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InSAR Svalbard

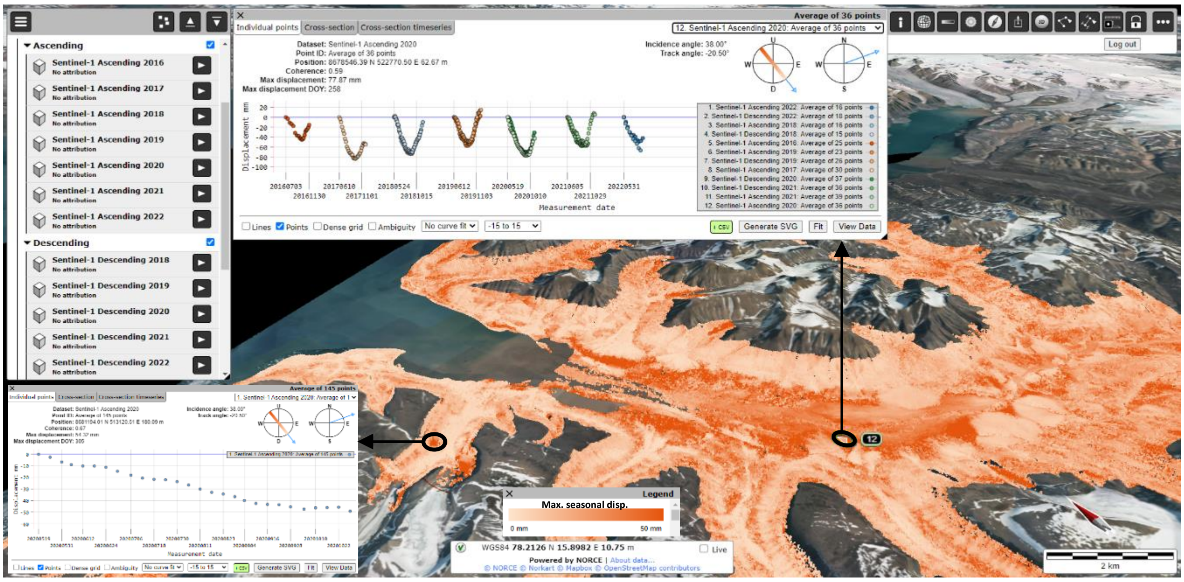
User requirements, technical considerations, and product development plan

Brukerkrav, tekniske hensyn og produktutviklingsplan

Authors

Line Rouyet[1], Marie Bredal[2], Tom Rune Lauknes[1], John Dehls[2], Yngvar Larsen[1], Jelte van Oostveen[1], Heidi Hindberg[1], Lotte Wendt[1]

[1] NORCE Norwegian Research Centre AS
[2] Geological Survey of Norway (NGU)



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Summary	The *InSAR Svalbard* development project (2023–2025) is a partnership between the Geological Survey of Norway (NGU) and NORCE Norwegian Research Centre AS, with funding from the Norwegian Space Agency (Post 74, contract number: 74CO2301). The project aims to start the development of a Ground Motion Service (GMS) in Svalbard, providing spaceborne Synthetic Aperture Radar Interferometry (InSAR) ground displacement maps and time series tailored to Arctic conditions. This report presents the findings from the project's first year, including the outcomes of a user workshop and a user survey conducted in 2023. The study's main goal was to identify the user requirements for an *InSAR Svalbard* GMS, and to highlight past InSAR research and known for processing limitations. The report also presents a product development plan that considers both user needs and technical considerations.

English summary

The *InSAR Svalbard* development project (2023–2025) is a partnership between the Geological Survey of Norway (NGU) and NORCE Norwegian Research Centre AS, with funding from the Norwegian Space Agency (Post 74, contract number: 74CO2301). The project aims to start the development of a Ground Motion Service (GMS) in Svalbard, providing spaceborne Synthetic Aperture Radar Interferometry (InSAR) ground displacement maps and time series tailored to Arctic conditions.

This report presents the findings from the project's first year, including the outcomes of a user workshop and a user survey conducted in 2023. The study's main goal was to identify the user requirements for an *InSAR Svalbard* GMS and to highlight past InSAR research and known processing limitations. The report also presents a product development plan that considers both user needs and technical considerations.

Norsk sammendrag

InSAR Svalbard utviklingsprosjektet (2023–2025) er et samarbeid mellom Norges geologiske undersøkelse (NGU) og NORCE Norwegian Research Centre AS, med finansiell støtte fra Norsk Romsenter (Post 74, kontraktsummer: 74CO2301). Prosjektet tar sikte på å starte utviklingen av en InSAR karttjeneste på Svalbard som vil benytte satellittbasert Syntetisk Apertur Radar Interferometri (InSAR) til å lage kart som viser hvordan bakken beveger seg.

Denne rapporten presenterer resultatene av prosjektets første år og oppsummerer konklusjonene fra en brukerworkshop og en brukerundersøkelse utført i 2023. Studiens hovedmål var å kartlegge brukerbehovene til en *InSAR Svalbard* karttjeneste, diskutere tidligere InSAR forskning og kjente begrensninger for prosessering. Rapporten presenterer også en produktutviklingsplan som tar hensyn til brukernes krav og tekniske hensyn.

Acknowledgment

We acknowledge the invaluable contribution of the *InSAR Svalbard* workshop participants who helped to set the user requirements. All participating institutions are listed in Appendix 7.2. A draft version of Chapter 3 has been communicated to all attendants for commenting and corrections based on their feedback. However, the authors of this report take full responsibility for how the inputs from externals are summarized in the present document.

Anerkjennelser

Vi anerkjenner det uvurderlige bidraget fra *InSAR Svalbard*-workshopdeltakerne som bidro til å stille brukerkravene. Alle deltakere er oppført i vedlegg 7.2. Utkastversjon av kapittel 3 har vært kommunisert til alle deltakere for kommentarer og har vært korrigert basert på tilbakemeldingene. Forfatterne av denne rapporten tar imidlertid fullt ansvar for måten innspillene fra eksterne er oppsummert i nåværende versjonen av dokumentet.

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1. Introduction

1.1. Project background and timeline

Since 2018, *InSAR Norway* (http://insar.ngu.no), also known as the Norwegian Ground Motion Service (GMS), has generated ground displacement maps and time series for mainland Norway. This is done using Synthetic Aperture Radar (SAR) images from Sentinel-1 satellites, processed with the interferometric SAR (InSAR) methodology. *InSAR Norway* has proven valuable for detecting, mapping, and monitoring unstable areas that threaten public safety and infrastructure stability (e.g., landslides and urban subsidence). More recently, a similar initiative called the European Ground Motion Service (EGMS) was funded by the European Environment Agency and focuses on mapping ground displacement in the land area of the Copernicus member states. Svalbard is currently not covered by *InSAR Norway* or EGMS. Svalbard has very different environmental conditions from those of the mainland, leading to different technical challenges and user needs. To properly provide InSAR displacement maps and times series in Svalbard, there is a need for further development of InSAR processing strategies, product types, and visualisation solutions.

The *InSAR Svalbard* development project started in 2023. The project is a partnership between the Geological Survey of Norway (NGU) and NORCE Norwegian Research Centre AS, with financial support from the Norwegian Space Agency (NOSA) (Post 74, contract number 74CO2301).

The project aims to establish the foundation for a future operational Ground Motion Service in Svalbard, under the *InSAR Norway* framework. *InSAR Svalbard* is a three-year project (2023–2025) structured into four work packages (WP) (Table 1):

- **WP1 (Product Definition)** aims to establish a reference group consisting of relevant government and private institutions in Svalbard, along with remote sensing experts, researchers, and local stakeholders. This group will collaborate to identify user needs and guide the development of product specifications based on user requirements and technical considerations.
- **WP2 (Pilot Products)** aims to develop pilot products and visualisation solutions targeting areas of high priority, such as the Norwegian settlements and research stations (e.g. Longyearbyen and Ny-Ålesund).
- **WP3 (Pilot Product Evaluation and Adjustment)** aims to gather feedback on the pilot products from the reference group and make necessary adjustments to better meet their needs.
- **WP4 (Product Upscaling)** aims to systematically generate and upscale the selected products to cover Svalbard and deliver them in an open, accessible map service named *InSAR Svalbard*.

This report summarises WP1 outcomes, detailing user requirements based on a workshop and a survey conducted in the summer and autumn of 2023. It presents technical considerations and proposes preliminary product specifications to guide the development plan for pilot production in WP2.

Table 1: Gantt diagram with *InSAR Svalbard* workplan

#	Work package (WP)	04.2023–09.2023	10.2023–03.2023	04.2024–09.2024	10.25–12.25	01.2025–06.2025	07.2025–12.2025
1	Product Definition	UW1	D1				
2	Pilot Products			D2			
3	Pilot Product Evaluation and Adjustment			UW2	D3		
4	Product Upscaling						D4 FW

UW: User workshop. FW: Final workshop. D1–4: Deliverables.

1.2. Report structure and content

The report identifies user requirements and technical considerations for developing a future *InSAR Svalbard* GMS.

Chapter 1 introduces the project background and the scope of the document.

Chapter 2 presents the objectives of *InSAR Svalbard* GMS, the potential applications, the general criteria for the product definition, and the available data sources.

Chapter 3 summarises the user requirements based on the workshop and user survey results.

Chapter 4 presents past InSAR results in Svalbard and their limitations before highlighting the technical considerations for generating *InSAR Svalbard* products.

Chapter 5 concludes with a summary of user requirements, technical considerations, and a product development plan.

2. Relevance and applications

2.1. Objectives and potential applications

InSAR Svalbard is designed to address the rapid environmental changes due to climate change in the Arctic, serving the needs of various scientific disciplines and management agencies:

- **Operational purpose (geohazard assessment and monitoring):** *InSAR Svalbard* targets operational purposes such as geohazard assessment and monitoring, which are critical for the inhabited areas and infrastructure of the Svalbard archipelago. This region, characterized by sensitive cultural heritage sites and infrastructure, faces risks due to permafrost degradation, which impacts the ground's stability and bearing capacity, essential for the safety of residents and local economic activities (Hollesen et al., 2018). Climate changes in Svalbard increase the activity of slope creeping processes, which may cause more frequent landslides and affect infrastructure like buildings, roads, and pipelines' stability. Longyearbyen, Ny-Ålesund, Hornsund, Gruve 7, and Isfjord Radio are areas of concern due to their permanent staffing, industrial, or touristic activities (Longyearbyen Lokalstyre, 2023). InSAR products could significantly aid in hazard assessment, areal planning, and existing monitoring efforts, offering valuable resources for national agencies and local authorities responsible for areal planning, infrastructure, and geohazard management in Svalbard.
- **Research purpose (polar and climate science):** *InSAR Svalbard* aims to support polar and climate science research, leveraging the archipelago's unique conditions, where sixty percent is covered by glaciers and the remaining ice-free land has perennially frozen ground (permafrost). This setting makes Svalbard ideal for observing cryospheric processes (Verret et al., 2023). Seasonal freeze and thaw processes in the upper part of the ground (active layer) lead to cyclic subsidence and heave displacement patterns, and frost- and gravity-driven landforms like landslides and rock glaciers are well-spread on slopes. Climate warming causes a thickening of the active layer and potential ice melting at the top of the permafrost, which can lead to long-term subsidence (Hanssen-Bauer et al., 2019). These changes also affect groundwater availability and the frequency and magnitude of slope processes. Due to the relations between environmental factors and ground dynamics, surface displacements can be used as climate change indicators when measured consistently and systematically. Hence, *InSAR Svalbard* GMS can become an invaluable resource for Norwegian and international institutions engaged in Arctic climate change impact studies.

2.2. Criteria for product specification

In the initial phase of the *InSAR Svalbard* project, the primary objective is to determine which products are to be developed for the upcoming GMS. The product specifications will adhere to two main sets of criteria:

- **User relevance:**
  - General value for operational purposes (geohazard assessment and monitoring).
  - General value for research purposes (polar and climate science).
  - Exploitability of the products and services for end-users.
  - Ease of access to the products and services for end-users.
  - Inter-compatibility and comparability with other products and services.

- **Technical feasibility:**
    - Properties of the available SAR data sources.
    - Measurement capability of available InSAR methods.
    - Maturity of the available InSAR methods.
    - Repeatability and consistency of the products.
    - Resources sustainability concerning personnel and computational demands.

The product specification process involves a balance between user demand ("What do we want?") and technical feasibility ("What can we do?"), requiring ongoing dialogue between the end-users and the InSAR experts. This report examines user needs and technical factors to inform future project phases. In 2024, the focus will shift to pilot production inspired by this report's findings, leading to the refinement of product specifications and the creation of final products by 2025, as outlined in Table 1.

2.3. Available and applicable data sources

InSAR Ground Motion Services depend on regular and consistent delivery of spaceborne SAR images to maintain operational services. While numerous satellites equipped with SAR sensors have been launched since the 1990s, commercial agreements often limit their use for open monitoring services.

The Sentinel-1 mission, initiated in 2014 by the European Commission's Copernicus Programme, marked a significant advancement due to its free and open data policy, extensive spatial coverage, and long-term mission commitment, positioning Sentinel-1 as the primary satellite for GMS in Norway, including Svalbard. Sentinel-1 employs C-band SAR for detailed observations, with its initial dual-satellite configuration enabling a revisit time of 6 days. However, the conclusion of Sentinel-1B's operational phase in December 2021 has led to extended revisit times (12 days). The expected launch of Sentinel-1C aims to restore the 6-day cycle.

Currently, the *InSAR Svalbard* development project primarily relies on Sentinel-1 data, but future sources, such as the next-generation Sentinel missions, could provide valuable new data. Particularly, the use of L-band SAR, expected from the upcoming NISAR mission and later Sentinel L-band SAR (ROSE-L), could enhance InSAR applications in Svalbard as it allows for an increase in the maximal detection capability for high-velocity objects and improves the signal stability over complex surfaces. Nonetheless, coverage limitations (NISAR has a left-looking SAR configuration and only covers up to 77.5°N) and mission schedules (ROSE-L is expected to launch in 2028) necessitate exploring additional data sources in the coming years, such as ALOS-2, ALOS-4, and SAOCOM, under potential agreements with JAXA and CONAE/ASI.

3. User requirements

3.1. User workshop

With the objective of creating a reference user group contributing to *InSAR Svalbard* product definition, the project consortium reached out to several representatives from national authorities, local officials, private stakeholders, and research institutions actively engaged in activities in Svalbard. The user workshop conducted on August 31, 2023, in Longyearbyen, welcomed attendees from various significant entities, including the Governor of Svalbard (Sysselmesteren på Svalbard), Longyearbyen Community Council (Longyearbyen Lokalstyre), Store Norske Spitsbergen Kulkompani (Norwegian coal mining company), Avinor (operator of Svalbard airport), the Norwegian Polar Institute (NPI), the Norwegian Meteorological Institute (MET), the University Centre in Svalbard (UNIS), the Norwegian Geotechnical Institute (NGI) and the independent research organisation SINTEF.

The workshop aimed to introduce the *InSAR Svalbard* project and its potential products to diverse stakeholders, gathering their insights on envisioned applications and necessary product specifications for *InSAR Svalbard* GMS utilization. During the first part of the workshop, NGU presented the project's background, the mainland operational service (*InSAR Norway*), and the fundamental principles of InSAR, while NORCE showcased past research and InSAR product examples pertinent to Svalbard. The second part of the workshop allowed participants to share their work and specific needs to take advantage of an operational *InSAR Svalbard* GMS. The last part of the workshop was dedicated to a constructive dialog between InSAR experts and end-users. Comprehensive details, including the workshop agenda and participant roster, are documented in Appendices 7.1 and 7.2. In the following, we summarise the key feedback from the represented institutions.

3.1.1. The Governor of Svalbard (Sysselmesteren på Svalbard)

The Governor of Svalbard has identified two principal areas where the *InSAR Svalbard* GMS could offer significant benefits. The first area involves utilizing InSAR technology to oversee the integrity of existing infrastructure and new projects within designated civil protection and preparedness zones. The second area pertains to the monitoring of 100 prioritized cultural heritage sites scattered across Svalbard, which are difficult to access and at risk from various threats, including erosion, traffic wear, organic material decay, active layer dynamics, and landslides. *InSAR Svalbard* provides a remote monitoring solution to observe these sites' conditions and environmental changes in their surroundings, enabling quick identification of areas requiring urgent repair and informing strategies for cultural heritage protection prioritization. Furthermore, an *InSAR Svalbard* mapping service could contribute to integrating new data sources into the MOSJ system (Environmental Monitoring of Svalbard and Jan Mayen), enhancing cultural heritage site analyses.

