Geo-data for risk management in a changing Arctic

"If we don't measure, we don't know."

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WGIC World Geospatial Industry Council

FUGRO

Foreword

The World Geospatial Industry Council (WGIC) wants to amplify the Calls for Action from the Arctic Observing Summits, past and present (AOS'). This paper and others will show the significant and widespread impacts in the Arctic from the Earth's changing climate on its peoples, environment, and infrastructure. We must leverage all the work being done in both the public and private sectors to better address these impacts and mitigate future challenges.

Advances in data acquisition, storage and management, and innovation in geospatial tools, technologies and services are continually emerging. These innovations often arise from the private sector, given their flexibility, access to talent and speed-to-market. Partnerships between and among public and private organisations need to be communicated, encouraged, and strengthened.

Events, such as the AOS, have historically done a wonderful job bringing academia, citizen groups, indigenous peoples, non-profit organisations, and the public sector together. AOS is, now, to be commended for opening-up its Arctic dialogue to the private sector. This white paper is endorsed by WGIC (a not-for-profit trade association of private companies working in the geospatial and Earth observations sectors) and developed by Fugro with input from e-GEOS. In this way, WGIC can provide an overview of existing and planned capabilities of its members, thereby ensuring private-sector capabilities are being leveraged to the greatest extent possible.

Time is of the essence. No single organisation, government or country can solve the climate challenge alone. We must do a better job working across our organisational entities. This effort signals our commitment to ensuring that the most up-to-date technologies and services are understood, accessible and utilised to address the Arctic's changing environment.

Barbara Ryan
Executive Director, WGIC
March 2022

For millennia the Arctic region was the realm of people who adjusted their lives to the harsh polar environment only infrequently visited by often ill-fated adventurers. With the onset of global climate change the future outlook for this region is increasingly uncertain, temperatures are rising twice as fast as the global average, and as a result of permafrost thaw and sea ice melting the locally built environment is threatened and economic parameters are changing. This is both a challenge and an opportunity for the ecosystem and livelihood of the local population.

This white paper shows the geospatial frameworks and technology enablers for policy and decision-making, not instead of local knowledge, but in support of it. It is also a testament to the breadth of applications and solutions the geospatial industry provide to address global societal challenges, like climate change, sustainable infrastructure and energy transition.

On display are state-of-the-art technologies that have developed over decades, but can now, in the age of digitalisation and remote operation, be converged to a single source of truth. This provides valuable input into building solid policies and keeping stakeholders equitably informed, enabling local policy makers to utilise the most accurate data to balance the challenge and opportunity for 5 million Arctic inhabitants.

We as a company are dedicated to contribute to a safe and liveable world.

Robert Hoddenbach
Global Director – Land Asset Integrity, Fugro
March 2022

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1. Introduction

The Arctic region is warming more than twice as fast as the global average, as shown by recent studies[1]. This is observed through decreasing sea ice, snow and glaciers as well as thawing permafrost. Permafrost covers around a quarter of the northern hemisphere's land surface while accounting for nearly half of all organic carbon stored within our planet's soil. A variety of climatic feedbacks can cause permafrost thaw to accelerate global warming even further, making it a grave (and yet lesser discussed) threat to Arctic residents, ecosystems, economies, and overall health of our planet in four key ways[2]: erosion, destabilising infrastructure, floods and forced migration, and diseases.

Arctic coastlines have seen an average erosion rate of nearly half a meter per year over the last 50 years. The Arctic permafrost, including Russia, North America and Scandinavia, is home to 5 million people, at least 120,000 buildings, 40,000 km of roads and 9,500 km of pipelines, as well as airstrips. 70% of infrastructure and 30-50% of critical infrastructure in the Arctic is at high risk of damage by 2050, with projected cost of tens of billions of dollars[3]. As global warming is expected to continue for decades, these trends are expected to continue.

In this paper, we focus on the risks of multiple climate change impacts including permafrost thaw, reduced sea-ice and glaciers, and sea-level rise on (critical) infrastructure and coastlines, to demonstrate the role of geo-data in understanding, predicting and mitigating these risks. We illustrate a selection of geospatial and geophysical *technology enablers* (characterised by having a high degree of innovation and the ability to offer solutions that respond to the challenges imposed by users and current demands[4]) that contribute towards understanding and adapting to the changing Arctic.

