience and Remote Sensing*, *54*(12), 7197-7209.

Treichler, D., & Kääb, A. (2017). Snow depth from ICESat laser altimetry—A test study in southern Norway. *Remote sensing of environment*, *191*, 389-401.

Treichler, D., Kääb, A., Salzmann, N., & Xu, C. Y. (2019). Recent glacier and lake changes in High Mountain Asia and their relation to precipitation changes. *The Cryosphere*, *13*(11), 2977-3005.

Van den Heuvel, F., Hübner, C., Błaszczyk, M., Heimann, M., & Lihavainen, H. (eds) (2020). SESS report 2019. Svalbard Integrated Arctic Earth Observing System, Longyearbyen.

Vickers, H., Malnes, E., & Høgda, K. A. (2019). Long-Term Water Surface Area Monitoring and Derived Water Level Using Synthetic Aperture Radar (SAR) at Altevatn, a Medium-Sized Arctic Lake. *Remote Sensing*, *11*(23), 2780.

Vickers, H., Karlsen, S. R., & Malnes, E. (2020). A 20-year MODIS-based snow cover dataset for Svalbard and its link to phenological timing and sea ice variability. *Remote Sensing*, *12*(7), 1123.

Vickers, H., Malnes, E., van Pelt, W. J., Pohjola, V. A., Killie, M. A., Saloranta, T., & Karlsen, S. R. (2021). A Compilation of Snow Cover Datasets for Svalbard: A Multi-Sensor, Multi-Model Study. *Remote Sensing*, *13*(10), 2002.

Villas Bôas, A. B., Ardhuin, F., Ayet, A., Bourassa, M. A., Brandt, P., Chapron, B., ... & Van Sebille, E. (2019). Integrated observations of global surface winds, currents, and waves: requirements and challenges for the next decade. *Frontiers in Marine Science*, 425.

Wakabayashi, H., Matsuoka, T., Nakamura, K., & Nishio, F. (2004). Polarimetric characteristics of sea ice in the Sea of Okhotsk observed by airborne L-band SAR. *IEEE Transactions on Geoscience and Remote Sensing*, *42*(11), 2412-2425.

Wang, C., Cheng, B., Wang, K., Gerland, S., & Pavlova, O. (2015). Modelling snow ice and superimposed ice on landfast sea ice in Kongsfjorden, Svalbard. *Polar Research*, *34*(1), 20828.

Wang, C., Zhang, Z., Zhang, H., Zhang, B., Tang, Y., & Wu, Q. (2018). Active layer thickness retrieval of Qinghai–Tibet permafrost using the TerraSAR-X InSAR technique. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *11*(11), 4403-4413.

Webster, M. A., Rigor, I. G., Nghiem, S. V., Kurtz, N. T., Farrell, S. L., Perovich, D. K., & Sturm, M. (2014). Interdecadal changes in snow depth on Arctic sea ice. *Journal of Geophysical Research: Oceans*, *119*(8), 5395-5406.

Wesselink, D. S., Malnes, E., Eckerstorfer, M., & Lindenbergh, R. C. (2017). Automatic detection of snow avalanche debris in central Svalbard using C-band SAR data. *Polar Research*, *36*(1), 1333236.

Widhalm, B., Bartsch, A., Leibman, M., & Khomutov, A. (2017). Active-layer thickness estimation from X-band SAR backscatter intensity. *The Cryosphere*, *11*(1), 483-496.

Winsvold, S. H., Kääb, A., Nuth, C., Andreassen, L. M., Van Pelt, W. J., & Schellenberger, T. (2018). Using SAR satellite data time series for regional glacier mapping. *The Cryosphere*, *12*(3), 867-890.

Wolfe, S. A., Short, N. H., Morse, P. D., Schwarz, S. H., & Stevens, C. W. (2014). Evaluation of RADARSAT-2 DInSAR seasonal surface displacement in discontinuous permafrost terrain, Yellowknife, Northwest Territories, Canada. *Canadian Journal of Remote Sensing*, *40*(6), 406-422.

Xu, X., Liu, L., Schaefer, K., & Michaelides, R. (2021). Comparison of surface subsidence measured by airborne and satellite InSAR over permafrost areas near yellowknife Canada. *Earth and Space Science*, *8*(6), e2020EA001631.

Yitayew, T. G., Larsen, Y., Sivertsen, A. Lauknes, T.R. (2021). Feasibility study on InSAR experiments with Dornier SAR, Technical report. ESA contract number - 4000132514

Zwieback, S., Hensley, S., & Hajnsek, I. (2017). Soil moisture estimation using differential radar interferometry: Toward separating soil moisture and displacements. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(9), 5069-5083.

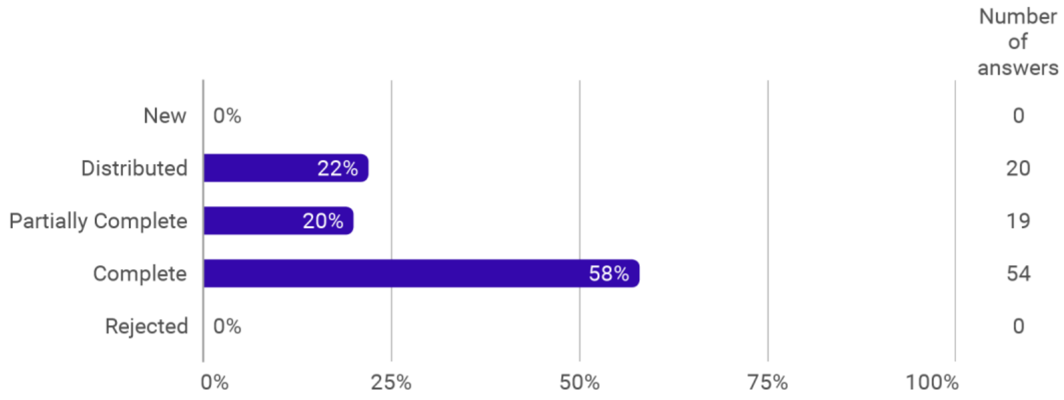
Zwieback, S., Westermann, S., Langer, M., Boike, J., Marsh, P., & Berg, A. (2019). Improving permafrost modeling by assimilating remotely sensed soil moisture. *Water Resources Research*, *55*(3), 1814-1832.