3.1.2. Longyearbyen Community Council (Longyearbyen Lokalstyre)

The Longyearbyen Community Council highlighted that Longyearbyen has evolved considerably from its initial establishment around the first mine (Gruve 1) to an extensive development in the valley (Longyeardalen). This transition has been heavily influenced by mining, with recent large-scale development projects continuing to reshape the area. Permafrost and various natural hazards, such as river flooding, coastal erosion, and landslides, pose significant challenges for infrastructure and areal planning. Additionally, high turnover among personnel complicates knowledge transfer, underscoring the need for clear, accessible baseline planning tools. The Council underscored the necessity for user-friendly, interpretive products, including hotspot identification, hazard zonation, and construction advisories, to support effective decision-making and urban development.

3.1.3. Store Norske Spitsbergen Kulkompani

Store Norske, the Norwegian coal mining company owned by the Ministry of Trade, Industry, and Fisheries, is considering *InSAR Svalbard* for monitoring decommissioned mines and surrounding areas to detect ground settlements and environmental changes. Although mining is expected to cease by 2025, the company is mandated to conduct environmental monitoring of old mining locations, such as Svea, until 2044. Additionally, as a significant property manager in Longyearbyen, Store Norske oversees the upkeep and modernisation of numerous residences, demanding strategic prioritization of foundation maintenance, renovation, and rehabilitation. *InSAR Svalbard* could assist in this process by providing high-resolution data to differentiate structural movements from ground surface changes, enabling effective identification of necessary structural and foundational repairs. Moreover, Store Norske is interested in using InSAR to document seasonal and long-term ground displacements and monitor critical infrastructure like avalanche defences, remote facilities (e.g., Isfjord Radio), and renewable energy installations.

3.1.4. The Norwegian Polar Institute (NPI)

NPI plays a crucial role in studying, mapping, and monitoring the Norwegian polar regions, including Svalbard. NPI manages TopoSvalbard (https://toposvalbard.npolar.no/), providing aerial imagery and topographic maps, and hosts Svalbardkartet (https://svalbardkartet.npolar.no/), which offers various thematic geospatial datasets. While NPI has limited research activity related to permafrost and geohazard, it excels in polar geology and glaciology, for which remote sensing is a crucial tool. Glaciers are often too rapid for current InSAR methods, so NPI typically employs optical and SAR feature tracking for glacier flow analysis. However, many glaciers in Svalbard move slowly, and data is currently lacking to document low velocity. InSAR-based flow maps could provide valuable complementary data for glacier modelling and mass balance calculations. This data would also aid in early surge detection and understanding of ice dynamics impacted by subglacial hydrology and climate change. Achieving this would necessitate the development of InSAR products specifically tailored for glacier applications, distinct from those used on ice-free terrain.

3.1.5. The Norwegian Meteorological Institute (MET)

MET operates numerous meteorological stations across Svalbard, providing data on air, permafrost temperatures, precipitation, and snow depth, accessible via https://cryo.met.no/ and through an API at https://frost.met.no/. These real-time datasets allow for a comparison with InSAR-based displacement patterns to verify *InSAR Svalbard* product relevance. The stations, anchored in bedrock, can serve as reference points, enabling documentation of surrounding subsidence and comparison with InSAR results. MET's 13 stations also measure snow depth in real-time, offering data during snow-free periods that are potentially comparable with InSAR surface displacements. By integrating MET datasets with *InSAR Svalbard*'s, comprehensive comparisons and insights can be achieved, highlighting a need for effective service integration.

3.1.6. Avinor

Avinor is primarily focused on detecting and monitoring deformations of the Longyearbyen airport runway, as differential movements can jeopardize air traffic safety and operations. The main objective is to distinguish between cyclic deformations, which return to original levels annually, and long-term alterations like the formation of bumps and holes over distances of 10–100m. Accuracy in measurement and positioning is crucial for effective monitoring. Runway monitoring requires data year-round, particularly during the freezing and thawing periods when ground dynamics are most pronounced. Despite challenges posed by snow, Avinor seeks displacement measurements during winter and spring, questioning the feasibility of continuous monitoring if the runway remains clear of snow. Frequent updates would be beneficial: weekly during freeze-thaw periods and bi-weekly to monthly at other times.

3.1.7. The University Centre in Svalbard (UNIS)

UNIS, involved in numerous research and educational activities, views *InSAR Svalbard* as an essential tool for both research and teaching in areas such as glaciology, permafrost, and remote sensing. By integrating *InSAR Svalbard* into academic programs, UNIS ensures that students not only understand but also correctly use InSAR datasets made available by the GMS. InSAR is especially valuable for analysing hydrological dynamics in permafrost areas and exploring terrain recently exposed by glacier retreat. As leader of the PermaMeteoCommunity project, developing a monitoring and response system for Longyearbyen's geohazard management and climate adaptation, UNIS underscores the importance of incorporating *InSAR Svalbard* findings into this system and advocates for frequent updates, ideally daily. UNIS also stresses the importance of connecting *InSAR Svalbard* activities with those coordinated by the Svalbard Integrated Arctic Earth Observing System (SIOS). *InSAR Svalbard* could also be linked to the UNIS SvalBox, a platform aiming to compile and visualise geological datasets over Svalbard.

3.1.8. The Norwegian Geotechnical Institute (NGI)

NGI, engaged in geoscientific and geotechnical research and consultancy, utilizes and processes InSAR data extensively. As a regular user of the *InSAR Norway* service, NGI employs these datasets for validation purposes and as supplements to other datasets. NGI is also part of the EGMS validation consortium. With its advisory capacity, NGI aids end-users in interpreting and applying InSAR data effectively. Moreover, NGI has a longstanding engagement with Svalbard research, an active involvement in SIOS, and durable educational collaborations with UNIS. NGI is particularly interested in InSAR applied to areas such as coastal erosion, cultural heritage, and permafrost changes. NGI's contribution to *InSAR Svalbard* could include developing user-specific products based on initial GMS data and leveraging its extensive in-situ data collection (e.g., Norwegian Geo-Test Sites, deep boreholes measuring temperature, geophysical surveys) for validating InSAR results. This would support both the service’s development and operational phases, ensuring that NGI's expertise benefits end-user applications and service enhancements.

3.1.9. SINTEF

SINTEF is actively involved in research studies focusing on the impact of changing ground conditions and coastal erosion on Svalbard's infrastructure and cultural heritage sites. SINTEF leads the Research Council of Norway PCCH-Arctic project examining the effects of future climate changes on cultural heritage sites in Longyearbyen and Ny-Ålesund. PCCH-Arctic aligns closely with the NORCE-led Fram Centre project, PermaRICH. Within PermaRICH, SINTEF contributes by collecting in-situ geodetic monitoring data and analysing the stability of specific structures. This initiative includes comparing SINTEF's geodetic measurements with NORCE InSAR data to assess InSAR's utility in monitoring Svalbard structures. *InSAR Svalbard* could complement traditional monitoring methods by offering a broader analysis of vulnerable sites. SINTEF requires inter-annual and high-resolution InSAR measurements to track long-term environmental effects, study small-scale infrastructure, and distinguish structural deformation from surrounding ground changes.

3.1.10. Summary

The workshop endorsed the *InSAR Svalbard* project, revealing a keen interest in applying InSAR data across various fields and underscoring the importance of collaboration between project partners and participating institutions. This collaboration aims to leverage concurrent initiatives and existing datasets to validate and interpret forthcoming InSAR products. The workshop participants expressed interest in joining a reference group for regular consultation and updates throughout the project's lifecycle.

To sum up, we highlight three main general comments mentioned by several participants and discussed at the end of the workshop:

- The workshop showed the necessity of integrating *InSAR Svalbard* with other local services like Svalbardkartet, Cryo.met, and SvalBox for improved data comparison and collective analysis. Establishing connections between *InSAR Svalbard* activities and those coordinated by the SIOS community was highlighted as crucial for reaching a wide range of users. The service can benefit from the users who own datasets useful for calibration, validation, and intercomparison (e.g., MET meteorological stations, UNIS permafrost stations, NGI geotechnical sites, SINTEF geodetic measurements).
- The participants stressed prioritizing precise and user-friendly InSAR products for critical infrastructure in vital areas like Longyearbyen and Ny-Ålesund. Comprehensive archipelago coverage is seen as less urgent but beneficial for monitoring remote sites (e.g., cultural heritage management) and research purposes (e.g., permafrost science).
- The dialogue revealed distinct requirements between geoscientific research and operational needs (infrastructure and hazard management), highlighting the challenges in meeting diverse data property demands. The necessity for high-resolution and frequent updates for operational purposes stands in contrast with the current SAR mission capabilities and the mature InSAR methods (see Chapter 4), pointing to the complexities in formulating product specifications for varying user applications.

3.2. User survey

The *InSAR Svalbard* project consortium conducted a user survey to understand the interest, potential applications, and specific needs for an *InSAR Svalbard* Ground Motion Service. The survey was disseminated within the SIOS network via newsletters in May 2023, communicated during a SIOS webinar on May 26, 2023, and presented at the Svalbard Science Conference in late October 2023. Additionally, it was shared electronically with a targeted list of essential stakeholders and research entities (e.g., NVE, NPI, SIOS, UNIS, MET, UiO, SINTEF, NGI, NILU, Miljødirektoratet, NIKU, Riksantikvaren, Sysselmesteren, Longyearbyen Lokalstyre, Store Norske, Kings Bay).

From May 2 to November 15, 2023, the survey garnered 60 responses, both partial and complete, demonstrating a high level of interest and engagement. The analysis includes all responses, though the response rate for individual questions varied. Survey responses were almost evenly split between Norwegian (41%) and English (59%). Detailed results are compiled in Appendix 7.3.

3.2.1. Organisation affiliation and position

The survey collected responses from a diverse group of participants: 27% from research and development (R&D) institutes, 23% from universities, 18% from governmental institutions, 10% from industry, and 5% from consulting firms, with the remaining 17% from other organizations. The respondents roles varied, with 38% in research positions, 17% engineers, 15% students, 8% professors or teachers, and 8% managers. Detailed breakdowns can be found in questions 1 and 2 in Appendix 7.3.

3.2.2. Field of work and experience with InSAR data

The survey revealed that most respondents are involved in remote sensing (42%) and geology/geomorphology (33%), followed by glaciology (23%) and hydrology (18%). Public/governmental management and civil engineering were represented by 13% and 10% of respondents, respectively. Notably, 23% identified with categories outside the provided options, selecting “Other” and adding comments for clarification. Details are available in question 4 in Appendix 7.3.

Regarding the relationship with InSAR data, 54% of the respondents are current data users, while 21% expressed an interest in using data. Several respondents (17%), identified as end-users, communicated that they have no interest in interpreting InSAR themselves, but are interested in the final outcomes of InSAR-based analyses. Data providers made up 13% of the responses. For further information, refer to question 5 in Appendix 7.3.

3.2.3. Awareness and use of existing InSAR Ground Motion Services

A significant majority (70%) were aware of existing InSAR Ground Motion Services (*InSAR Norway* or EGMS). Nearly half (47%) had used datasets from these services for one or other application listed in the survey, including slope movements and other natural phenomena such as subsidence, deformation of man-made structures, technology development, ICT (Information and Communication Technology), and Calibration/Validation. See questions 6 and 8 in Appendix 7.3.

Among those who have used the existing services, 67% reported having used Sentinel-1 line-of-sight displacement maps and time series, and 43% reported using Sentinel-1 horizontal and vertical displacement maps and time series. Products from Radarsat-2 were reported to be used by 24% of the respondents. See question 9 in Appendix 7.3.

3.2.4. Applications and value of InSAR Svalbard Ground Motion Service

Key applications identified for Svalbard include researching and monitoring slope movements, thaw subsidence, frost heave, glacier movement, and deformation of man-made structures. The varied response spread, between 14% and 43%, indicates wide-ranging interest in diverse applications. Detailed distributions are available in question 10 of Appendix 7.3.

The primary value of InSAR data in Svalbard lies in its ability to detect, map, understand, and monitor moving landforms and structures, with interest levels between 36% and 55%. Furthermore, respondents valued InSAR for complementing and cross-validating other displacement measurements, with a 29% interest rate. For more details, see question 11 in Appendix 7.3.

3.2.5. Areas of interest

Areas of primary interest for the respondents include central and western Spitsbergen, particularly around major settlements such as Longyearbyen and Barentsburg (50%), and areas surrounding research stations like Ny-Ålesund and Hornsund (38%). Although other locations received fewer mentions (5–10%), 19% of respondents specified other areas in their comments. For more details, see question 12 in Appendix 7.3.

3.2.6. Spatio-temporal resolutions and updates

A significant majority (80%) of the survey respondents indicated a need for spatial resolution finer than 100 meters: 41% require less than 10 meters, and 39% require between 10 and 100 meters. These preferences are detailed in question 13 of Appendix 7.3.

For temporal resolution, most respondents indicated a need for monthly (22%) to annual (37%) resolution in the displacement time series, with fewer respondents needing more frequent (daily to weekly) information. See question 14 in Appendix 7.3.

Regarding the update of the product release, the highest demand was for annual updates (47%), followed by monthly (21%) and weekly (11%), as noted in question 22 of Appendix 7.3.

3.2.7. Expected maximum displacement and seasonal behaviour

Respondents primarily anticipate maximal annual amplitude or velocity in the order of centimetres per year for the processes they are targeting (41%), but slower/faster processes are also reported. See question 15 in Appendix 7.3.

A notable 41% of participants expect significant short-term or seasonal changes in velocity and displacement direction, as detailed in question 16 of Appendix 7.3. Importantly, a significant number of respondents were uncertain, answering "I don't know" to these queries.

3.2.8. Data types and interest in high-level InSAR products

Interest was shown by 56% of the respondents in time series documenting the horizontal and vertical displacement and in displacement time series along the radar line-of-sight (38%). With lower priority, 15% showed interest in single interferograms (image pairs), and 26% showed interest only in higher-level products, that is, already interpreted results. See question 17 in Appendix 7.3.

The responses show similar interest for several types of high-level products, including seasonal and long-term displacement time series, maximum displacements on slopes and flat terrain, and timing of subsidence and heave, ranging from 44% to 54%. Interest is relatively lower for glacier products: glacier velocity (28%) and grounding lines of calving glaciers (21%). See question 18 in Appendix 7.3.

Interest in other SAR-based datasets includes SAR backscatter (28%), SAR offset tracking (26%) maps and time series, and InSAR coherence products (15%). A significant portion of respondents (49%) answered “I don’t know” to this question. See question 19 in Appendix 7.3.

3.2.9. Other relevant datasets and services

In decreasing order of importance, respondents valued the inclusion of digital elevation models (DEMs) (79%), aerial optical imagery and topographical maps (both at 67%), satellite optical imagery (56%), the locations of man-made structures and in-situ measurements (each at 46%), as well as geological/geomorphological maps (44%) for visualisation alongside InSAR data in a web portal. See question 20 in Appendix 7.3.

The most requested services for an *InSAR Svalbard* ground motion service included a WebGIS tool for data viewing (89%), a tool for data download (79%), and an API interface (58%). Requests of lower priority included a user manual for the service, a helpdesk, and dedicated courses or seminars for data utilization. For more details, refer to question 21 in Appendix 7.3.

3.3. User requirements: summary

In Table 2, we list the main user requirements (URs) for an *InSAR Svalbard* Ground Motion Service, including both information from the workshop (Section 3.1) and survey (Section 3.2). We define two levels of requirements: the threshold requirement, which is the minimum needed to make the service useful, and the target requirement, which is the ideal request from the users.

Table 2: *User Requirements (URs) for an InSAR Svalbard Ground Motion Service.*

UR-01 **Spatial coverage**	**Threshold requirement**: The *InSAR Svalbard* GMS must cover areas with main settlements, research stations and major infrastructure. **Target requirement**: The *InSAR Svalbard* GMS should cover the entire Svalbard archipelago.
UR-02 **Spatial resolution**	**Threshold requirement:** The *InSAR Svalbard* GMS products must have a minimum spatial resolution of 10–100 m. **Target requirement:** The *InSAR Svalbard* GMS should have spatial resolution better than 10 m.
UR-03 **Temporal resolution**	**Threshold requirement:** The *InSAR Svalbard* GMS products must have an annual temporal resolution. **Target requirement:** The *InSAR Svalbard* GMS should have a daily temporal resolution in priority areas with settlements, research stations and major infrastructure.
UR-04 **InSAR products (1)**	**Threshold requirement:** The *InSAR Svalbard* GMS must include ground surface displacement time series along the radar line-of-sight and time series documenting the horizontal and vertical displacements in ice-free terrain. **Target requirement:** The *InSAR Svalbard* GMS should provide products dedicated to ice-covered terrain (glaciological applications) and high-level products (already interpreted) for selected applications and locations.
UR-05 **InSAR products (2)**	**Threshold requirement:** The *InSAR Svalbard* GMS products must document the distribution and evolution of ground surface displacement (value for geohazard assessment and earth science applications). **Target requirement:** The *InSAR Svalbard* GMS products should document both ground surface displacements and structural deformation (value for infrastructure monitoring).
UR-06 **InSAR products (3)**	**Threshold requirement:** The *InSAR Svalbard* GMS must document seasonal displacement time series during each snow-free period. **Target requirement:** The *InSAR Svalbard* GMS should document interannual displacement trends (time series connecting the snow-free seasons).
UR-07	**Threshold requirement:** The *InSAR Svalbard* GMS must make available auxiliary data in the web portal, digital elevation model (DEM), topographical maps, and optical imagery.