2. Geo-Risk Management Framework

The Geo-Risk Management Framework or GRMF[5,6] is a framework developed by Fugro that guides approaches to managing risk associated with the development and management of natural and built assets, for a safe and liveable world. It provides a unique conceptual framework for risk-managing decisions to be made, centred on the need to identify and reduce time-dependent uncertainties relevant to transient and permanent stakeholders.

The GRMF is implicitly flexible and applies to all risk environments including infrastructure development in Arctic regions – effectively a starting point for building a tailored approach to managing risk. Risk for natural and built assets largely arises from epistemic uncertainty (generalised by a lack of knowledge or information), and, if not effectively managed, risk can have negative

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[1] Yumashev, D., Hope, C., Schaefer, K. *et al.* Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nat Commun* 10, 1900 (2019)
[2] https://www.thearcticinstitute.org/permafrost-thaw-warming-world-arctic-institute-permafrost-series-fall-winter-2020/, accessed 1 February 2022
[3] Climate change destroying homes across the Arctic, https://www.bbc.com/news/science-environment-59915697, accessed 1 February 2022
[4] https://www.lisainsurtech.com/2021/02/09/know-everything-about-the-impact-of-technology-enablers/, accessed on 2 March 2022
[5] Eddies and Wood, Risk Managers of the Ground, *Ground Engineering*, May 2021
[6] Wood and Eddies, All in The Frame, *New Civil Engineer*, April 2021

consequences for stakeholder organisations that develop and manage natural and built assets. Epistemic uncertainty is a measure of the accuracy and completeness of understanding and predictability of the state, condition and structure of assets and of time-dependent performance or behaviour and of time-dependent processes acting on those assets. By identifying then reducing uncertainty, it follows that risk can be better managed. In Arctic regions, challenges that present future risk underpin the need for developing the right observational infrastructure.