Zwieback, S., & Meyer, F. J. (2021). Top-of-permafrost ground ice indicated by remotely sensed late-season subsidence. *The Cryosphere*, *15*(4), 2041-2055.

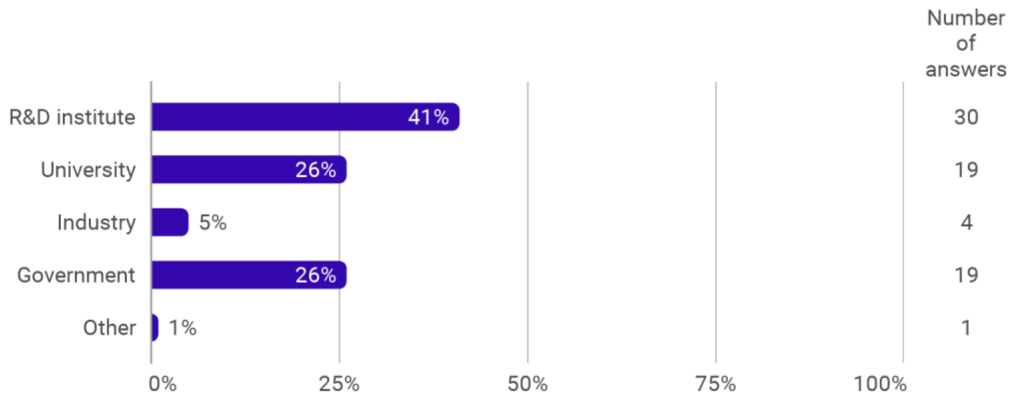
Appendix 1 – User survey report

This section describes all results of the SIOS/NORCE user survey that was conducted between December 17, 2021, and February 7, 2022.

Overall Status

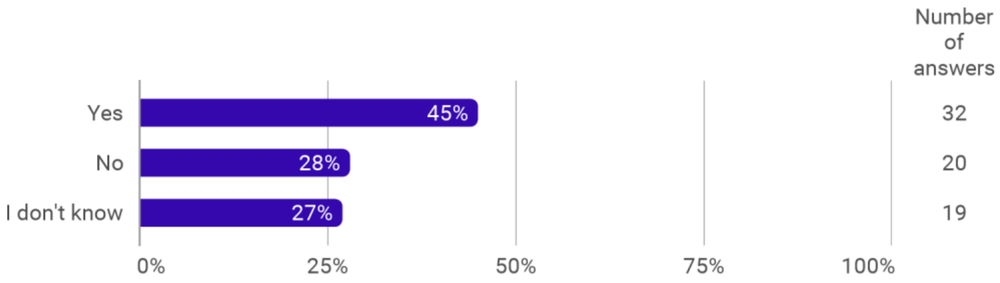


Which type of organization are you affiliated to?

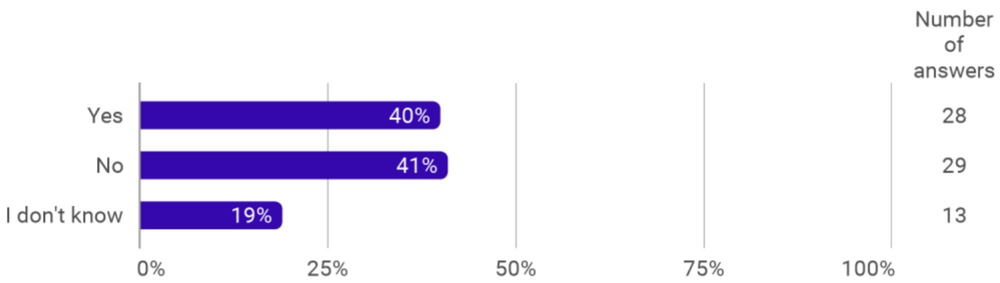


Which type of organization are you affiliated to? - Other
academic research institute

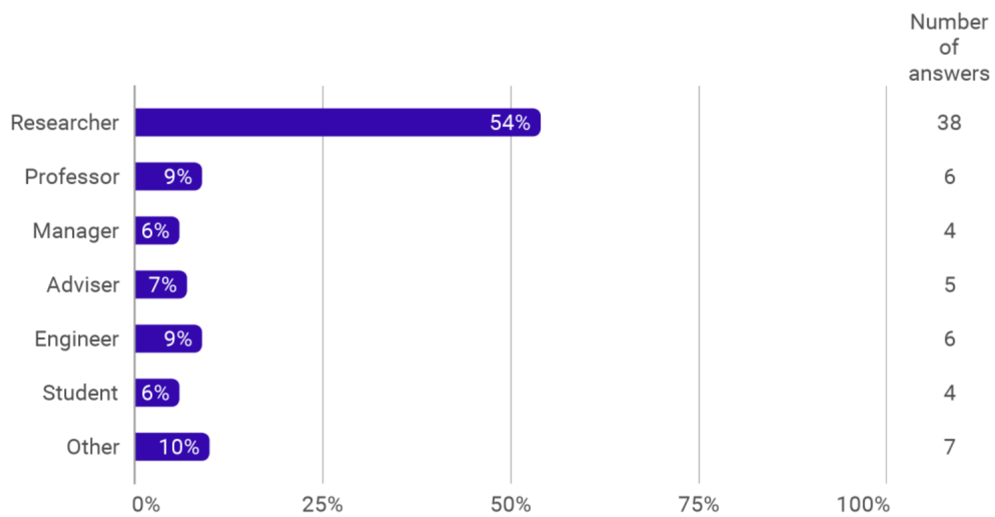
Is your organization member of SIOS?



Is your organization located or have permanent infrastructure in Svalbard?