Auxiliary data	**Target requirement:** The *InSAR Svalbard* GMS should make available additional auxiliary data in the web portal: thematic maps (e.g. geology), location of man-made structures and in-situ measurement devices.
UR-09 **Product format and comparability**	**Threshold requirement:** The *InSAR Svalbard* GMS products must be delivered in a standard, consistent, well-documented data format. **Target requirement:** *InSAR Svalbard* should be integrated with other services such as Svalbardkartet.no, Cryo.met and SvalBox to ensure data intercomparison.
UR-08 **Service functions**	**Threshold requirement:** The *InSAR Svalbard* GMS must include functionalities for viewing and downloading the data and guidelines describing the data value and limitations for various applications. **Target requirement:** The *InSAR Svalbard* GMS should be supported by a dedicated helpdesk and offer training courses and seminars to the end-users.
UR-10 **Product update**	**Threshold requirement:** The *InSAR Svalbard* GMS products must be updated annually. **Target requirement:** The *InSAR Svalbard* GMS products should be updated more frequently (monthly or weekly) in priority areas with settlements, research stations and critical infrastructure.
UR-11 **End-user involvement**	**Threshold requirement:** The end users must be informed on the new developments of the *InSAR Svalbard* GMS. The *InSAR Svalbard* GMS products shall be delivered to the users operationally and continuously. **Target requirement:** The end-users should be regularly consulted regarding the applicability and quality of the products, both during the development and the operational phases.

4. Technical considerations

4.1. Summary of past InSAR studies in Svalbard

In 2009 and 2010, NORCE (formerly known as Norut) and UNIS conducted an initial pilot study on using InSAR for permafrost applications in Svalbard, with funding from the Norwegian Space Agency (NOSA). This pilot project showed promising results and led to larger follow-up studies: the *PermaSAR* project funded by the Research Council of Norway (212022) and the PRODEX *PermaSAT* project funded by NOSA and the European Space Agency (ESA) (C4000119115). Both projects began in 2012–2013 and aimed to explore permafrost dynamics using InSAR before the availability of Sentinel-1, relying on TerraSAR-X and RADARSAT-2 sensors. Challenges identified included limitations related to image availability and the loss of signal coherence on wet and rapidly changing surfaces. However, these studies demonstrated InSAR's potential for investigating permafrost processes in Svalbard (Norut, 2016).

The Svalbard Environmental Protection Fund's 2017 project (17/59) combined all available SAR data, including early Sentinel-1 images, to create simplified geohazard assessment products around Longyearbyen (Norut, 2018), as illustrated in Figure 1. These efforts highlighted InSAR's capability for mapping ground movement without detailing temporal changes. Subsequently, the *FrostInSAR* project, funded by the Research Council of Norway (project 263005), leveraged Sentinel-1's frequent revisits and high coherence for ground dynam3ics studies in Svalbard, particularly observing seasonal thaw subsidence and frost heave patterns. The project's results, processed with a Small Baseline Subset (SBAS) InSAR algorithm, provided novel information on the distribution and timing of seasonal ground movement. While the amplitude of the cyclic displacements depends on the frost-susceptibility of the ground material and the water content in the active layer (Figure 2), the temporal patterns are indicators of the freeze/thaw timing (Figure 3) (Rouyet et al., 2019; 2021). The project also showed the feasibility of decomposing East-West horizontal and vertical movements from a combination of ascending and descending satellite data.

Initially processed for one single year, further processing tests indicated the potential for consistent seasonal displacement analysis using Sentinel-1 data across various seasons (Figure 4). At this stage, the processing chain requires several manual steps and would, therefore, need to be adjusted for the automated generation of operational products at a large scale. While inter-annual trends like long-term thaw subsidence could be inferred in slowly moving areas with relatively constant ground surface conditions, focused research on such trends has yet to be extensively conducted in Svalbard.

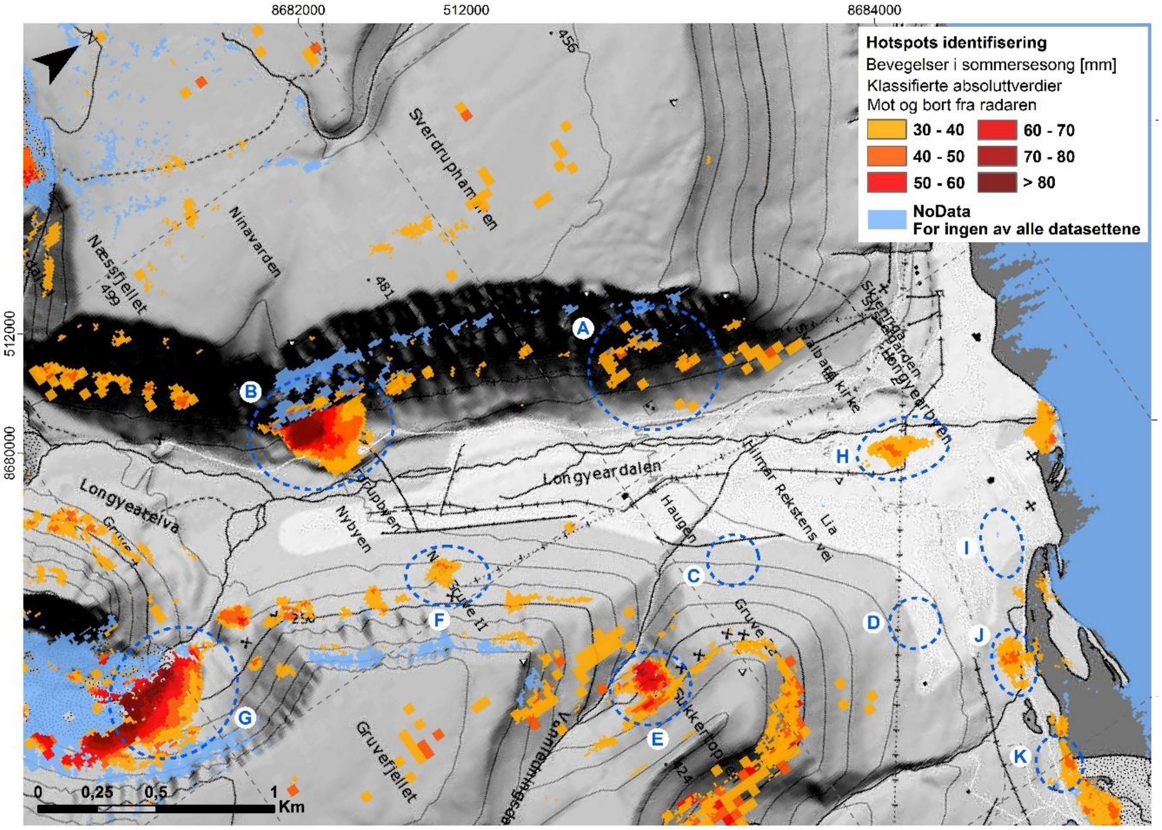

Figure 1: *Combined InSAR map based on several available sensors (Sentinel-1, RADARSAT-2 and TerraSAR-X) and geometries (ascending and descending) used to identify hotspots with absolute displacements > 30 mm during the summer season (Norut, 2018).*

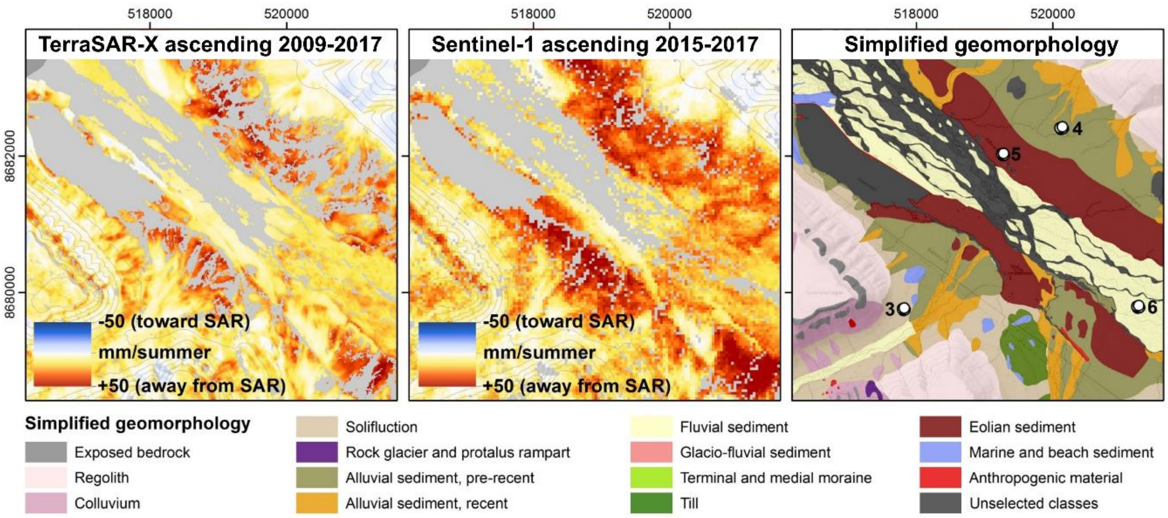

Figure 2: *Comparison of TerraSAR-X and Sentinel-1 ascending multi-year stacking Line-of-Sight (LoS) displacement rates during the 4-months thawing periods (June to September 2009–2017 for TerraSAR-X, 2015–2017 for Sentinel-1) with a simplified geomorphological map in the bottom of Adventdalen (modified from Rouyet et al., 2019).*

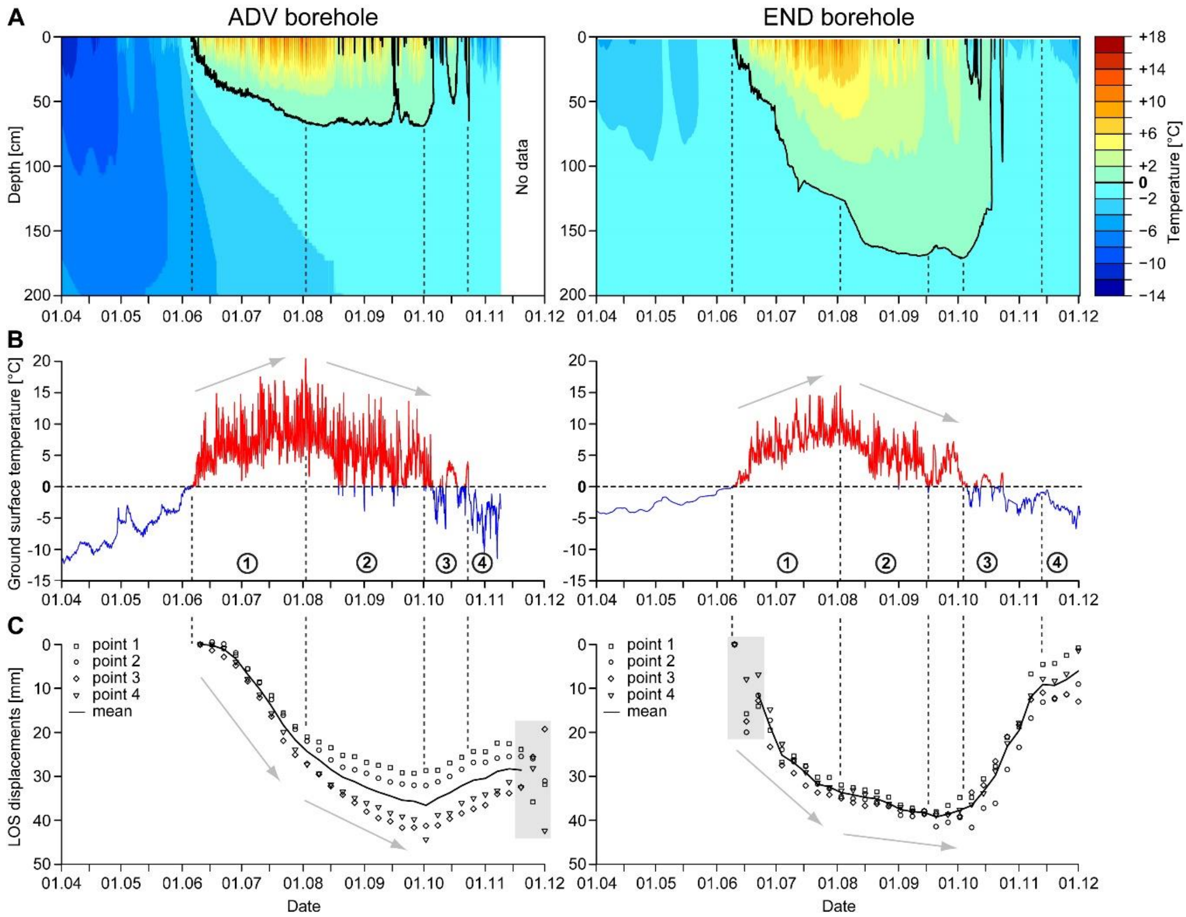

Figure 3: *2017 ground temperature and Sentinel-1 SBAS displacement time series during summer thawing, autumn freezing, and the start of winter cooling at two borehole locations. Left: Adventdalen (ADV) borehole. Right: Endalen (END) borehole. A. Temperature from the ground surface down to 200 cm depth. B. Ground surface temperature. C. InSAR displacements at the four neighbouring pixels closest to the two boreholes (Rouyet et al., 2019).*

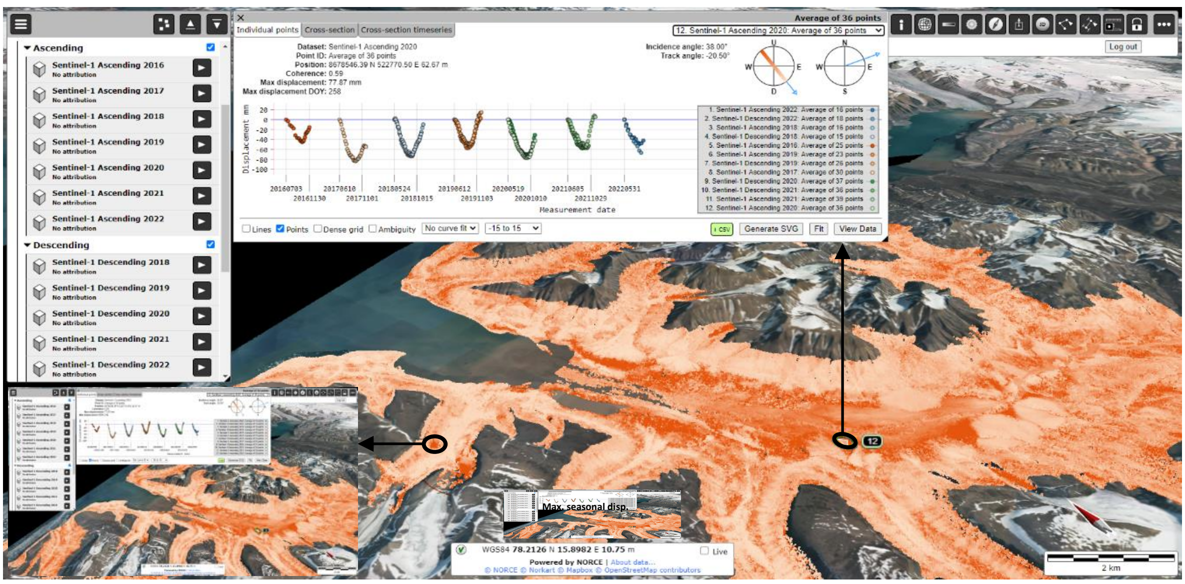

Figure 4: *Seasonal InSAR displacement time series, based on Sentinel-1 2016–2022 snow-free periods, visualised in the NLIVE WebGIS (similar to InSAR Norway).*

Since 2019, a pilot study has been underway to develop specific products tailored for the development of climate change indicators in mountain permafrost environments (rock glacier velocity time series). This study is supported by the ESA Climate Change Initiative (CCI) (project number 4000123681/18/I-NB). Nordenskiöld Land in Svalbard was one of the selected study areas. Initial results have shown the value of using InSAR-based classified velocity products to characterize the multi-annual creep rate of rock glaciers in regional inventories (Bertone et al., 2022) (Figure 5). The project also highlights the potential of using InSAR to monitor interannual velocity changes on targeted landforms (Bertone et al., 2020). However, further conclusions cannot be drawn at this stage due to short time series and the early phase of this research field. Due to the high velocity of rock glaciers and their gradual creep (even during undocumented winter periods), interannual SAR pairs (interferograms) are not included. The pilot products include only interferograms with short temporal baselines (6 days) that could be seasonally averaged to document long-term trends.