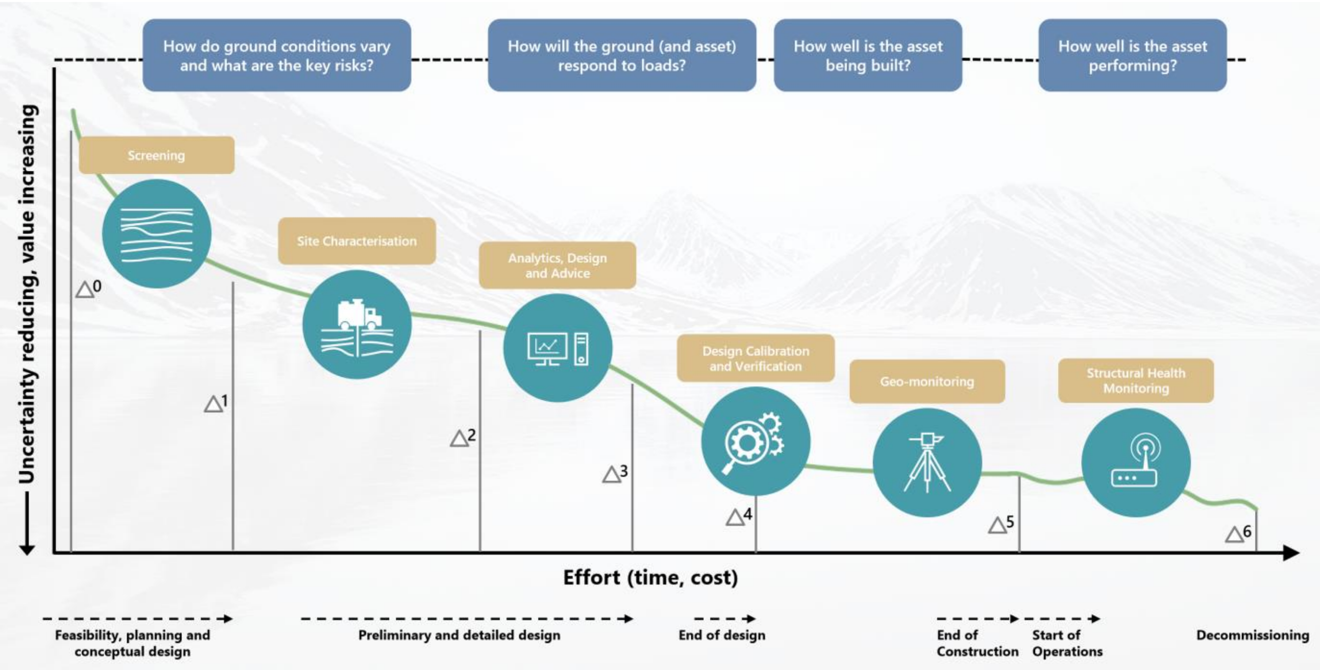


Figure 1. Example GRMF applied to risk associated with key phases of asset development. Solutions such as *Screening* that address key questions relating to uncertainty involve delivery at 'deltas' 1 through to 6 in this example. The 'deltas' are also data and information interfaces where information can add value to downstream activities. The GRMF provides a starting point to approach identification and reduction of epistemic uncertainty (the primary source of geo-risk) to acceptable levels. Innovation, technical development and operational excellence are the key drivers to steepening the value-add curve and to drive both efficiency and sufficiency.

Organisations developing and/or managing natural and built assets in the Arctic have business objectives or strategic end games relating to engineering, environmental and resource management activities. A deep understanding of stakeholder objectives is a pre-requisite to applying a consulting mindset to manage risks and translate this effort into tangible project or business value. Example stakeholders include policy makers and planners (e.g. risk management for prioritising strategic effort in a spatial sense), insurers (managing underwriting risk), asset developers (e.g. managing capex and schedule risks and effective risk transfer to other parties), designers (e.g. managing their own indemnity risks and capex risks on behalf of their clients), constructors (e.g. managing risks related to unforeseen ground conditions) and asset operators (e.g. managing risks related to opex).

Reducing uncertainty requires acquisition and analysis of the right geo-data at the right time to provide insights that are reconciled and consolidated into risk-management advice delivered to stakeholder organisations that develop and manage natural and built assets. Risk management addresses stakeholder uncertainties relevant to specific phases and delivery points of projects, for example at the planning or conceptual design phase.

The GRMF comprises linked or digitally connected solutions to help identify, investigate, analyse and then reduce these uncertainties. Solutions provide digital delivery through projects as context-specific mechanisms to deliver value-adding insights from geo-data that are necessary for effective risk management. Solutions are highly flexible, insight delivery mechanisms that are tailored from (solution) components assembled using a consulting mindset and are not necessarily off-the-shelf. Solution components include data acquisition, processing, modelling and visualisation technologies, digital workflows and digital delivery including cloud computing and data analytics as well as domain expertise to derive and communicate relevant insights. For example, a screening solution targeting characterisation of key geohazards relating to permafrost in a region for early evaluation of risks for existing or future infrastructure might draw upon satellite, airborne lidar and land geophysical screening technologies in addition to ground modelling, data integration, modelling, and permafrost engineering expertise.

Reduction of uncertainty leading to value-add requires effort (factored into time and cost) to be expended by stakeholder organisations with interests in Arctic regions. It follows that reducing effort to achieve an equivalent or greater reduction of uncertainty drives both efficiency and sufficiency (as an example: how much investigation is enough?), positively impacting stakeholder budgets and schedules relating to the development and management of assets. A good understanding of stakeholder objectives is required to select appropriate solution components to build one or more appropriate (relevant) value-adding solutions.

Reduction of effort for a given objective of value-add can be driven by a number of mechanisms including operational excellence, innovation and development of improved technologies and methodologies such as digital connectivity and delivery, and remote and robotic operations. In general, early phases of asset development and management provide the greatest opportunity for stakeholders to positively impact their project outcomes at lowest cost; it follows that early reduction of uncertainty (intervention in the form of screening) can add significant value for stakeholders by helping to understand the key risks prior to the commitment of significant resources or effort.

3. Geospatial and geophysical technology enablers

Working on land, transition zone and offshore, the provision of integrated data acquisition, analysis and advice through tailored solutions developed within the GRMF helps to manage land and resources, as well as design, build and operate infrastructure in a safe, sustainable and efficient manner. Ideally, geo-data flows digitally between solutions resulting in continuous uncertainty reduction. A technology enabler is a tool that allows digital transformation to be possible, providing the advantages of geo-data interoperability, automation, cost reduction and improved operations[7].

Arctic geo-data operations fall into two broad categories:

- **Regional geo-datasets**: Utilising satellite data and/or performing wide-area collects such as topographic and hydrographic surveys, state-wide road condition surveys, terrestrial hydrology and shoreline mapping, just to name a few. These activities fall within the *Screening* solution

[7] https://www.lisainsurtech.com/2021/02/09/know-everything-about-the-impact-of-technology-enablers/, accessed on 2 March 2022

delivered at Δ1 in the GRMF (Figure 1). The primary consumers of these baseline geo-data are national or local governments who use them for land and resource management and policy/planning decisions, to model and predict how what we do now will impact future generations and the environment.