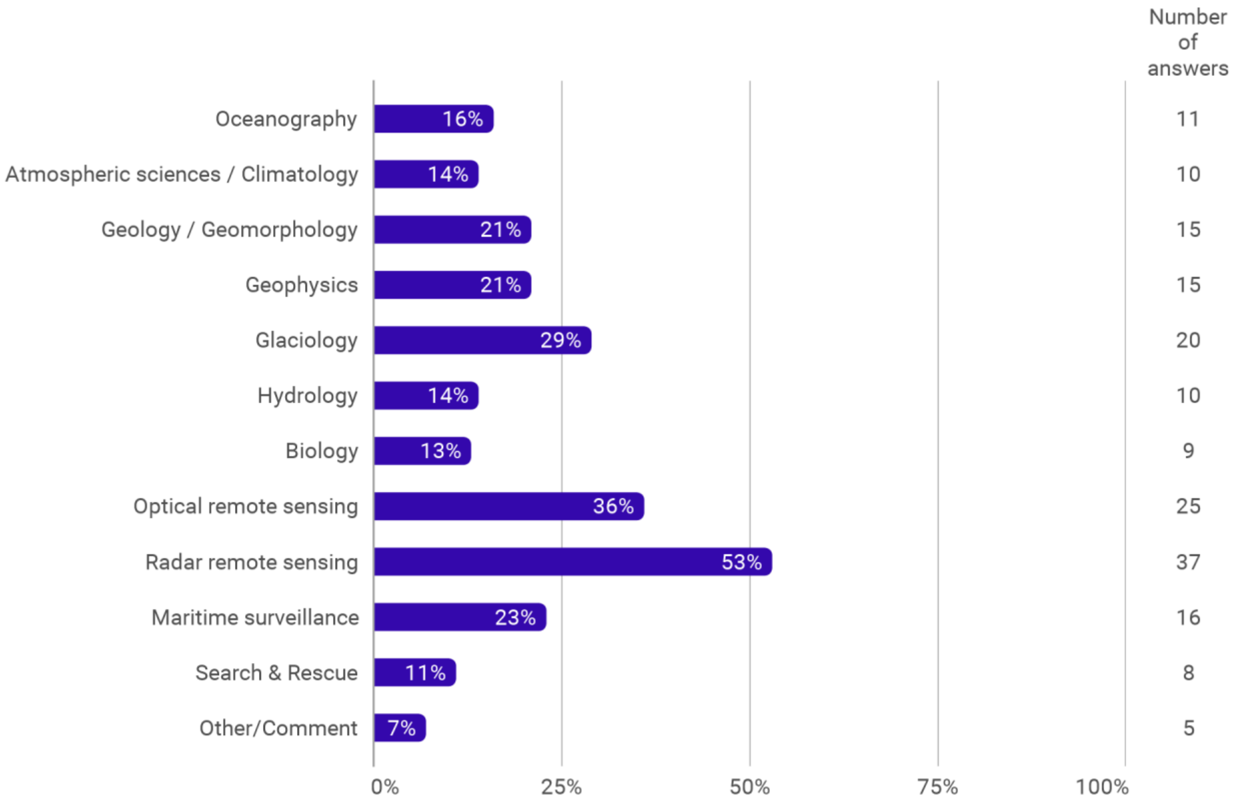


What is your position?



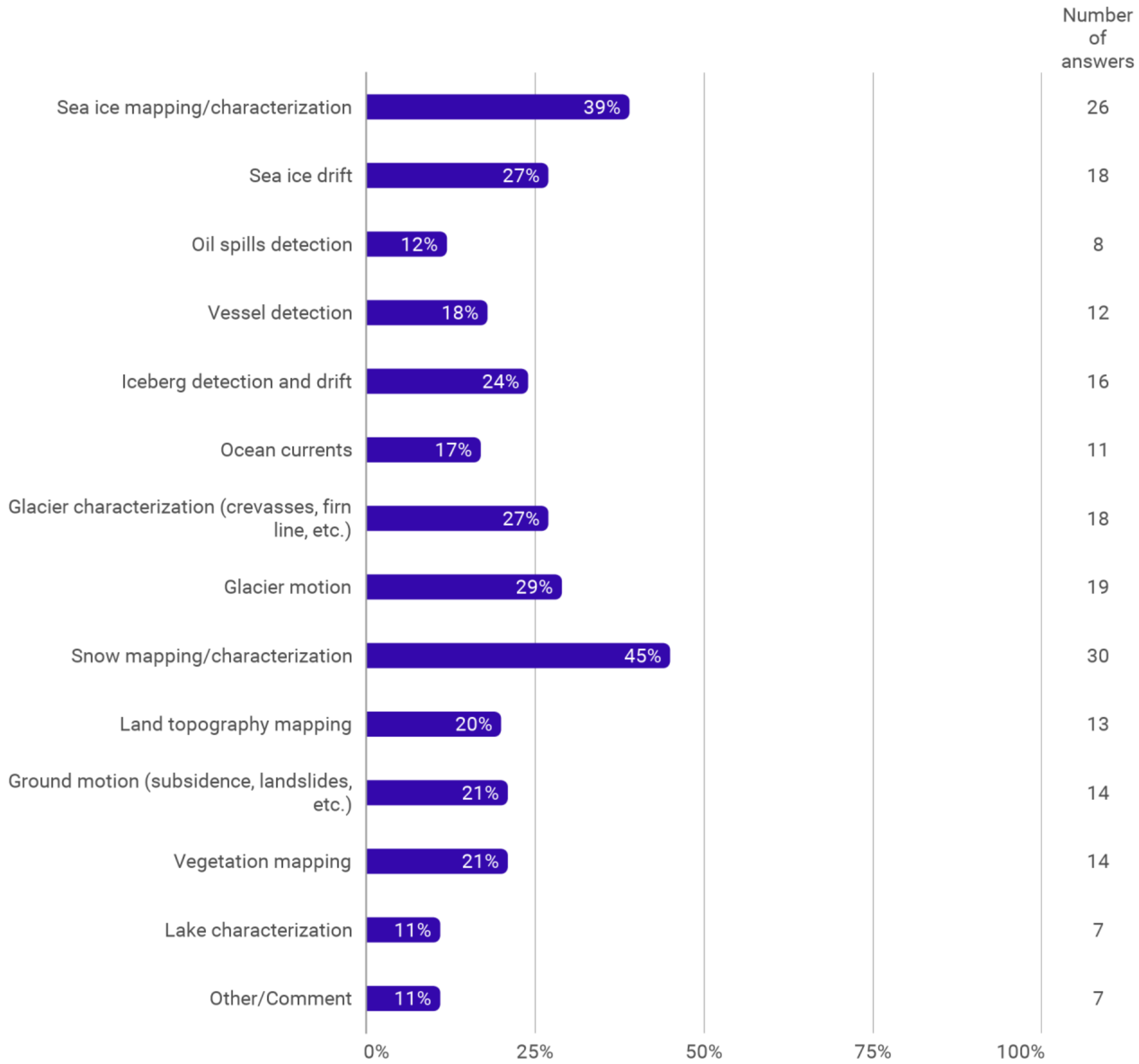
What is your position? - Other
Utvikler (*Developer*)
Operativ personell (*Operative personnel*)
Kystvakt (*Coast guard*)
Kystvakt (*Coast guard*)
Høgskolelærer instruktør maritime polare operasjoner (*University instructor maritime polar operations*)
Geolog (*Geologist*)
Assc. Prof

What is your field of work?