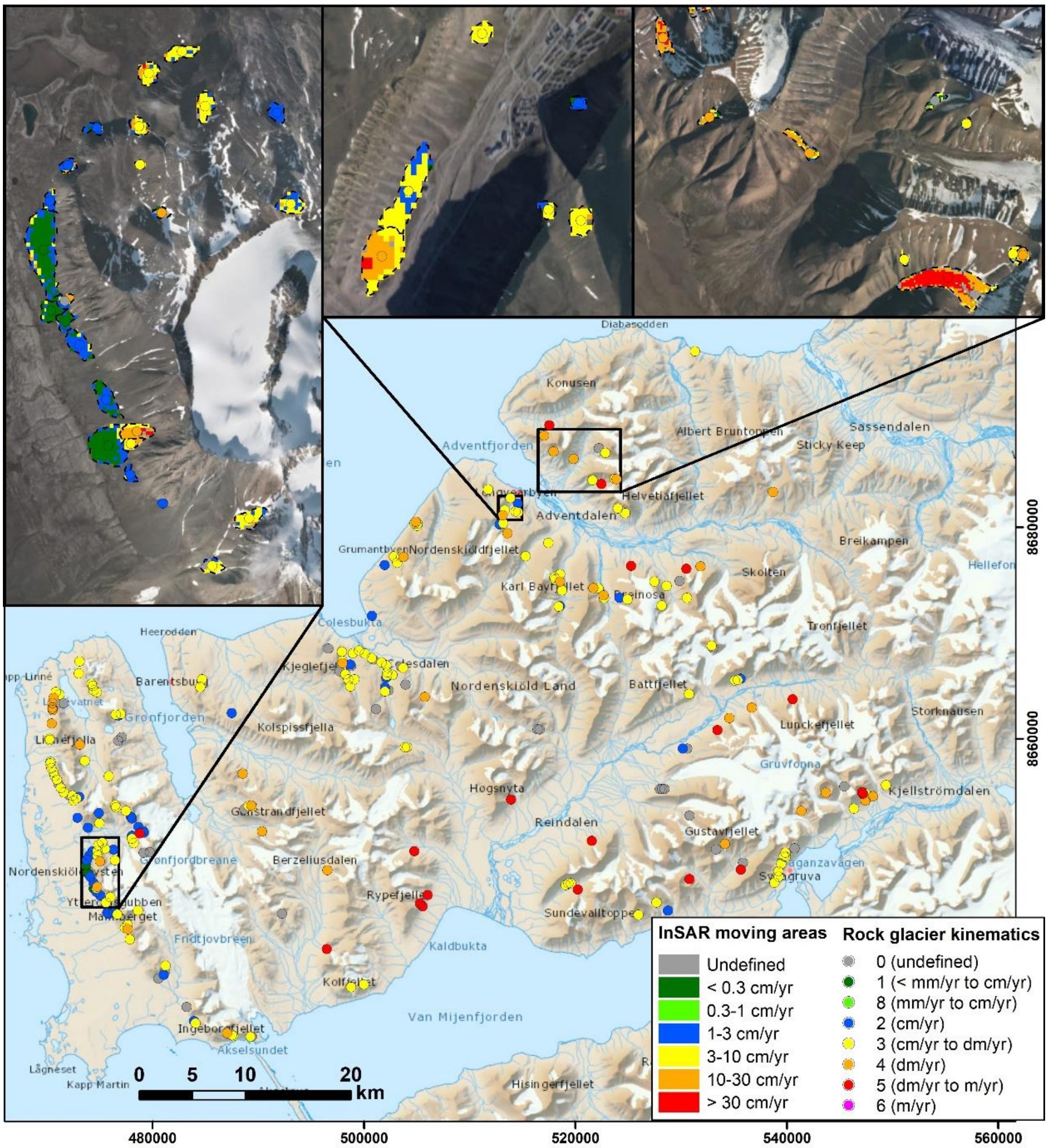

Figure 5: *Classified InSAR velocity extracted at the location of identified rock glaciers in Nordenskiöld Land and corresponding kinematic attribute in a standardized rock glacier inventory (modified from Bertone et al., 2020; 2022).*

Additionally, research has been conducted to use InSAR to document glacier flow fields in Svalbard, with a pilot study conducted over Kongsvegen glacier (van Oostveen et al., 2023). While not applicable for fast-moving ice bodies, the use of interferograms with short temporal baselines (6–12 days) has shown the potential to monitor the changes of slow-moving glaciers (Figure 6). Such products would be valuable to provide time series on features that move too slowly to be robustly documented by other techniques (like optical or SAR feature/offset tracking) and could contribute to the earlier detection of surges, a dramatic increase in speed and advance of glaciers. The processing parameters and the optimal period to exploit SAR images (winter) differ from InSAR strategies on ice-free ground. The integration of this application in the GMS would, therefore, require specific additional products.

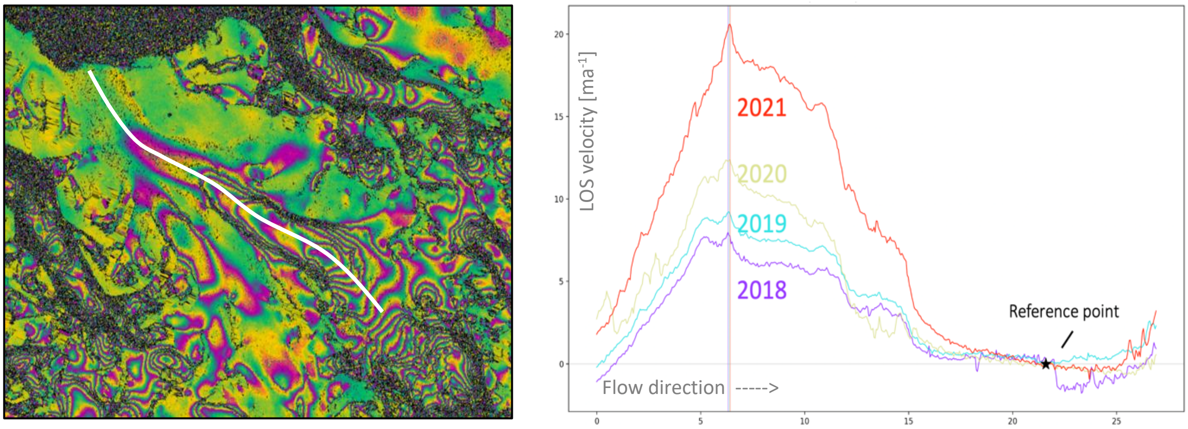

Figure 6: *Example of InSAR velocities indicating the onset of a surge of Kongsvegen, Svalbard. Left: interferogram and centreline (white). Right: Line-of-Sight (LoS) velocity profiles taken along the glacier centreline from individual 6-day interferograms in 2018–2021, showing a clear increasing trend that is indicative of the onset of a surge (van Oostveen et al., 2023).*

4.2. InSAR limitations in Svalbard

In addition to the usual InSAR limitations, as described in various conventional literature (e.g. Bamler & Hartl, 1998; Massonnet & Feigl, 1998; Rosen et al., 2000; Hanssen, 2001; Woodhouse, 2006; Ferretti, 2014) and summarized in the *InSAR Norway* user guide on NGU webpage (NGU, 2024), specific challenges related to the Arctic conditions further impact InSAR processing in Svalbard.

Svalbard presents a highly dynamic environment with diverse processes affecting the ground surface, including freeze/thaw processes, gravity, human disturbances, and erosion from surface water. With extensive glacial coverage (approximately 60%) and a complex network of fjords, Svalbard features spatially disconnected ice-free ground surfaces. Furthermore, abrupt changes in ground conditions, flooded surfaces, and snow cover diminish the applicability of InSAR in several areas, as illustrated in Figure 7. The remaining surfaces are anticipated to experience movement with varying amplitudes and temporalities. Additionally, Svalbard's complex and diverse topo-climatic and geological setting results in a combination of factors influencing the ground dynamics. These processes may occur simultaneously and be spatially overlapping, each exhibiting different spatiotemporal characteristics. Consequently, highly variable displacement patterns (in terms of amplitude and directionality) occur over short distances and time scales. Figure 8 illustrates some expected displacement patterns.

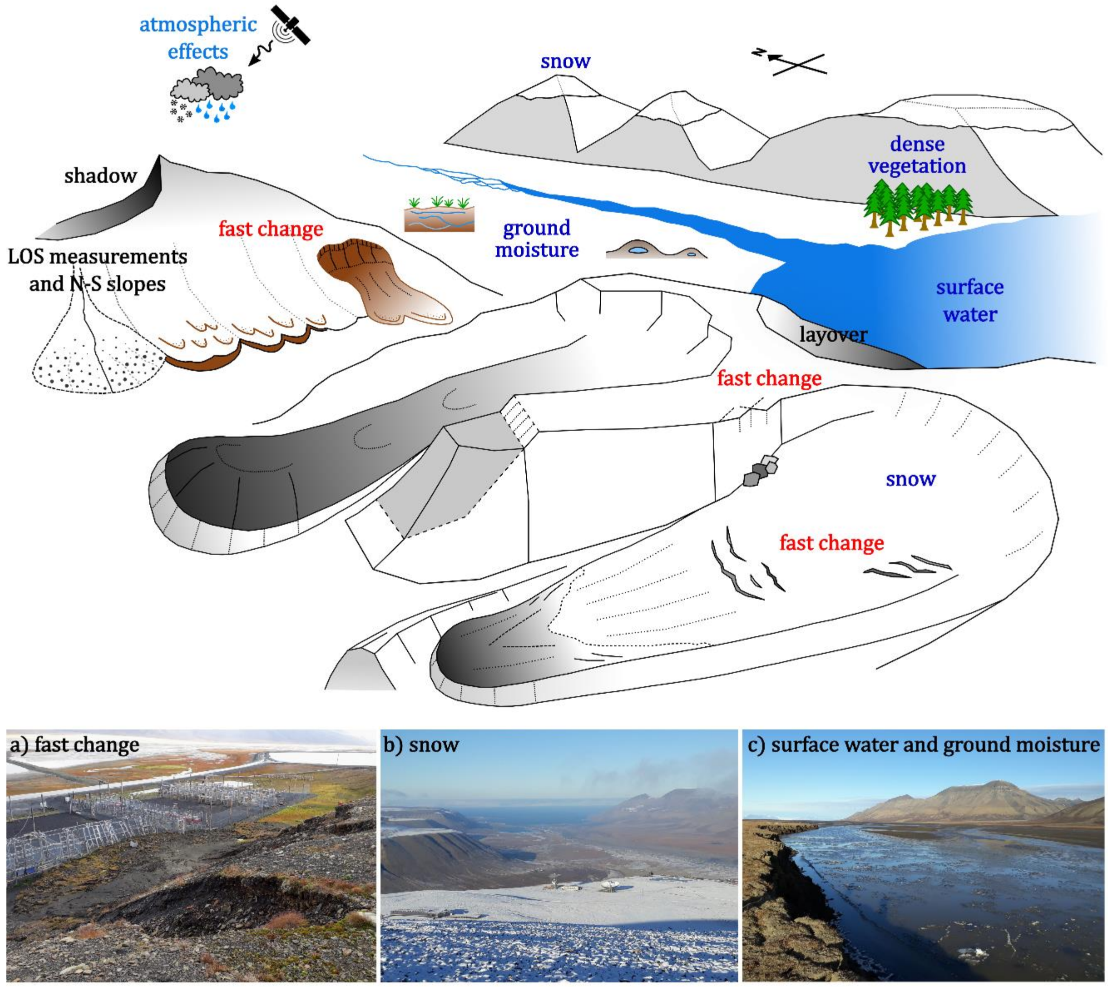

Figure 7: *Schematic representation of a periglacial landscape focusing on the main limitations that reduce the InSAR coverage or the reliability of the measurement (Rouyet, 2021).*

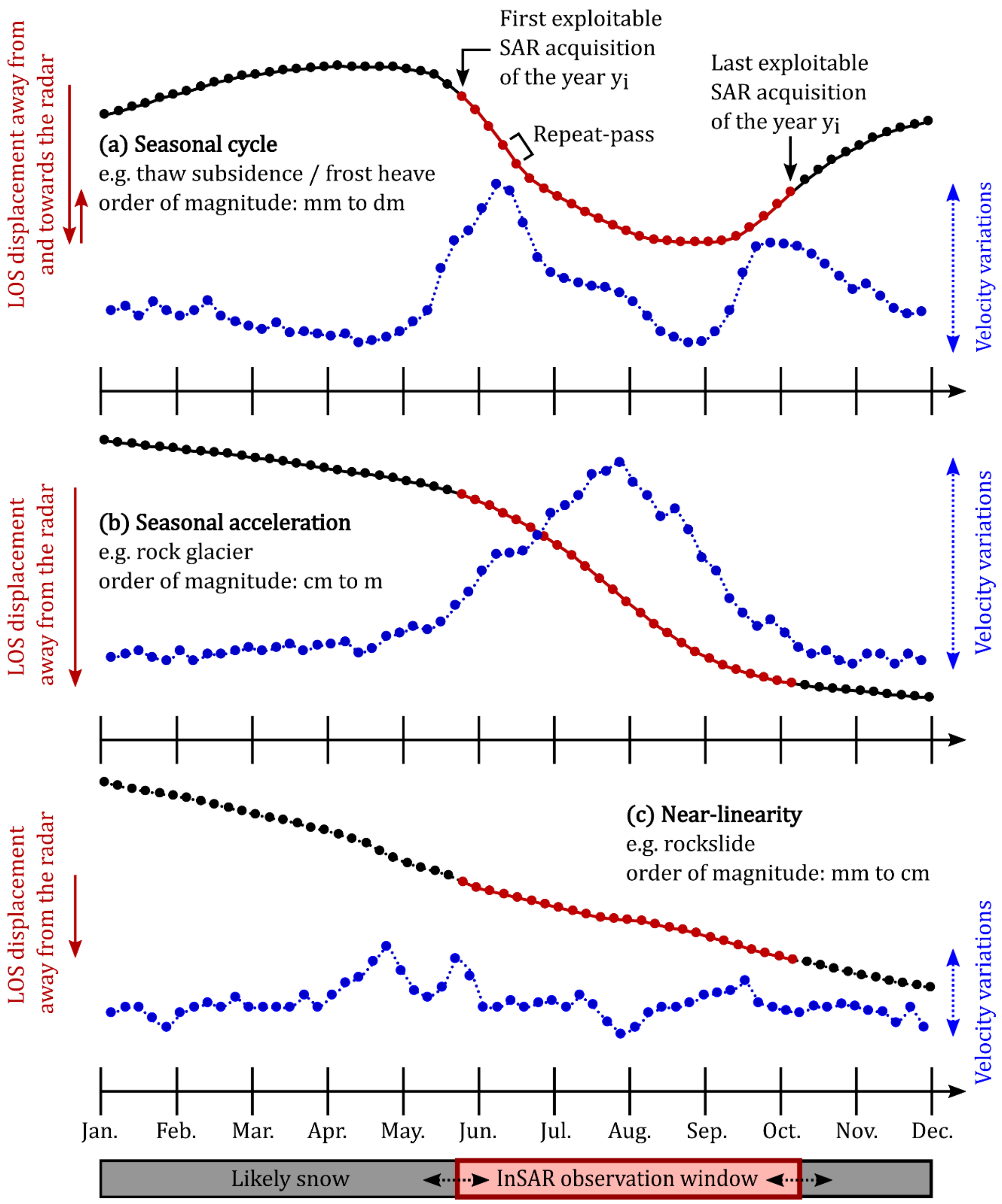

Figure 8: *Illustration of the diversity of the temporal behaviour of moving features in periglacial environment and InSAR measurements illustrated with synthetic displacement time series with a 6-day temporal sampling (Rouyet, 2021).*

Given these characteristics, several limitations arise when considering the development of a GMS processing chain, the delivery of products in a WebGIS, and the technical feasibility criteria outlined in Section 2.2.

4.2.1. Applicable InSAR algorithms and maturity of the processing chain

In Svalbard, the InSAR processing strategy differs significantly from the mainland, primarily due to the distinct environmental conditions. Unlike the Persistent Scatterer Interferometry (PSI, e.g., Ferretti et al., 2001), commonly applied on the mainland, research in Svalbard has focused on Distributed Scattering (DS) InSAR algorithms, particularly the Small Baseline Subset technique (SBAS, e.g., Berardino et al., 2002). This shift is necessitated by Svalbard's unique geological and climatic characteristics, which lead to a sparser and more unevenly distributed network of Persistent Scatterers (PS). PSI is generally more suited to urban or stable natural landscapes, as it relies on pixels that maintain consistent amplitude and phase statistics over time. These usually come from man-made structures or specific rock formations. However, in Svalbard, the predominantly snow-ice covered surfaces, combined with loose, wet sediments, make the formation of a dense PS network challenging.

Moreover, PSI involves generating a large stack of image pairs, or interferograms, compared to a single reference image. This process is complicated in regions like Svalbard, where rapid ground movement can cause decorrelation or phase ambiguities in interferograms spanning long time periods. While such issues can be partially mitigated during Svalbard's well-documented summer periods by extrapolating velocity to estimate displacement, this approach is constrained by the need to adhere to specific deformation models, such as linearity, which may not be universally applicable due to the varied displacement patterns observed in permafrost landscapes.