- **Site-specific ground characterisation**: For the private sector, the focus is on engineering data to support foundation design, siting and routing of land-based and marine infrastructure. In the Arctic, this translates into decisions like picking an optimal site for a village that may have to be re-located, or making and defending (sometimes in court) a particular routing alternative, or identifying what exactly is causing ground instability, for example. These projects are typically smaller in geographic scale but much more refined in accuracy, precision, and density of data typically delivered at Δ2 in the GRMF within the *Site Characterisation* solution (Figure 1).

In this section, we highlight geospatial and geophysical technology enablers in the context of three common challenges: 1) coastal hazards; 2) geological and infrastructure hazards related to degrading permafrost; and 3) geo-data management.

3.1 Coastal hazards

Flooding, erosion and landslides impact our natural and built environment, our lives and activities on the coast. Land and public works managers rely on coastal screening geo-data such as nearshore bathymetry, imagery and topography of the coastal uplands, hydrology, and vector shoreline among other datasets to understand a broad suite of risks including impacts to legal and geographic boundaries, resource ownership and - not the least - our public safety.

Coastal mapping data are critical for several reasons[8], including informed management of coastal lands, safe navigation in an ice-diminished Arctic, and responsible resource and energy exploration. Community resilience to coastal hazards such as flooding, erosion, and tsunami begins with mapping data to establish baseline conditions and model change.

Coastal zone geo-data acquisition challenges:

- Traditionally hard to get = white ribbon data gap on maps
- Remote and extreme environment increases risks, cost, pace of collection and regularity of refresh

In terms of acquiring and analysing the right geo-data, the coastal zone presents an acquisition challenge as it is too shallow, dangerous and inefficient for a marine vessel and inaccessible for a traditional land survey approach. We need to have fit-for purpose tools to access the areas that are the busiest in terms of use, yet the most challenging to survey, often leaving what is called a “white ribbon data gap” on maps. A systematic approach to mapping the shallow water, shoreline, and coast is therefore needed, for a seamless land-sea interface.

Advances in technology and innovation have helped in addressing this white ribbon data gap challenge on our maps. Efficiency, accuracy, detail and capability are the fundamental factors that

[8] https://iocm.noaa.gov/about/documents/strategic-plans/alaska-mapping-strategy-june2020.pdf, accessed 18 February 2022

need to be evaluated when selecting an appropriate remote sensing technology (solution components) for shallow water surveys as part of a screening solution.

3.1.1 Regional topographic mapping

3.1.1.1 Airborne lidar

The spatial resolution and coverage, repeatability, and capability of mapping vegetation heights as well as surface elevations below tree canopies make airborne lidar a powerful contributor to research-oriented and operational topographic mapping in the Arctic. High-resolution orthophotography is often acquired concurrently with the lidar data.

Airborne lidar data acquisition challenges:

- Timing collection to optimise with weather (clouds/fog)
- Snow cover on ground limits working window for lidar data acquisition; low sun angle limits photography window
- Need for anti-icing/de-icing equipment on aircraft
- Remote locations need long-range fuel tanks; safety concern in case of an issue
- Hangar needed for aircraft and equipment at night

Flight planning is critical to mission success, optimising the cost/accuracy trade-off, especially in rough terrain. Wider swaths allow greater areal coverage with fewer flight lines, and therefore can significantly decrease the data collection cost in the Arctic. This is however at the expense of laser point spacing and/or range accuracy.

After data collection, the raw lidar point cloud is classified into ‘terrain’, ‘vegetation’, ‘building’ or any other class of interest depending on the application. Point misclassification can induce errors in the final digital elevation model (DEM) - successful application of classification algorithms is therefore critical to the accuracy of the final DEM.

Fugro has built cloud-based, machine learning lidar production processes as a powerful and scalable solution component to manage and extract value from the massive amount of lidar data collected over wide areas as part of the screening solution. The highly efficient process automatically classifies even low density lidar point clouds to a quality that allows the production teams to focus on the important details to get the most out of the geo-data.

It is recommended that the entity involved in data acquisition and mission planning is also involved in the post-processing operations to minimise the introduction of errors and ensure geo-data of the highest achievable quality. As an example, Fugro has acquired and processed 26,144 km^2 of aerial lidar data in northern Sweden to support derivation of their national height model.