What is your field of work? - Other/Comment
som leder har jeg ansvar for alt vi gjør (*As manager, I am responsible for everything we do*)
critical zone science
Remote sensing
Måleteknologi generelt (*Measurement technology in general)*
Interdisciplinarity

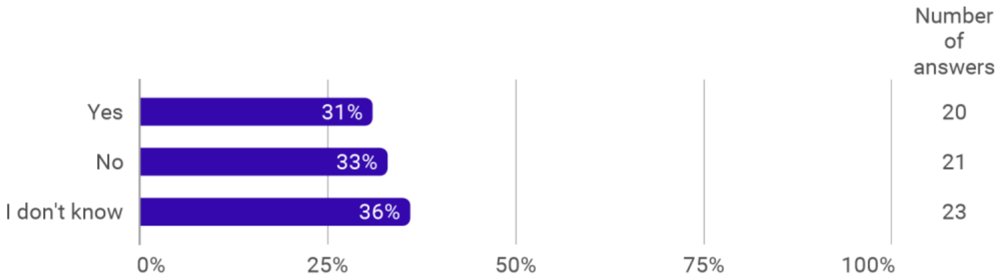
For which applications do you use, or aim to use remote sensing?



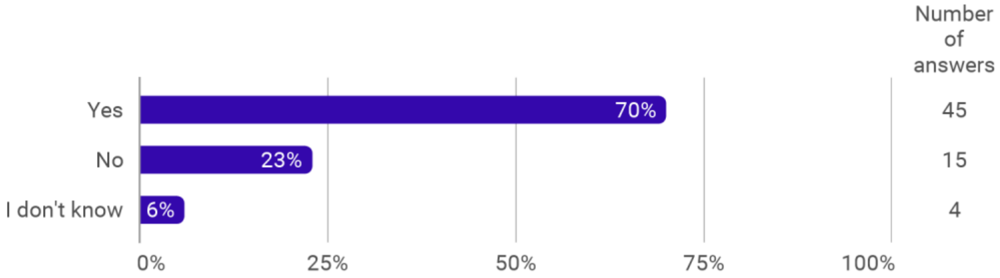
For which applications do you use, or aim to use remote sensing? - Other/Comment
space weather impact on L-band sensing
Ingen (*none*)
deteksjon dyr på land eller is (*detection of animals on land or ice*)

For which applications do you use, or aim to use remote sensing? - Other/Comment
citizen science (nature health monitoring)
Measuring calving activity
Flere (*several*)
Alt er av interesse, avhengig av pris og kvalitet (*everything is of interest, depending on price and quality*)

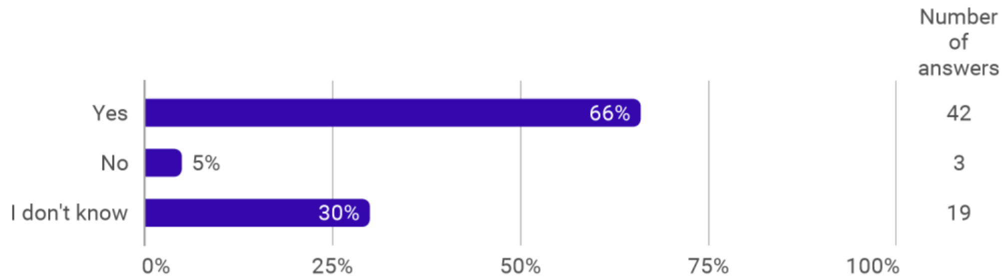
Have you used, or are you planning to use, optical data from the SIOS Dornier?



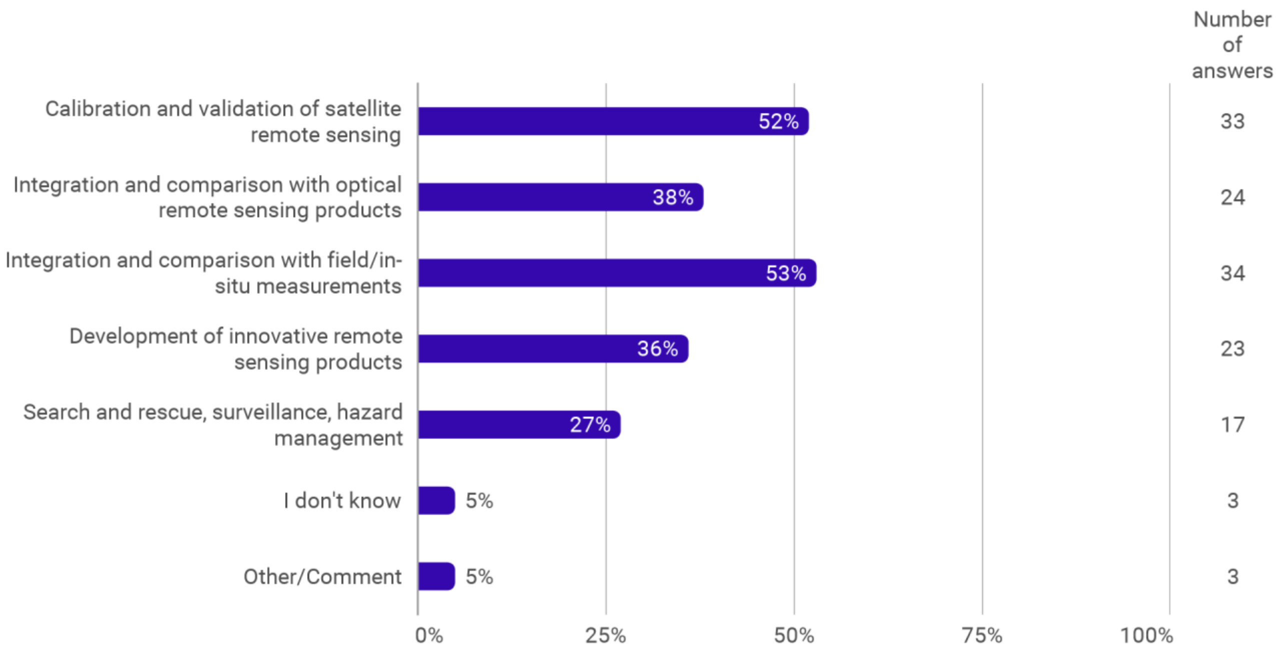
Have you used Synthetic Aperture Radar data (from spaceborne, airborne or terrestrial platforms)?