Consequently, the application of PSI in Svalbard has been limited, with past research opting for DS-based approaches instead. While hybrid algorithms that combine the strengths of both PS and DS techniques present a potential future solution, they currently lack the maturity needed for operational GMS use in the challenging conditions of Svalbard.

4.2.2. Spatial coverage and unwrapping

The DS InSAR approach is particularly advantageous in environments like Svalbard due to its adaptability to different temporal scales and ground conditions. DS InSAR constructs a complex network of interferograms from multiple reference images, allowing for the utilization of overlapping time measurements. This redundancy is critical for adjusting the time intervals between image pairs, which can be tailored according to the anticipated rates of ground displacement.

In regions with predictable, seasonal displacement patterns – such as areas experiencing cyclic subsidence and heave – DS InSAR is particularly effective. For example, in flat terrains expected to undergo these cyclic patterns, short temporal baselines are employed at the beginning and end of the snow-free periods, corresponding to times of rapid ground movement. When ground movement decelerates in mid or late summer, longer intervals between images can also be used.

Despite its flexibility, DS InSAR does present certain challenges, particularly in the context of Svalbard's unique geography. One significant issue is the requirement for spatial unwrapping, which involves integrating phase differences between adjacent pixels to construct a continuous displacement field. Svalbard's landscape, characterized by a mosaic of glaciers and fjords, results in spatially disjointed areas of ice-free ground. This fragmentation leads to discontinuous patches of coherent measurements, complicating the unwrapping process, especially when attempts are made to scale up the processing and cover the entire archipelago. This spatial discontinuity poses a notable drawback in applying DS InSAR techniques effectively across such a diverse and segmented landscape.

4.2.3. Multi-looking and spatial resolution

In the DS InSAR processing chain, the spatial averaging step, known as multi-looking, is crucial for improving signal quality but has the drawback of reducing the spatial resolution of the final outputs. For example, when using Sentinel-1 Interferometric Wide (IW) swath images and applying an 8 x 2 multi-looking factor (range x azimuth), the resultant ground resolution decreases to approximately 40 meters. Although this resolution has been sufficient for various applications in previous studies, it might not be adequate for monitoring small structures. Within a 40-meter resolution cell, different processes, such as the deformation of a specific structure and changes in the surrounding ground surface, can be indistinctly merged, leading to ambiguous interpretations.

An alternative is to use a finer 4 x 1 multi-looking factor, which would yield a higher resolution of approximately 20 meters. However, this approach compromises the signal-to-noise ratio and, consequently, the coherence estimate's quality, which is critical for reliable InSAR analysis. Addressing this issue could involve applying different multi-looking factors at different stages of the InSAR processing chain – using higher factors to estimate the coherence and choose suitable temporal baselines, and lower ones for the actual data processing. While theoretically feasible, this approach is computationally intensive, making it challenging to implement in practice, especially for large-scale or time-sensitive projects. This limitation underscores the inherent trade-offs between resolution, signal quality, and computational demands in DS InSAR techniques.

4.2.4. InSAR calibration

InSAR is a relative measurement method, necessitating reference points to calibrate and validate the displacement measurements. In places like Svalbard, this calibration presents specific challenges due to environmental and logistical factors.

One approach to calibration requires sites with known displacement rates, often validated by other measurement techniques like Global Navigation Satellite System (GNSS) stations. However, in Svalbard, such in-situ monitoring sites are sparse. Where they exist, they often do not directly correlate with InSAR data due to spatial and temporal scale differences.

Alternatively, reference points can be selected in areas assumed to be stable. This calibration approach poses its own set of challenges, especially in Svalbard, where few exposed bedrock outcrops are free from weathered material that could compromise stability. In settled areas, buildings anchored in bedrock might serve as potential reference points, but these are few and far between. Another option is the installation of corner reflectors with solid foundations; however, this solution is feasible only in a limited number of locations throughout the archipelago due to the harsh and varied terrain.

In practice, selecting calibration points for InSAR involves a two-step process: initially identifying highly coherent locations automatically and then manually excluding unsuitable ones based on geological considerations. This selection process is iterative, involving testing various locations to assess their impact on the detected movements.

Given these calibration challenges, InSAR in areas like Svalbard is typically processed in small tiles (e.g. 10–20 km^2) to manage local variations effectively. These tiles must then be merged to create comprehensive, large-scale products. However, this merging process is complex and can result in displacement value shifts at tile boundaries. Addressing these issues may involve using partly overlapping tiles, allowing for comparison and adjustment between them, though this adds another layer of complexity to the processing chain.

4.2.5. Fast movement and interannual analysis

InSAR's ability to detect rapid ground movements is limited by technical constraints, primarily due to the phase ambiguity limit. This limit is determined by half of the satellite sensor's wavelength. Specifically, for the Sentinel-1 satellite, which operates with a radar wavelength of about 5.6 cm, the maximum measurable ground movement between two points without ambiguity, from one satellite pass to the next, is approximately 2.8 cm. This fundamental limit impacts InSAR's effectiveness in tracking very rapid ground displacements. Given the 6-day repeat cycle with two Sentinel-1 satellites, this limitation restricts detection to a velocity of about 14 cm per month or 170 cm per year between two pixels. However, the situation is further complicated by the failure of one of the Sentinel-1 satellites (Sentinel-1B), resulting in a doubled interval to 12 days for repeat-passes when using just one satellite. This adjustment halves the maximum measurable velocity to approximately 7 cm per month or 85 cm per year.

Another significant constraint for InSAR applications in Svalbard is the snow cover, which renders the ground undetectable by InSAR techniques for much of the year, typically from November to May. To connect the periods when the ground is not snow-covered and thus measurable by InSAR, interferograms must span a minimum of 6–7 months. With such lengthy intervals, the detection capability significantly decreases to around 5–6 cm/year.

To counter these limitations and still capture a broad range of geological processes, InSAR analyses in Svalbard typically rely on seasonal stacks, which involve compiling interferograms with short intervals (temporal baselines) between the images. While interannual analyses are feasible, they must be carefully tailored to monitor slow processes, particularly given the gaps in data collection during the snowy winter months.

L-band sensors, which have longer wavelengths, could provide a solution to improve InSAR's detection capabilities, particularly for interannual processes. Unfortunately, there are currently no operational missions equipped with these sensors that are expected to cover Svalbard in the near future. The NISAR mission, while equipped with an L-band sensor, is anticipated to cover only the southernmost parts of Spitsbergen due to its left-looking SAR orientation. This limitation underscores the challenges faced in using InSAR technology to monitor rapid and seasonal ground movements in polar regions like Svalbard.

4.2.6. Update frequency of product delivery and InSAR monitoring

InSAR processing leverages the redundancy within a large stack of interferograms to filter out undesirable phase components. It is possible to incrementally add new images to an existing time series, but certain steps of the processing chain must be reprocessed. Additionally, in regions like Svalbard, the operational window for InSAR observations is limited to 4–6 months annually due to snow coverage.

On the mainland, the use of corner reflectors has proven beneficial for year-round InSAR monitoring by providing stable scattering points. However, implementing the same strategy in Svalbard faces unique challenges due to the dynamic nature of the ground processes, including the varying effects of seasonal frost heave and thaw subsidence. Corner reflectors in these conditions may be prone to tilting or damage over time, especially if not anchored in stable, bedrock locations.

While corner reflectors could be used to monitor deep-seated rock slope deformation similar to mainland rockslides, the effectiveness is limited in areas with significant surface weathering and mixed types of ground movement. Furthermore, the logistical aspects of installing and maintaining these instruments in the harsh, remote Arctic conditions contribute to the overall challenge, encompassing both high costs and operational difficulties.

Despite these challenges, corner reflectors might still offer value as stable calibration points within specific, strategically chosen sites across the archipelago, aiding in the improvement of InSAR data accuracy and reliability in those areas.

4.2.7. Product visualisation and interpretability

In Svalbard, interpreting InSAR data presents unique challenges compared to the mainland, primarily due to the non-linear nature of many geological processes. Typically, on the mainland, GMS maps use a colour scale to represent the interannual mean velocity of ground movement. These products usually include multi-annual Line-of-Sight (LoS) displacement maps and time series for a specific SAR geometry. Users can click on a point within a WebGIS interface to view the time series showing the displacement evolution relative to the first acquisition.

However, in Svalbard, where the situation is complicated by the presence of dominant cyclic patterns in ground displacement at the seasonal level, the annual mean velocity is not necessarily a relevant measure. In these cases, the annual velocity might register as zero despite significant centimetre to decimetre scale movements within the measured time period. To better capture and visualise these dynamics, it has been suggested to map the maximum displacement observed in the series instead, offering a clearer picture of intra-annual ground displacement.

While interannual products could be displayed like those in *InSAR Norway*, using the mean velocity for instance, this approach would necessitate multiple visualisation modes to accurately represent the different product types. This diversity of modes could potentially confuse users, especially those not well-versed in interpreting InSAR data nuances. This highlights the need for careful consideration of how InSAR data is presented, particularly in regions with complex ground movement patterns like Svalbard.

4.3. Technical considerations: summary

In Table 3, we provide a summary of the primary technical considerations discussed in Sections 4.1 and 4.2. This table is not intended to cover all possible issues but rather focuses on highlighting the principal challenges associated with meeting user requirements and establishing a functional InSAR GMS in Svalbard.

Table 3: *Technical Considerations (TCs) constraining the InSAR Svalbard data properties and service functionalities.*

TC-01 **InSAR algorithm**	DS InSAR, particularly the SBAS approach, is considered the most appropriate and developed method for robust application in Svalbard. However, it faces two significant limitations: spatial unwrapping, which poses challenges for upscaling the technology (refer to TC-02), and multi-looking, which reduces the final spatial resolution (refer to TC-03). While the development of hybrid algorithms combining PS and DS InSAR is a potential area for exploration, they are not expected to reach a level of maturity suitable for operational use in the initial phase of the project.
TC-02 **Spatial coverage**	During the development phase, two primary practical challenges must be addressed to upscale the products to the entire archipelago: 1) spatial unwrapping in areas characterized by patchy coherent surfaces, and 2) the selection of stable calibration points and effective merging of processing tiles in regions with highly dynamic ground conditions. While these issues are typical limitations encountered in all InSAR applications, they are particularly pronounced in the unique environmental context of Svalbard.
TC-03 **Spatio-temporal resolutions**	Sentinel-1 stands as the sole operational mission offering the free, regular, and consistent SAR acquisitions essential for an InSAR GMS. Consequently, the InSAR products for Svalbard are restricted by the characteristics of this sensor, notably its IW ground resolution of approximately 5x20 m and its current 12-day repeat-pass interval. In practical terms, the effective resolution is further constrained by the applied multi-looking process and the gaps caused by winter snow cover. The potential for incorporating other SAR sources, such as L-band sensors, into the InSAR framework will be assessed during the development phase, although their inclusion is not guaranteed at this stage.
TC-04 **Seasonal InSAR products**	Seasonal SBAS products have been systematically generated and analysed since the initiation of Sentinel-1 acquisitions. Previous research has underscored the significance of these datasets for geohazard assessment and geoscientific interpretation. While these products are deemed mature enough for operational use, additional developments are necessary to automate and scale up the processing to meet broader application needs.
TC-05 **Extra InSAR products (1)**	Additional products like simplified averaged velocity maps or single interferogram analyses focused on slow-moving glaciers have proven valuable for specific applications. While technically feasible, their implementation would necessitate establishing parallel sub-processing chains and diversifying the output formats along with their corresponding visualisation modes. This approach poses significant challenges in terms of personnel and computing

	resources, and could also complicate the service, making it more difficult for users to interpret the results effectively.
TC-06 **Extra InSAR products (2)**	Interannual SBAS products are considered feasible for monitoring specific slow-moving processes, such as long-term thaw subsidence in flat terrains, particularly in areas where ground conditions remain relatively similar across winter data gaps. There is significant user interest in these types of products, and accordingly, their development is planned for the project's development phase. However, it is important to note that achieving this will likely involve setting up parallel processing chains and creating a range of complementary products, a process that demands substantial resources.
TC-07 **Visualisation tool and service functions**	The WebGIS platform used for *InSAR Norway*, which utilizes NORCE NLIVE technology, is well-established and mature. Adapting this system for visualising *InSAR Svalbard* products to suit specific data characteristics and user needs is expected to be straightforward, given the system's inherent flexibility. The platform allows for the integration of external data, enabling the comparison of *InSAR Svalbard* results with other services. However, it is important to note that the inter-compatibility with external systems may be constrained by factors beyond the control of the *InSAR Svalbard* team.
TC-08 **Update frequency**	InSAR relies on utilizing a large stack of interferograms to reduce unwanted phase components. Several steps must be reprocessed when new images are acquired. An incremental processing setup must be developed, where new images are added to an existing stack, and the needed steps are reprocessed. Annual update would include all newly acquired images within an entire snow-free season. Although the potential for more frequent updates at specific target locations will be assessed, this may not be practical in the initial phase of the project. Additionally, monitoring using corner reflectors, including during snowy periods, is unlikely to be feasible in many locations due to the highly dynamic nature of the ground surface.

5. Conclusion: product development plan

To summarize, the report concludes with tentative product specifications. This is derived from a trade-off analysis that balances user requirements with technical considerations. This preliminary product development plan is outlined in Table 4, reflecting the specific objectives targeted within the project's scope. Our goal is to meet all user-defined threshold requirements, as detailed in Section 3.3. However, due to technical constraints discussed in Sections 4.2 and 4.3, we may not prioritize some target requirements during the initial development phase.

It is important to note that these product specifications might undergo adjustments based on the outcomes of the pilot product generation and evaluation phases, referred to as WP2 and WP3 (see Section 1.1). We have scheduled the pilot generation of these products for 2024, focusing particularly on the regions surrounding Longyearbyen and Ny-Ålesund. Initial findings will be presented to the reference group and discussed in a second workshop planned for autumn 2024. The insights gained from this workshop will be crucial in refining the automated processing chain, paving the way for the systematic generation of large-scale products.

Table 4: *InSAR Svalbard tentative product specifications based on User Requirements (URs, Table 2) and Technical Considerations (TCs, Table 3). Green indicates areas where target requirements are expected to be met. Blue shows areas where threshold requirements are expected to be met. Fulfilling the target requirements may be possible and will be evaluated, but this objective has a lower priority during the development phase. Yellow denotes areas where only threshold requirements are achievable, with current data and methods unable to meet the target requirements.*

User requirement	**Tentative product specifications, with respect to the identified User Requirements (URs) and accounting for the Technical Considerations (TCs)**
UR-01 **Spatial coverage**	Our objective is to meet the target requirement of providing a GMS that covers the entire Svalbard archipelago. However, due to potential challenges associated with TC-01 and TC-02, we may prioritize meeting the threshold requirement, which focuses on ensuring coverage of areas encompassing main settlements, research stations, and key infrastructure during the development phase.
UR-02 **Spatial resolution**	Using Sentinel-1 IW imagery, achieving the target requirement of less than 10 m spatial resolution is unattainable due to TC-03. However, the threshold requirement, which ranges between 10 and 100 m, will be met. Employing DS InSAR, the expected resolution is around 40 m. A finer resolution of 20 m could potentially be reached by applying a lower multi-looking factor or by using a hybrid PS-DS algorithm, although this is not a priority in the current phase of the project, as indicated by TC-01.
UR-03 **Temporal resolution**	Using Sentinel-1 IW imagery, achieving the target temporal resolution of daily updates is not feasible due to TC-02. Nonetheless, the threshold spatial resolution requirement, ranging from 10 to 100 meters, will be met. The temporal resolution of the time series will span 6–12 days during the snow-free seasons.

UR-04 **InSAR products (1)**	The threshold requirement, which includes LoS and 2D-decomposed displacement time series in ice-free terrain, is expected to be met, as mentioned in TC-04. The potential for incorporating additional high-level products, aligning with target requirements will undergo evaluation. However, due to constraints such as limited personnel and computational resources, as well as concerns over increasing the service's complexity and possibly complicating user interpretation with the introduction of multiple products with diverse properties, this addition may receive lower priority during the development phase, as indicated by TC-05.
UR-05 **InSAR products (2)**	The *InSAR Svalbard* GMS products are designed to document ground surface movement, meeting the threshold requirement. The capability to document the deformation of man-made structures will depend on the size of the structures and the final resolution that can be applied, as addressed by TC-1 and TC-3. This aspect will be assessed during the development phase, though it is anticipated that ambiguities may persist due to overlapping effects of structural deformation and ground surface movement within the measurement pixel.
UR-06 **InSAR products (3)**	The threshold requirement, which entails producing seasonal displacement time series for each snow-free period, is expected to be met. Additionally, the development project focuses on creating interannual products that connect these snow-free seasons. Enhancing these products by increasing coherence and maximal detection capability through the application of L-band InSAR would be beneficial. However, this aspect is currently at the research stage, and the robustness of the final products remains uncertain, as indicated by TC-6.
UR-07 **Auxiliary data**	The target requirement is anticipated to be met without significant obstacles. Making various types of auxiliary data available on the web portal is feasible. Traditional background data, such as DEMs, topographical maps, and optical imagery, are already integrated into the existing WebGIS. Additionally, incorporating other thematic maps and enabling the import of the locations of man-made structures and in-situ measurement devices can be accomplished seamlessly.
UR-09 **Product format and comparability**	The threshold requirement of providing standard, consistent, and well-documented data formats is expected to be met. Efforts will also be directed towards achieving the target requirement. However, the ability to ensure inter-comparability and integration with other services extends beyond the scope of the InSAR GMS alone. Achieving this will necessitate dialogue and possible modifications by external institutions, as described in TC-07.
UR-08 **Service functions**	The threshold requirement, which includes functionalities for viewing and downloading data along with dedicated guidelines, is anticipated to be met. Efforts to achieve the target requirement, such as providing a dedicated helpdesk and organizing training courses and seminars, are planned to be undertaken. However, the implementation of these initiatives will depend on the resources available during the operational phase.