If a L-/X-band SAR would be available on the Dornier, would you use the radar data?

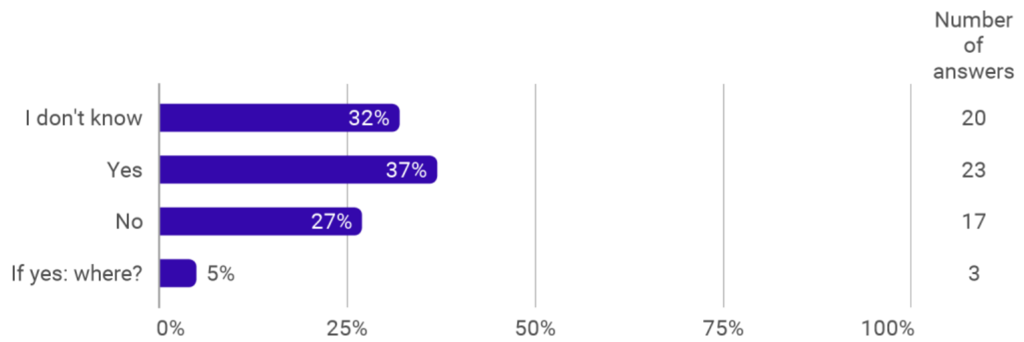


What would be the main value of airborne SAR in your work?



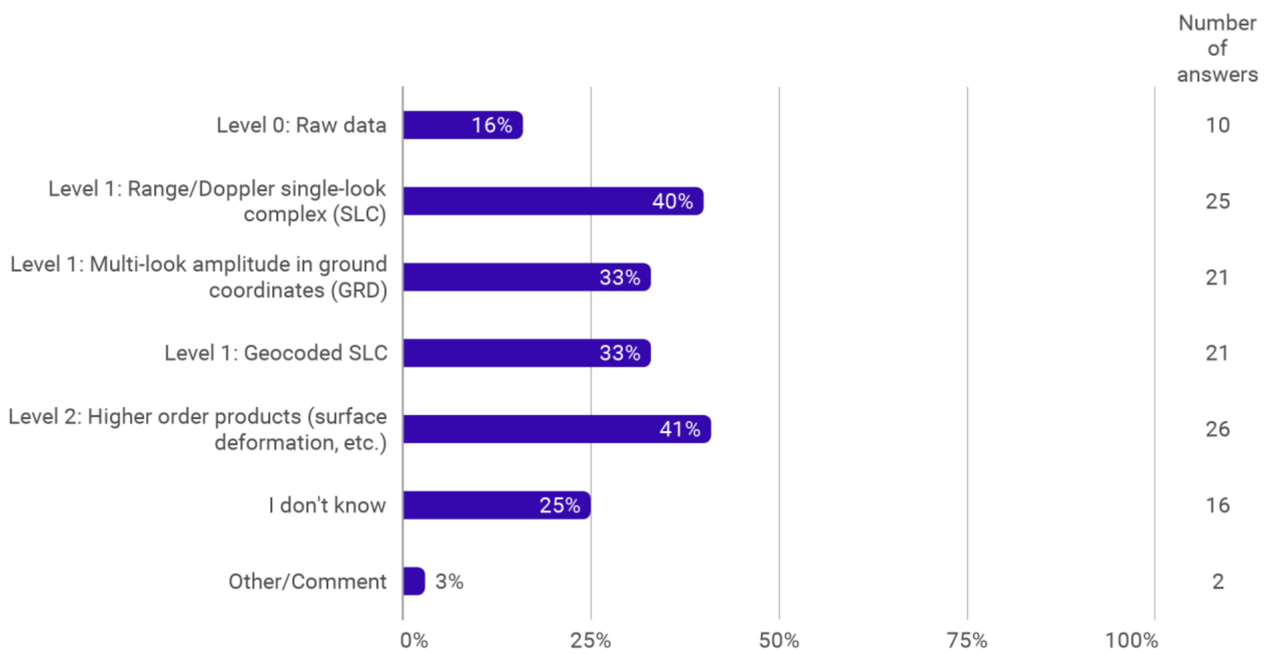
What would be the main value of airborne SAR in your work? - Other/Comment
overvåking av dumping av fisk (*monitoring of dumping of fish*)
contact me for more details
Would depend on the area which is covered

Does your organization have corner reflectors in Svalbard or are you considering to install corner reflectors in coming years?



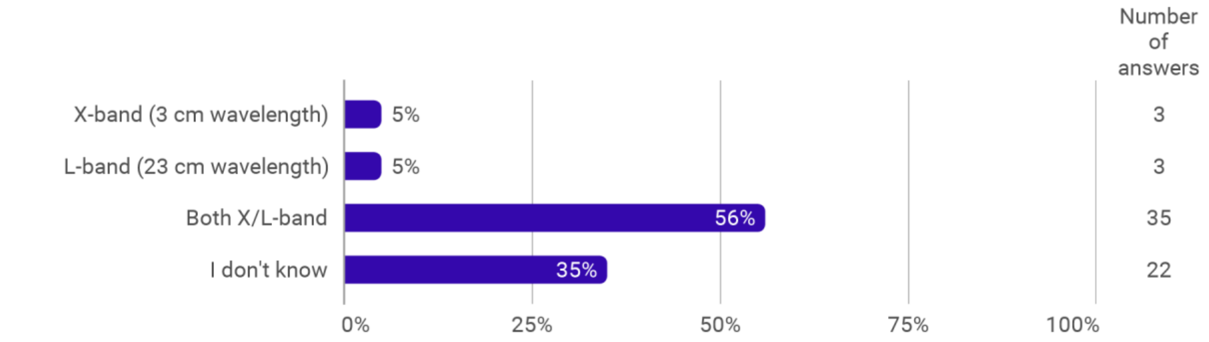
Does your organization have corner reflectors in Svalbard or are you considering to install corner reflectors in coming years? - If yes: where?
maybe, Hornsund
Portable, installert ved Corbell for tiden
Ny Alesund

Which level of SAR data are you interested in?