UR-10 **Product update**	The threshold requirement of providing annual updates is expected to be met. Fulfilling the target requirement for more frequent updates is resource-intensive, as indicated by TC-08, and may be challenging during the project's initial phase. However, the feasibility of more frequent updates, particularly for targeted locations such as critical infrastructure, will be evaluated.
UR-11 **End-user involvement**	The target requirement is anticipated to be met. End-users will be thoroughly informed about the new *InSAR Svalbard* developments. Additionally, through the reference group, end-users will be consulted about the applicability and quality of the products during both the development and operational phases.

6. References

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7. Appendices

7.1. User workshop: agenda

Torsdag 31.08.2023 (Møterom Kapp Wijk, UNIS)

09.00-09.15: Velkommen til deltakere, introduksjon av program og rundt bordet.
09.15-09.30: Introduksjon til prosjektet: bakgrunn og arbeidsplan (NGU).
09.30-09.45: Erfaringer fra 5-år med operasjonell InSAR Norge (NGU).
09.45-10.15: Eksempler av InSAR produkter i Svalbard (NORCE).
10.15-10.30: Spørsmål/diskusjon.

--- *Pause 10.15-10.30*

10.30-10.45: Foreløpige resultater av brukerundersøkelsen (NGU/NORCE).
10.45-10.00: Prioriteringer og brukerbehov fra Sysselmesteren.
11.00-11.15: Prioriteringer og brukerbehov fra Lokalstyret.
11.15-11.30: Prioriteringer og brukerbehov fra Store Norske.
11.30-12.00: Spørsmål/diskusjon.

--- *Lunsj 12.00-12.45*

12.45-13.00: Eksisterende og framtidig verdi av InSAR Svalbard for NPI.
13.00-13.15: Eksisterende og framtidig verdi av InSAR Svalbard for MET.
13.15-13.30: Eksisterende og framtidig verdi av InSAR Svalbard for UNIS.

--- *Pause 13.30-13.45*

13.45-14.00: Eksisterende og framtidig verdi av InSAR Svalbard for NGI.
14.00-14.15: Eksisterende og framtidig verdi av InSAR Svalbard for SINTEF.
14.15-14.45: Spørsmål/diskusjon

--- *Pause 14.45-15.00*

15.00-16.00: Diskusjon rundt nøkkelspørsmål om brukerbehov og produktspesifisering: bruksområder, datatyper, fokusområde, visualisering, oppløsning, oppdateringsfrekvens osv.
16:00-16:30: Oppsummering, hva er neste steg?

--- *Middag 18.30 - Kroa*

Fredag 01.09.2023

09.00-lunsj: Gåtur rundt Longyearbyen, ledet av Hanne Christiansen (UNIS). Forklaring om utfordring relatert til permafrost forhold og geofarer.

7.2. User workshop: participants

On-site participation:

The Governor of Svalbard (Sysselmesteren på Svalbard)

Longyearbyen Community Council (Longyearbyen Lokalstyre)

Store Norske Spitsbergen Kulkompani

The University Centre in Svalbard (UNIS)

The Norwegian Geotechnical Institute (NGI)

The Norwegian Space Centre (Norsk Romsenter)

NORCE Norwegian Research Centre

Digital participation:

The Norwegian Polar Institute (NPI)

The Norwegian Meteorological Institute (MET)

SINTEF

Avinor

University of Oslo (UiO)

Norwegian University of Science and Technology (NTNU)

National Taiwan University

NORCE Norwegian Research Centre

7.3. User survey: SurveyXact report

The survey has been created in the NORCE company account of the *SurveyXact* software (Ramboll). Introductive text and questions were available both in English and Norwegian. We here only report the English version. The written comments are reported as received, except for minor orthographic/typographic corrections. Italic parts in parentheses are tentative translations in English for comments received in Norwegian (i.e. not part of the initial survey responses, added by the report authors).

Introductive text:

The Geological Survey of Norway (NGU) and NORCE Norwegian Research Centre are starting a project to develop an InSAR Ground Motion Service (GMS) in Svalbard, and we need your help!

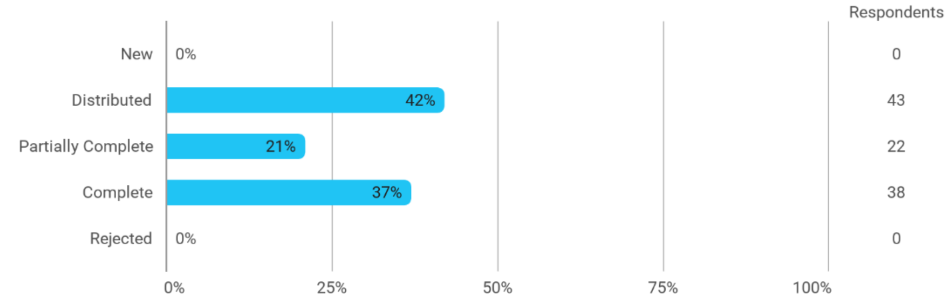
A Ground Motion Service (GMS) based on spaceborne Synthetic Aperture Radar Interferometry (InSAR) technology produces and delivers deformation maps and time series over large terrestrial areas based on open-access SAR satellite images, such as the Copernicus Sentinel-1. The InSAR Norway map service (https://www.insar.ngu.no) and the European Ground Motion Service (EGMS) (https://egms.land.copernicus.eu/) are two examples of GMS managed at different levels. InSAR Norway and EGMS provide datasets useful, for example, to the authorities in charge of geohazards and public safety (e.g. to detect, map or monitor unstable areas, such as landslides or urban subsidence), civil engineers (e.g. to identify deformation of man-made structures and study the impact on structural stability) and/or researchers (e.g. to study the dynamics of natural processes in a changing climate).

Svalbard is currently not covered by either InSAR Norway or EGMS. In a new project supported by the Norwegian Space Agency (2023–2025), NGU and NORCE are developing the necessary foundation to implement an operational GMS covering Svalbard. Svalbard has a very different environment to the mainland with specific technical challenges and user needs. We therefore need your expert help to define new products, properties and visualizations that are suitable for Svalbard.

If you would like to contribute to *InSAR Svalbard* product specification, please answer the following questions. The survey is targeting InSAR data users or end-users interested in the type of information InSAR may provide in Svalbard. For some questions, background in InSAR is required. If you don't have any, just answer "I don't know". It takes about 10-15 min to answer to the survey.

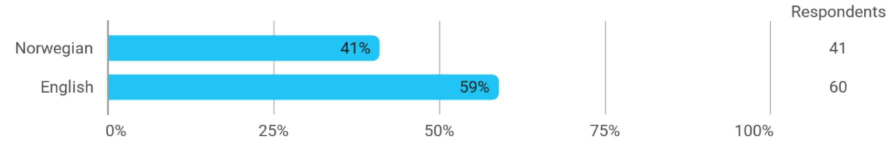
Marie Bredal, NGU project leader. Contact: marie.bredal@ngu.no
Line Rouyet, NORCE project leader. Contact: liro@norceresearch.no

Overall Status:

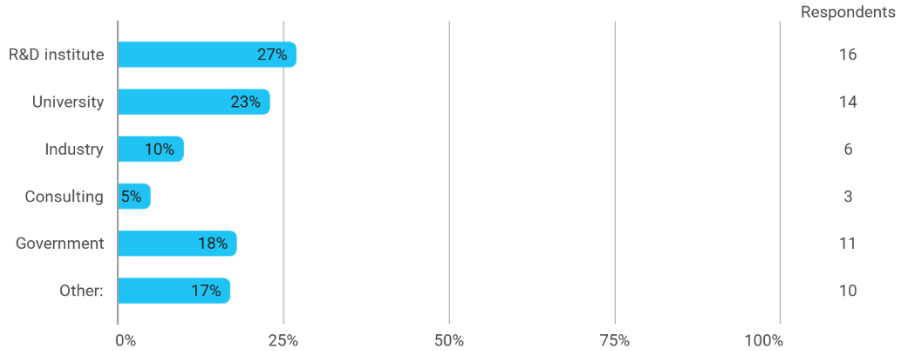


Note on these values: The survey has been completed by 60 people (38 fully completed forms and, 22 partially completed forms). The number of distributed surveys (43) corresponds to the people who clicked on the link, choose the language and read the introductive text but did not continue answering the survey.

Chosen Language:



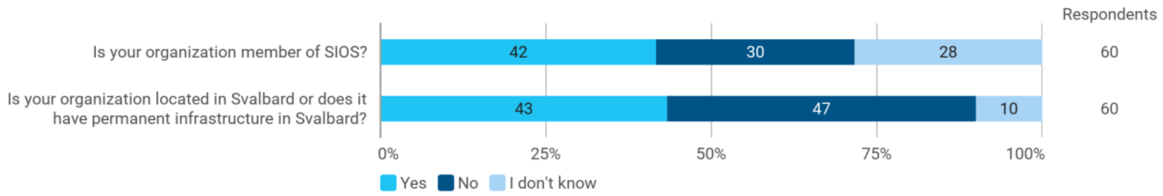
Question 1: Which type of organization are you affiliated to?



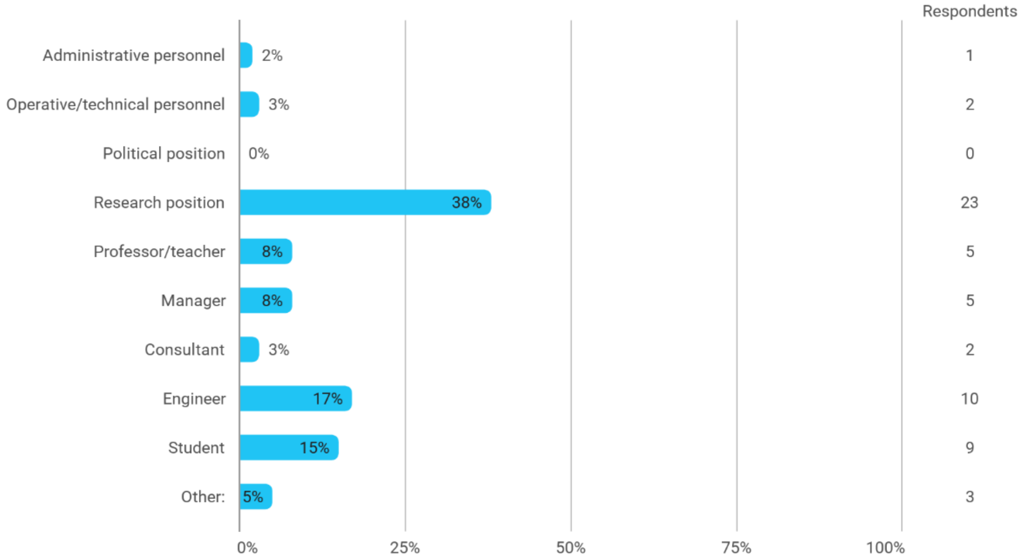
Which type of organization are you affiliated to? - Other:

- Kommune *(English: Municipality)*
- Luftfart *(English: Aviation)*
- Byggherre, Store Norske *(English: Building development project owner)*
- European agency
- EU agency
- Soon to join PhD
- Videregående *(English: High School)*
- Forvalter, Store Norske Næringsbygg *(English: Administrator)*
- Eiendomsaktør *(English: Property stakeholder)*

Question 2: Is your organization member of SIOS?



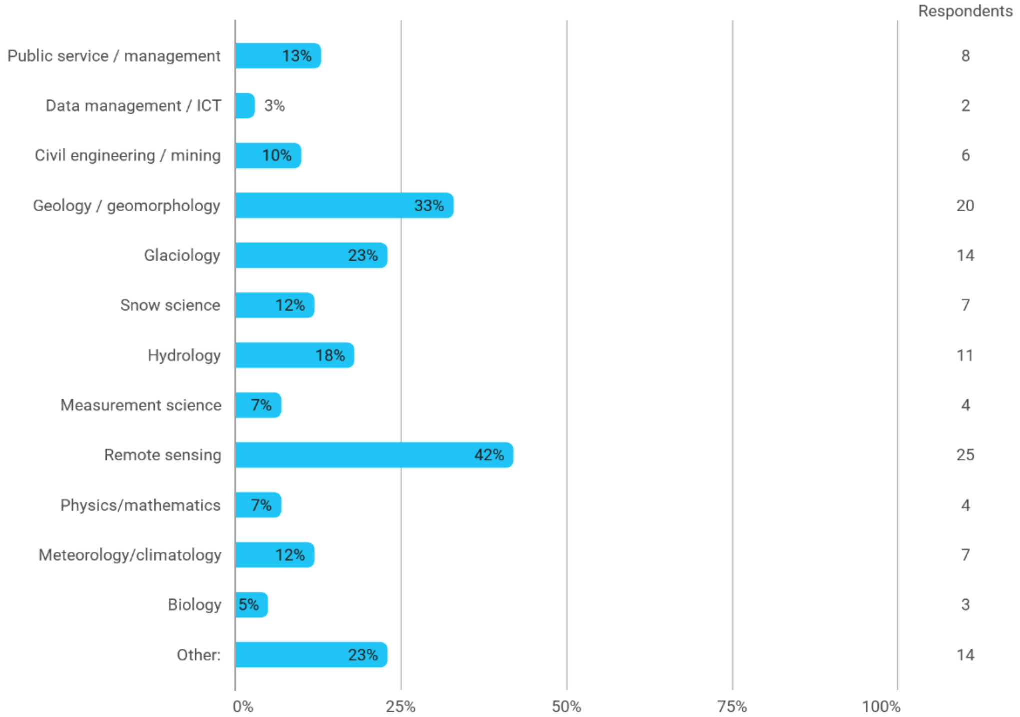
<u>Question 3</u>: What is your current position?



<u>What is your current position? - Other:</u>

- Rådgiver *(English: Advisor)*
- Forsker og Professor II *(English: Researcher and Adjunct Professor)*
- Seniorrådgiver *(English: Senior Advisor)*

<u>Question 4</u>: What is your field of work?

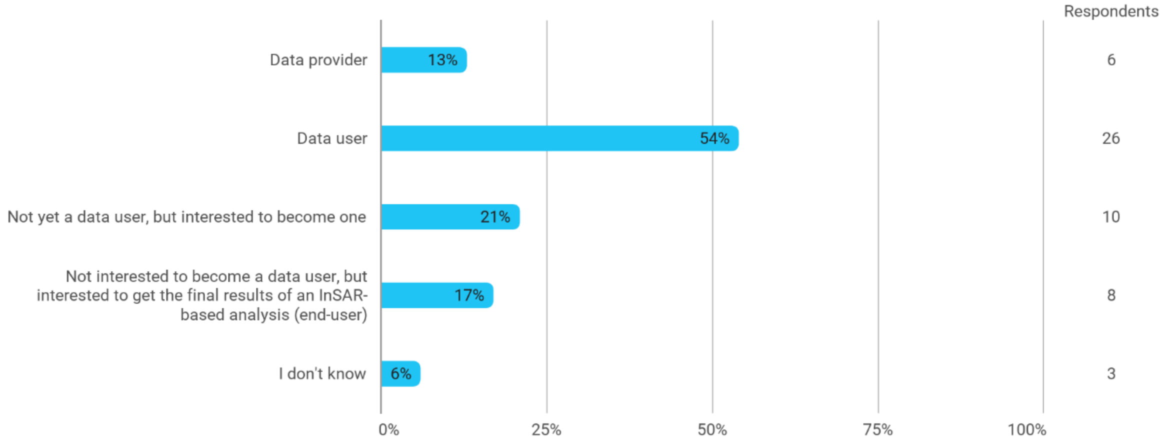


<u>What is your field of work? - Other:</u>

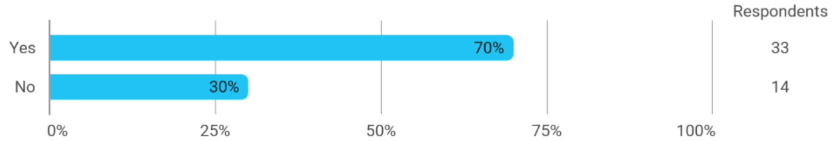
- Kulturmiljøvern *(English: Cultural Heritage Protection)*
- Kartproduksjon *(English: Map Production*)
- Permafrost, Engineering
- Permafrost
- Atmosfære *(English: Atmosphere)*

- Geoteknikk *(English: Geotechnics)*
- Eiendomsforvaltning *(English: Real estate management)*
- Geography
- Fulltime Geographer with Geoinformatics Cartographics and Remote Sensing skills
- Seismology
- Salesforce Service Cloud Consultant
- Videregående *(English: high school)*
- Bygningsteknikk *(English: Building technology)*
- Kulturminnevernet *(English: Cultural Heritage Protection)*

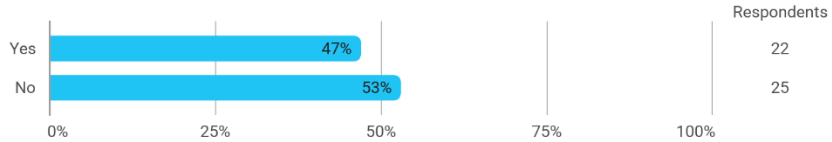
<u>Question 5</u>: How do you work with InSAR data?



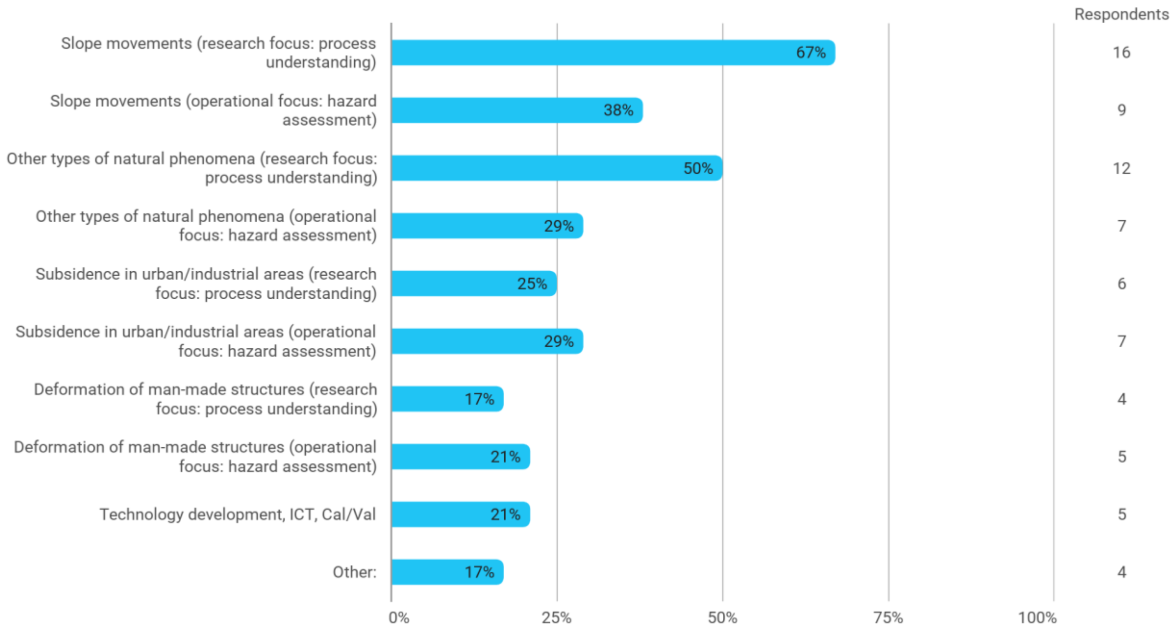
<u>Question 6</u>: Do you know about InSAR ground motion services in the mainland (insar.ngu.no or egms.land.copernicu.eu)?



<u>Question 7</u>: Have you already used datasets from InSAR ground motion services in the mainland (insar.ngu.no or egms.land.copernicu.eu)?



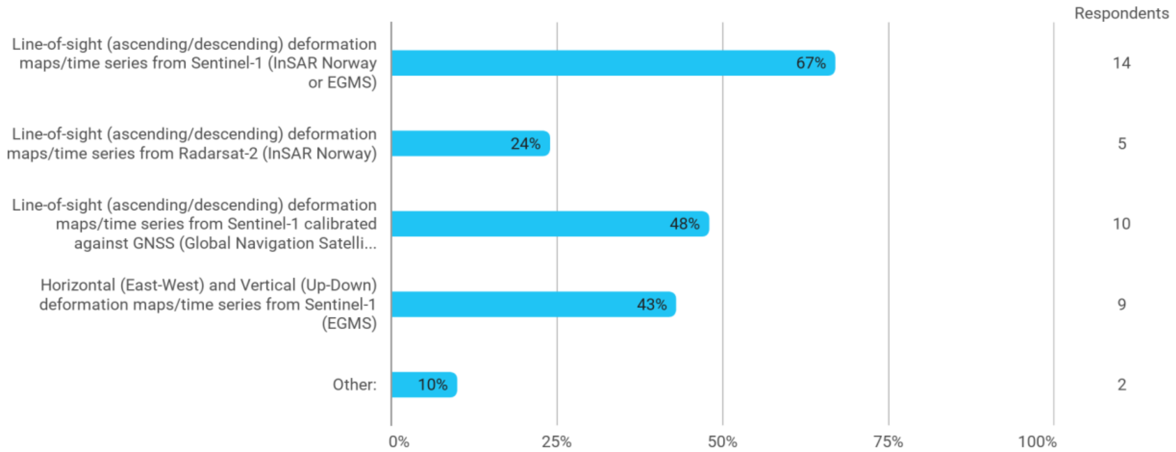
<u>Question 8</u>: If yes: For which purpose(s) have you used datasets from the existing InSAR ground motion services?



<u>If yes: For which purpose(s) have you used datasets from the existing InSAR ground motion services? - Other:</u>

- Subsidence of permafrost areas
- Vurdering av pågående setninger *(English: Assessment of ongoing subsidence)*
- Displacement assessment
- Ikke benyttet *(English: Not used)*

<u>Question 9</u>: If yes: Which dataset(s) from the existing InSAR ground motion services have you used?



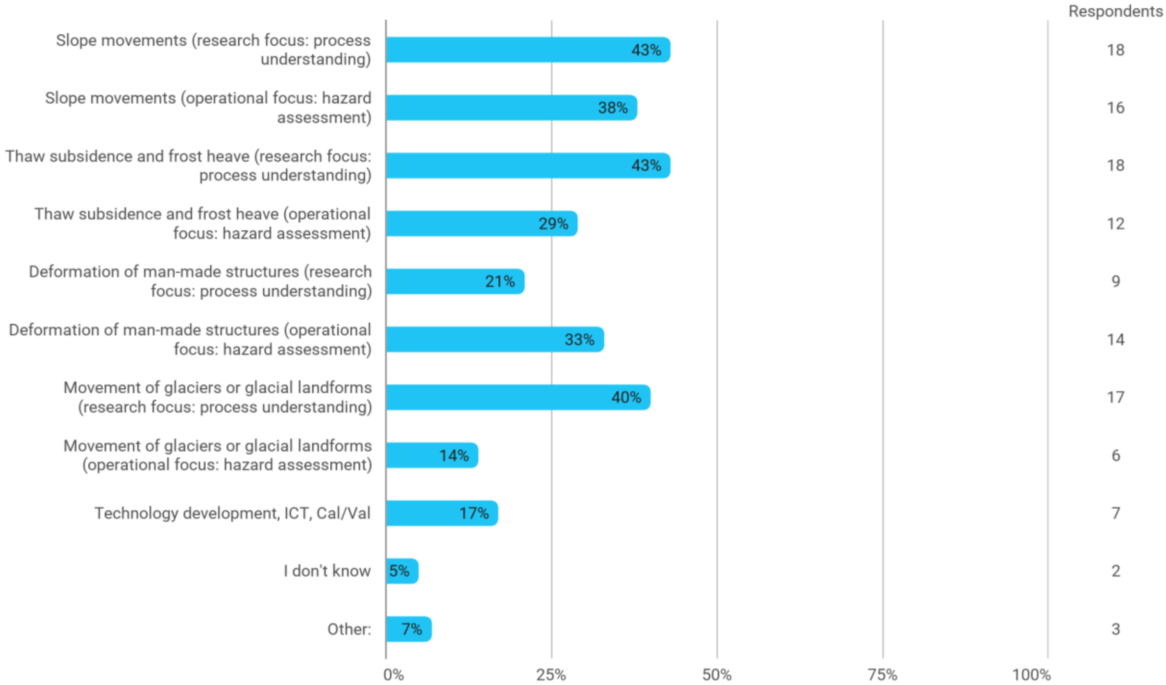
<u>If yes: Which dataset(s) from the existing InSAR ground motion services have you used? - Other:</u>

- TerraSAR-X
- Ikke benyttet *(English: Not used)*

<u>If yes: Do you have any comment regarding the existing InSAR ground motion services? Ideas for improvements?</u>

-

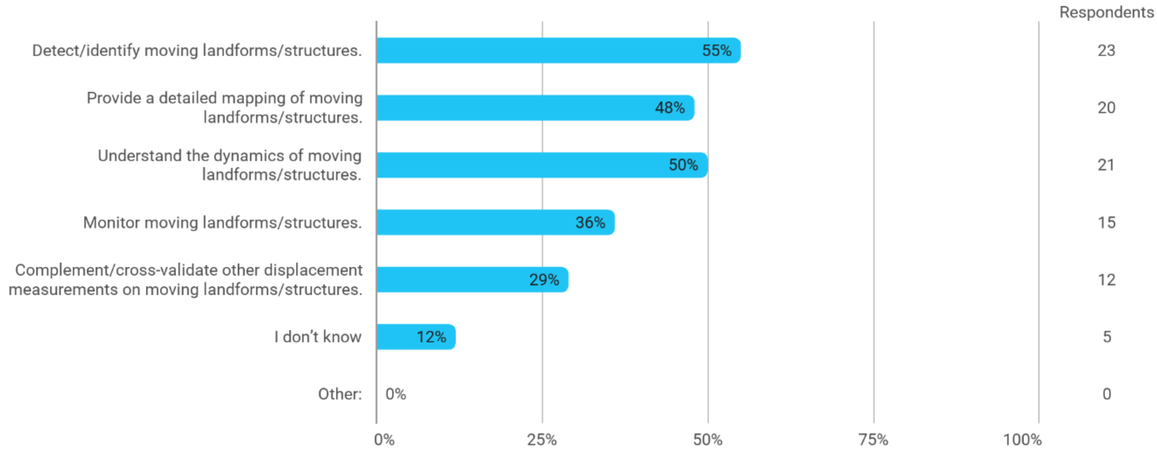
Question 10: For which application(s) would you be interested to use InSAR data in Svalbard?



For which application(s) would you be interested to use InSAR data in Svalbard? - Other:

- Pågående setninger *(English: Ongoing subsidence)*
- The general deformation patterns
- Combination with digital outcrop models from www.svalbox.no

Question 11: What is the main value of InSAR data for your application(s) in Svalbard?



What is the main value of InSAR data for your application(s) in Svalbard? - Other:

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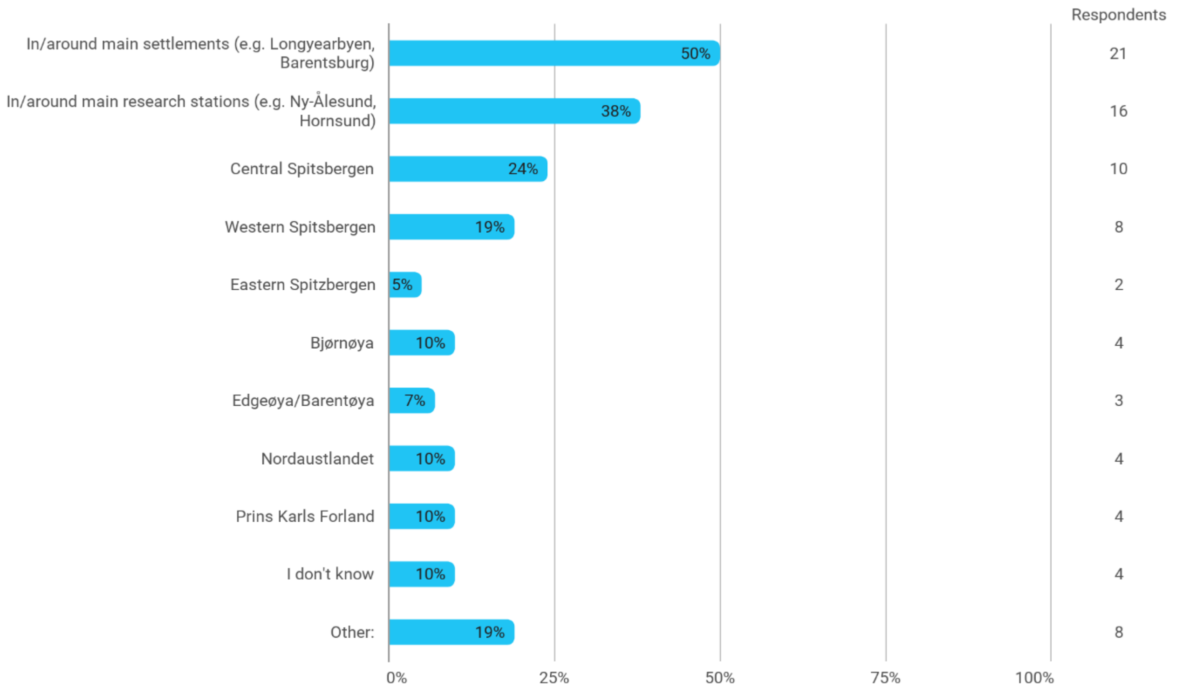
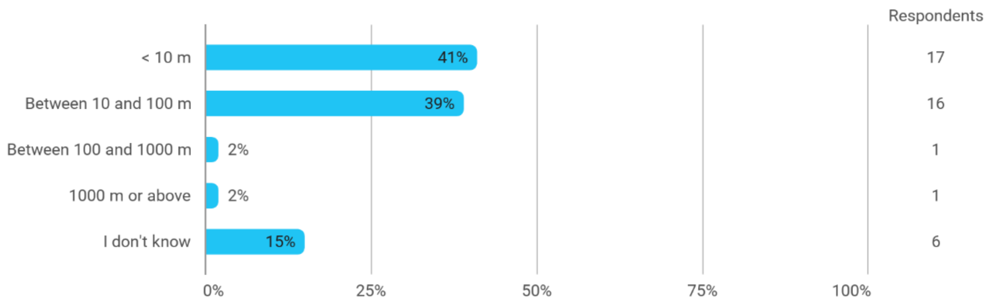
<u>Question 12</u>: What is your main area of interest in Svalbard?



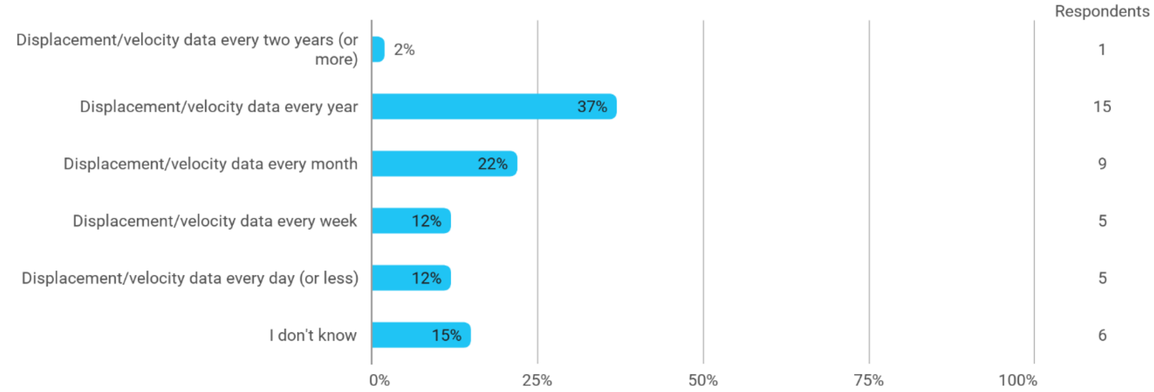
<u>What is your main area of interest in Svalbard? - Other:</u>

- Sørkapp Land, Southern Spitsbergen
- Hele Svalbard *(English: The entire Svalbard)*
- Svalbard lufthavn *(English: Svalbard Airport)*
- Hele Svalbard *(English: The entire Svalbard)*
- Entire Broegger Peninsula
- Ice free plateau areas, plateau blockfields
- Svalbard generelt *(English: Svalbard in general)*
- Southern Spitsbergen

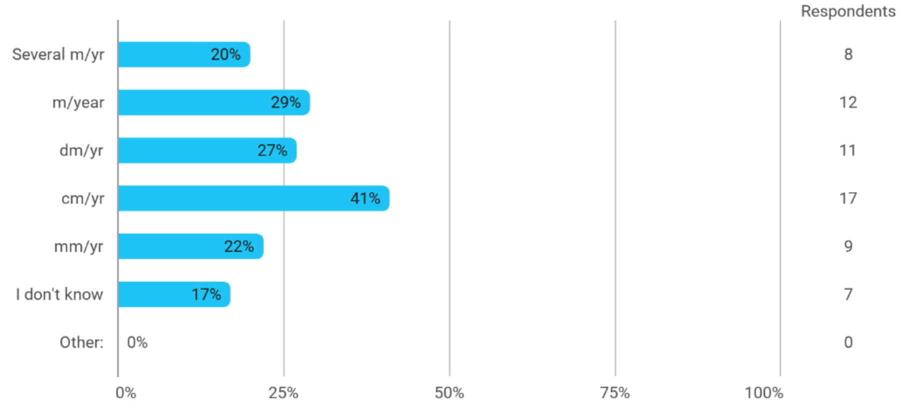
<u>Question 13</u>: What is the minimal spatial resolution of the displacement datasets required by your main application?