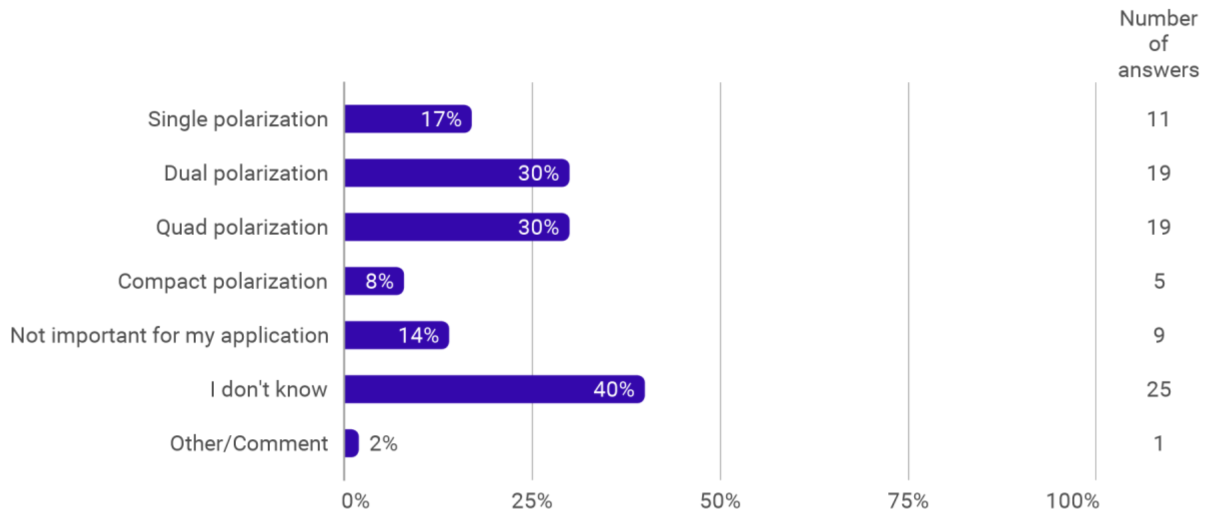


Which level of SAR data are you interested in? - Other/Comment
enhanced -- combined with other types of data
I represent Information Users

For your main application(s), which radar frequency is the most appropriate?



For your main application(s), which polarization is the most appropriate?



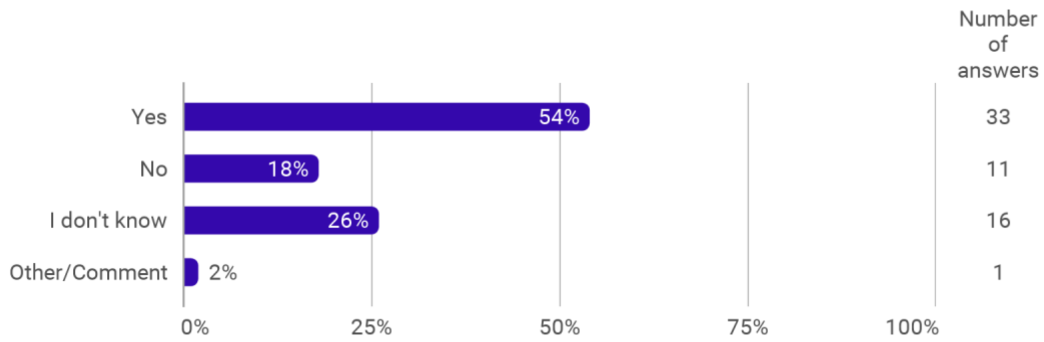
For your main application(s), which polarization is the most appropriate? - Other/Comment
Multiple bands always better than single

Single-pass, across-track interferometry (XTI)

By utilizing multiple antennas on the aircraft, it is possible to estimate surface topography during flight. We expect topographic sensitivity on the order of 0.75-1.5 m.

Examples of applications: topographic mapping.

Would this be of interest for your applications?



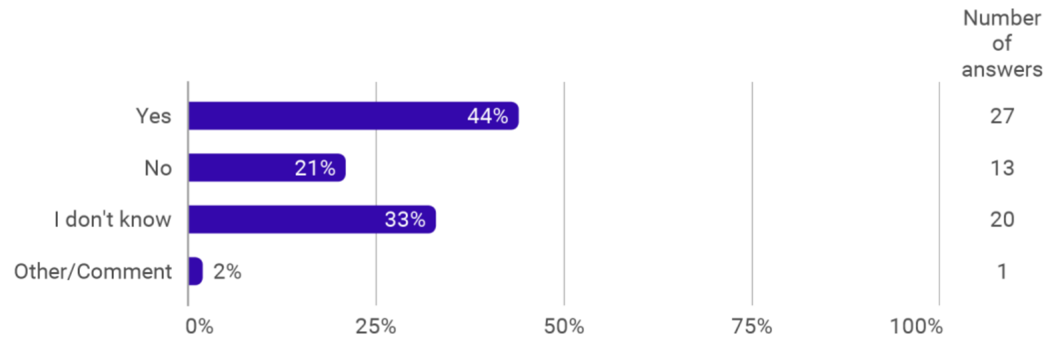
Single-pass, across-track interferometry (XTI) **By utilizing multiple antennas on the aircraft, it is possible to estimate surface topography during flight. We expect topographic sensitivity on the order of 0.75-1.5 m.** **Examples of applications: topographic mapping.** **Would this be of interest for your applications? - Other/Comment**
If it proves cost effective, yes

Single-pass, along-track interferometry (ATI)

By utilizing multiple antennas on the aircraft, it is possible to estimate surface drift velocities during flight. We expect sensitivity on the order of 5-10 cm/second.

Examples of applications: sea ice drift, ocean currents.

Would this be of interest for your applications?

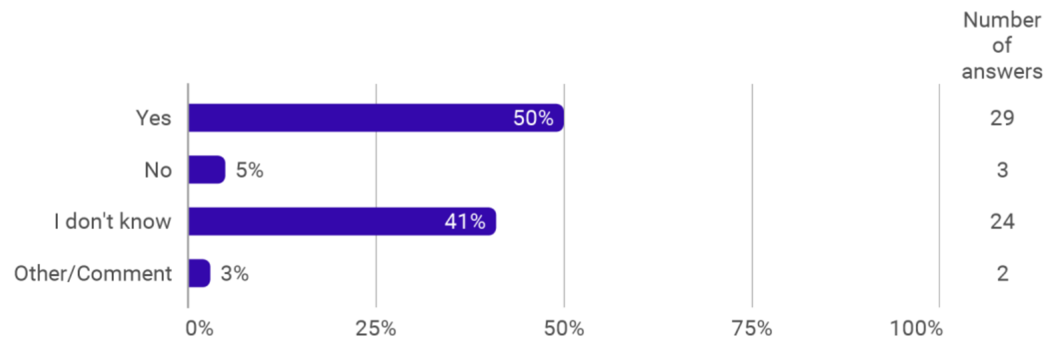


Single-pass, along-track interferometry (ATI) **By utilizing multiple antennas on the aircraft, it is possible to estimate surface drift velocities during flight. We expect sensitivity on the order of 5-10 cm/second.** **Examples of applications: sea ice drift, ocean currents.** **Would this be of interest for your applications? - Other/Comment**
glacier velocity

Left/right wide-area mapping

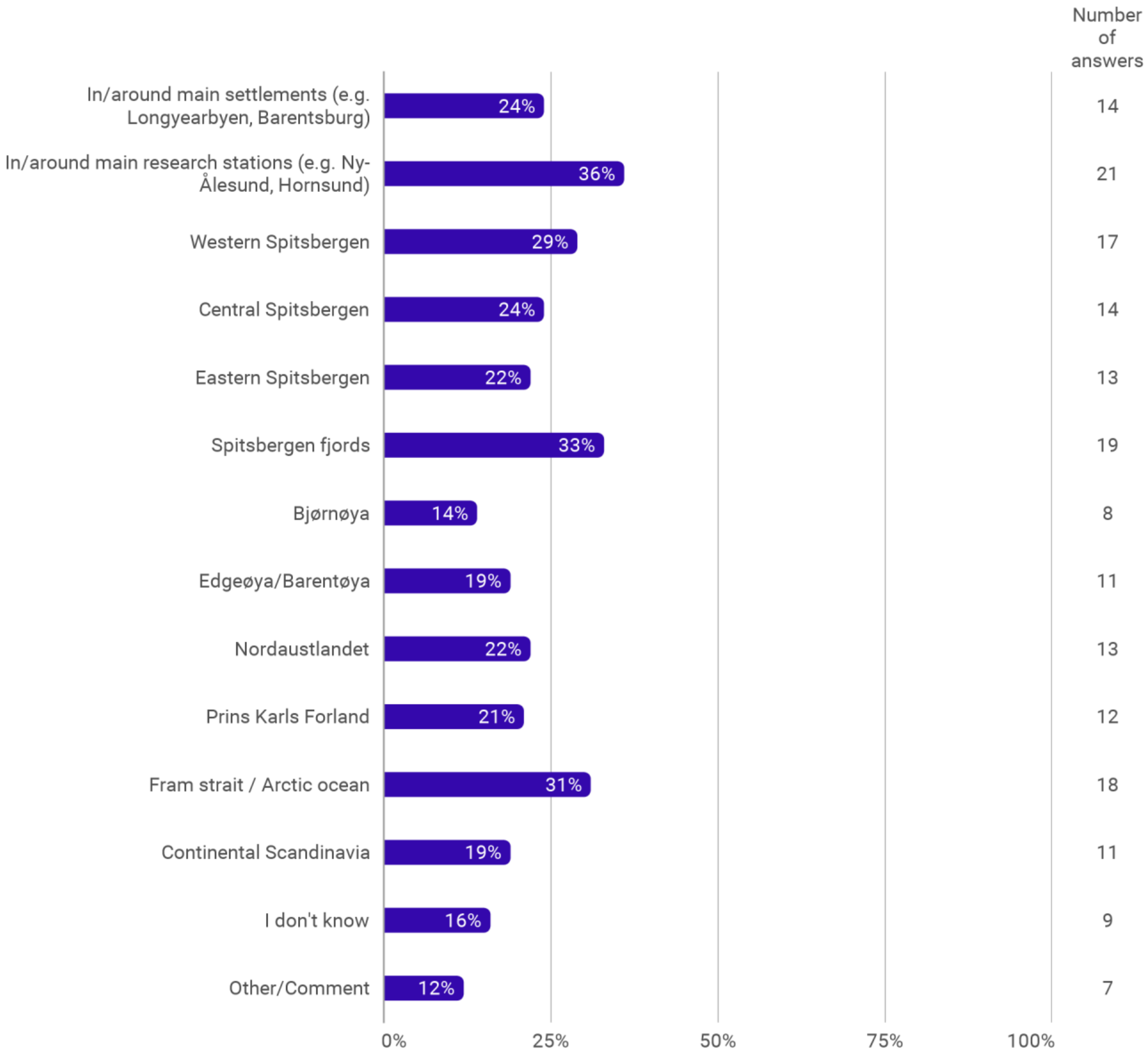
It could be relevant to support simultanous left/right side imaging from the aircraft. This would allow wide area coverage, of particular relevance for maritime surveillance and other mapping applications.

Would this be of interest for your applications?



Left/right wide-area mapping It could be relevant to support simultanous left/right side imaging from the aircraft. This would allow wide area coverage, of particular relevance for maritime surveillance and other mapping applications. Would this be of interest for your applications? - Other/Comment
depends on the setup (some are more robust than others)
An added complexity may make it less operational. Interesting research question