<u>Question 14</u>: What is the minimal temporal resolution of the displacement time series required by your main application?



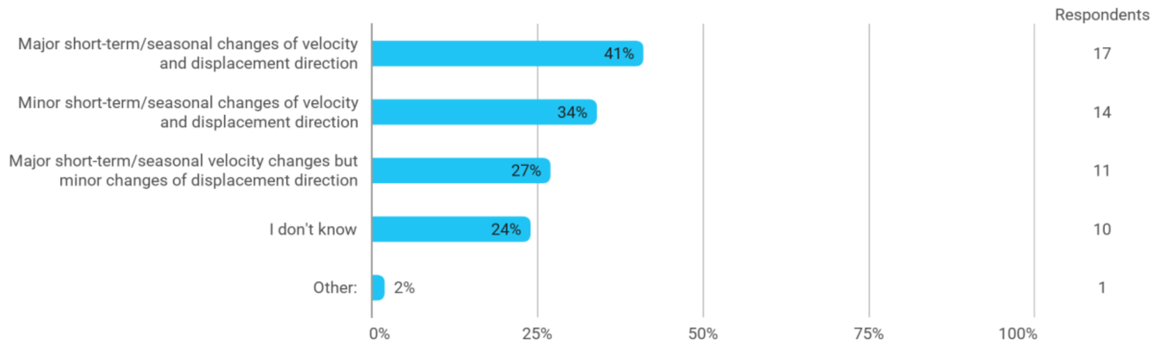
<u>Question 15</u>: What is the expected maximal velocity or annual amplitude of the displacement related to the processes you are interested in (order of magnitude)?



<u>What is the expected maximal velocity or annual amplitude of the displacement related to the processes you are interested in (order of magnitude)? - Other:</u>

-

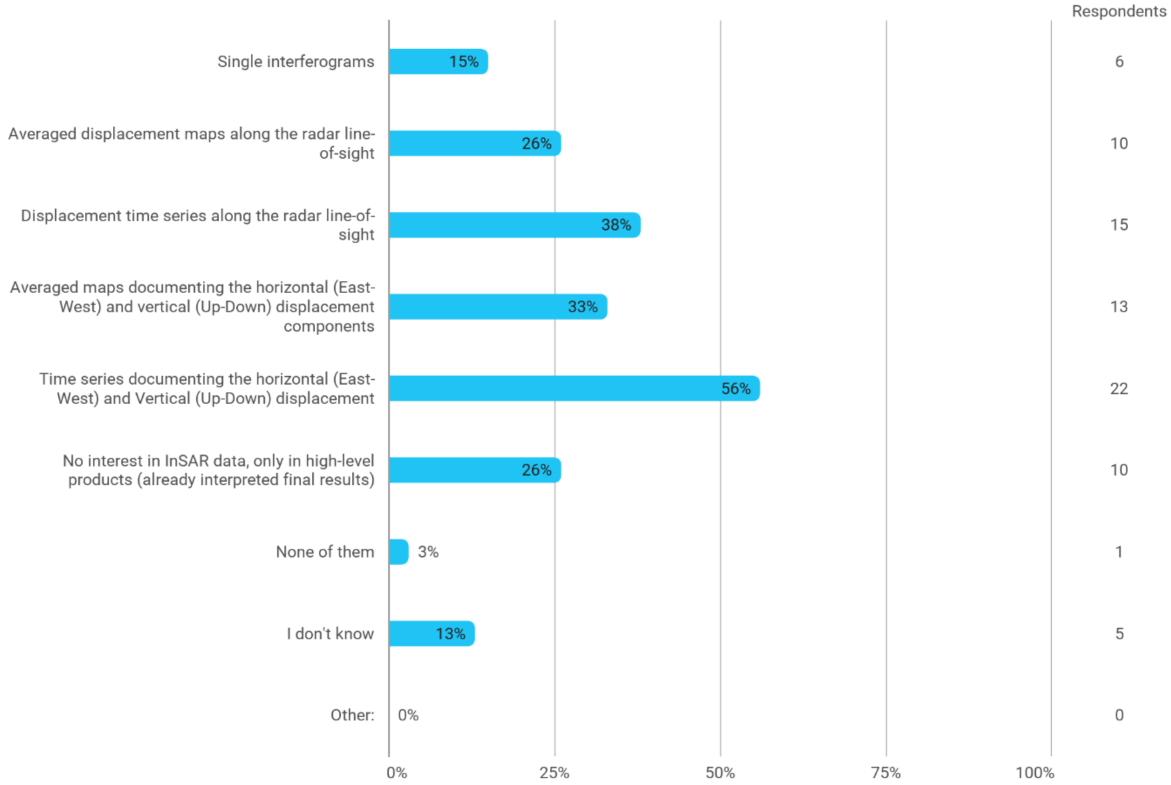
<u>Question 16</u>: What is the expected intra-annual / seasonal behaviour of the processes you are interested in?



<u>What is the expected intra-annual / seasonal behavior of the processes you are interested in? - Other:</u>

- Egentlig alt mulig :) *(English: Actually, everything that is possible)*

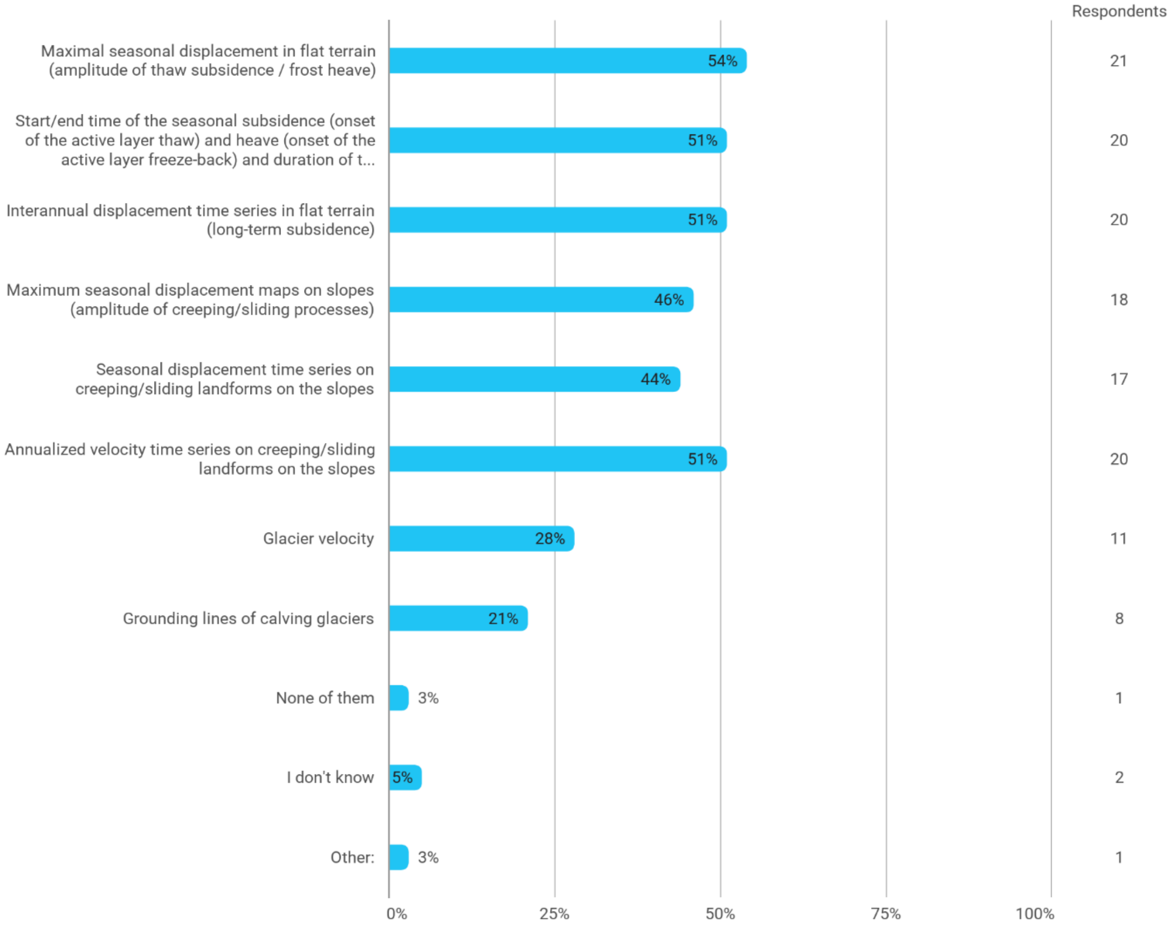
Question 17: Which type(s) of InSAR data are you interested in?



Which type(s) of InSAR data are you interested in? - Other:

-

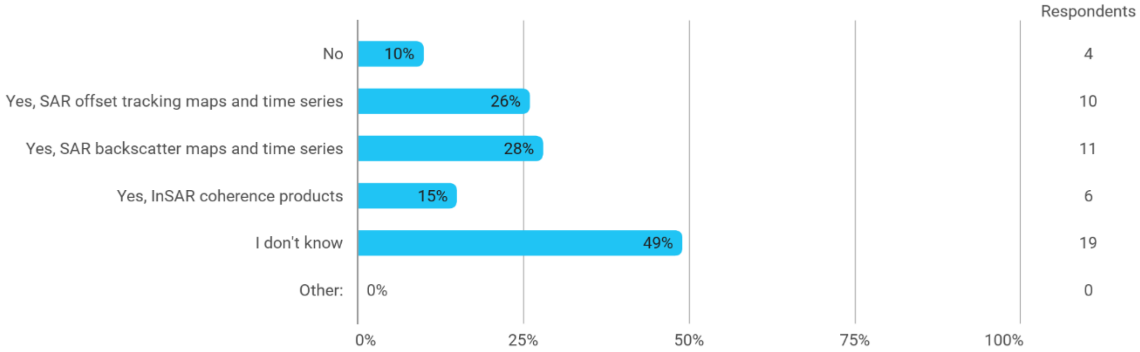
<u>Question 18</u>: Which of the following high-level InSAR products could interest you?



<u>Which of the following high-level InSAR products could interest you? - Other:</u>

- Separate product that focusses on very slow movements of low angle slopes and plateau areas

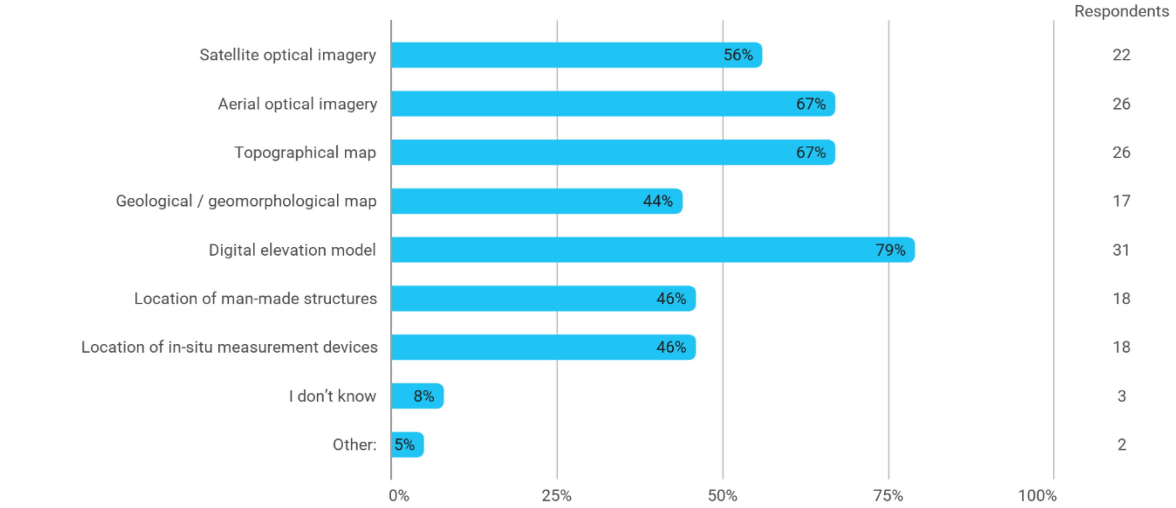
<u>Question 19</u>: Are other SAR-based datasets actual for your studies?



<u>Are other SAR-based datasets actual for your studies? - Other:</u>

-

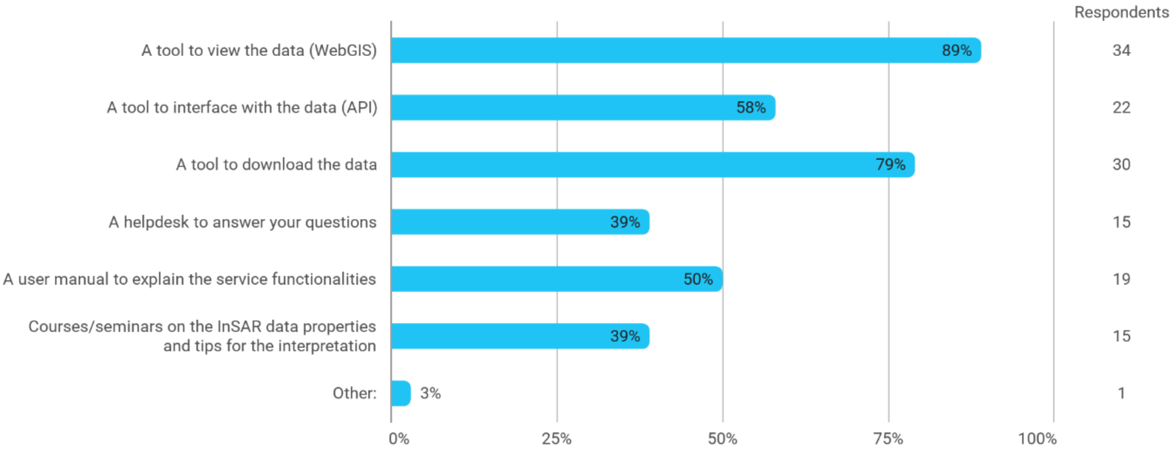
Question 20: Which other datasets necessary to your application(s) would be valuable to visualize in the same webportal as the InSAR data?



Which other datasets necessary to your application(s) would be valuable to visualize in the same webportal as the InSAR data? - Other:

- Seismic stations and data
- Svalbox doms - can be shared already now

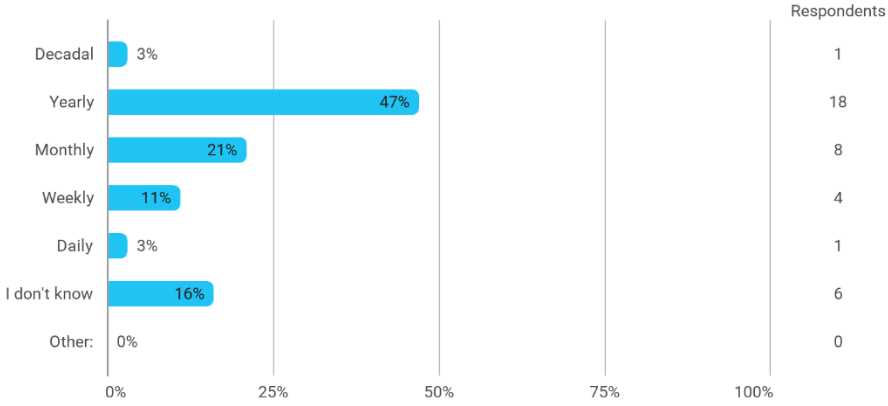
Question 21: Which services should an InSAR Svalbard GMS include?



Which services should an InSAR Svalbard GMS include? - Other:

- Vet ikke *(English: Do not know)*

<u>Question 22</u>: For your main application, which update of new data delivery is necessary?



<u>For your main application, which update of new data delivery is necessary? - Other:</u>

-

<u>Other comments?</u>

- Thanks a lot and sorry for late reply :)