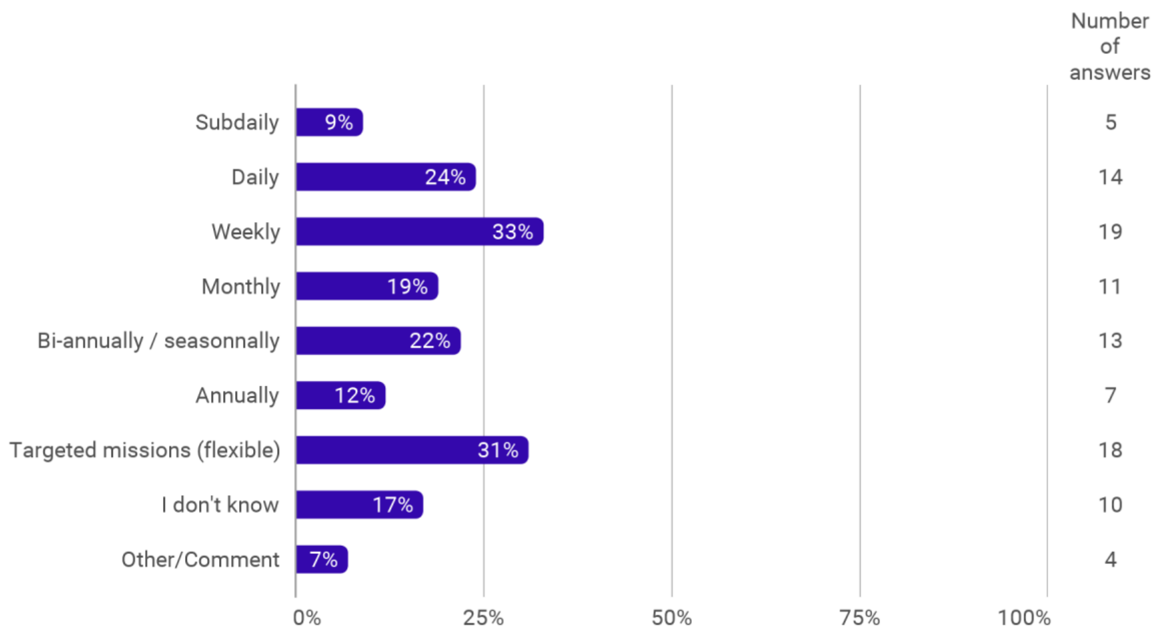
For your main application(s), what is your main region of interest?



For your main application(s), what is your main region of interest? - Other/Comment
havområdene f.o.m. Bjørnøya og nordover (*the sea areas from Bjørnøya and northwards*)
Om flyet har rekkevidde er dekning av Grønlandshavet og Norskehavet (Lofoten bassenget) også av interesse. (*If the aircraft has a range, coverage of the Greenland Sea and the Norwegian Sea (Lofoten basin) is also of interest*.)
Havområder (*marine areas*)

For your main application(s), what is your main region of interest? - Other/Comment
Havområdene... (*marine areas)*
Barentshavet (*Barents sea)*
Barents Sea but also applying the technology around the globe
Adventdalen (*Advent valley*)

For your main application, which revisit period is most appropriate?

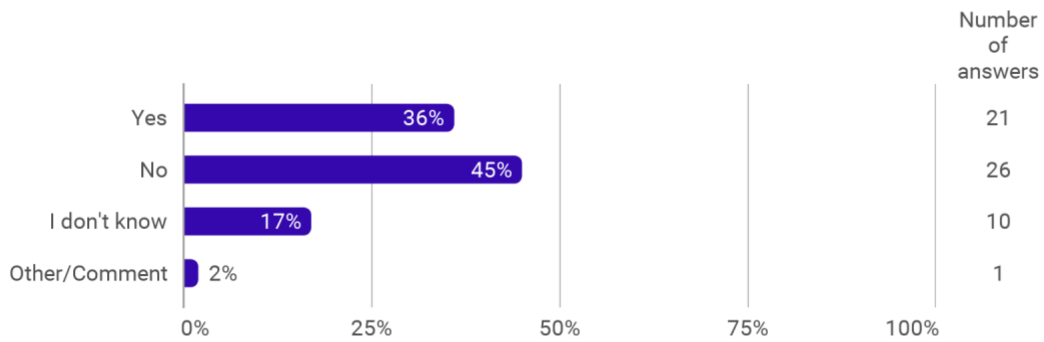


For your main application, which revisit period is most appropriate? - Other/Comment
Vanskelig å angi- men som regel er jo svaret så ofte som mulig. (*Difficult to state, as a rule the answer is as often as possible.)*
Så mye som mulig (*as often as possible*)
In conjunction with GLOFs if they occur
Aircaft are part of the surveillance OODA loop which starts with satellite images. When more detail is required aircraft can be the next step

Real-time processing

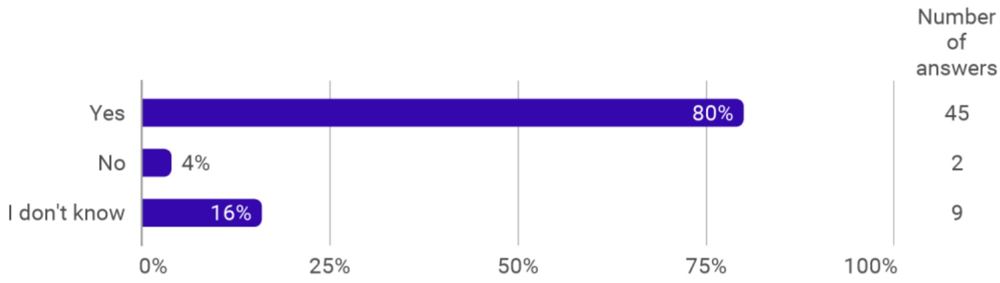
Some applications require on-board processing and facilitation of real-time observations. Examples related to this can be ship detection, oil spill detection, icebergs.

Is this relevant to your applications?



Real-time processing **Some applications require on-board processing and facilitation of real-time observations. Examples related to this can be ship detection, oil spill detection, icebergs.** **Is this relevant to your applications? - Other/Comment**
In conjunction with potential GLOF occurrences

Would you be interested in a SIOS webinar on Dornier SAR?



Other comments?
You cannot detect everything with one sensor platform but you can detect everything with a system of platforms The Dornier SAR represents one important component in the surveillance or monitoring system
We work at Indian Institute of Remote Sensing (IIRS), ISRO Dehradun, India. I have participated in the Indian winter expedition of Svalbard Arctic during March-April 2019. Our main research station is Himadri, at NyAlesund, and main work is on Glaciology and hydrology of Arctic Kind Regards, Praveen K Thakur Head, WRD, IIRS Dehrdaun
SAR! Nå! :-) (*SAR now*)
KOmbinasjon x og L er spennende for skog og særlig med ATI (*Combination of X and L is exciting for forests and especially with ATI)*
Don't hesitate to contact me for future questions we are developing algorithms for Arctic data processing incl. from drones and are interested in applications (see e.g. here https://norwegianscitechnews.com/2021/07/what-kind-of-sea-ice-is-that-ask-knut/)