The number of successful ground returns, and therefore the final lidar point density, decreases inversely with canopy cover density. In Arctic areas dominated by tundra biome (moss, low-lying vegetation) lidar is an ideal tool for elevation mapping. In areas with thicker (boreal) forest cover, interferometric SAR (InSAR) is an alternative technology that can be utilised.

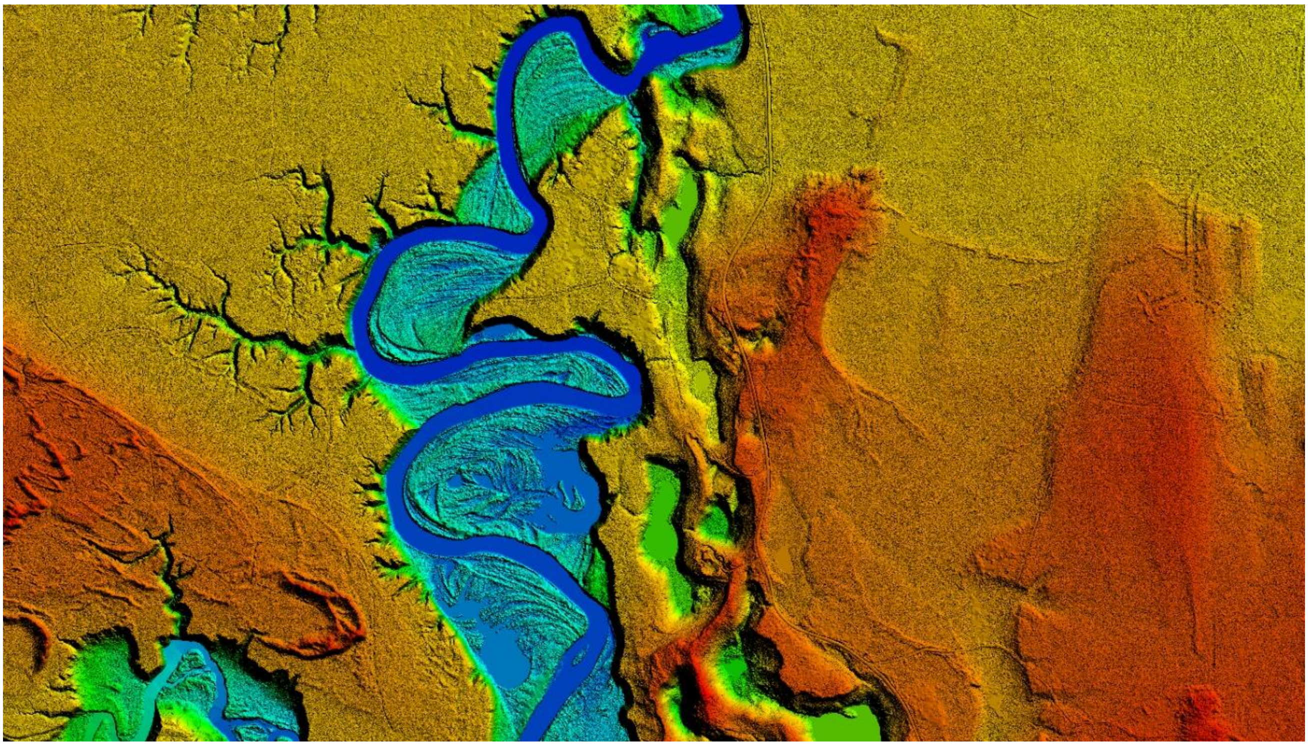


Figure 2. Example of a lidar-derived digital surface model (DSM) in Canada.

3.1.1.2 Airborne InSAR

As part of the Alaska statewide digital elevation mapping programme, Fugro acquired over 350,000 km^2 of airborne InSAR data, including parts in the Arctic, over one of the most challenging areas in the world – rugged, steep and heavily forested. The dual-band, dual-sided system collected X- and P-band radar data simultaneously from each side of the aircraft. X-band radar penetrates clouds and reflects from the tree canopy to deliver surface model data in forested areas and accurate terrain elevation in open areas. P-band radar penetrates both clouds and tree canopy to deliver terrain elevation and surface feature extraction in forested areas. This dual-band capability was therefore ideal for mapping Alaska's heavily forested regions.

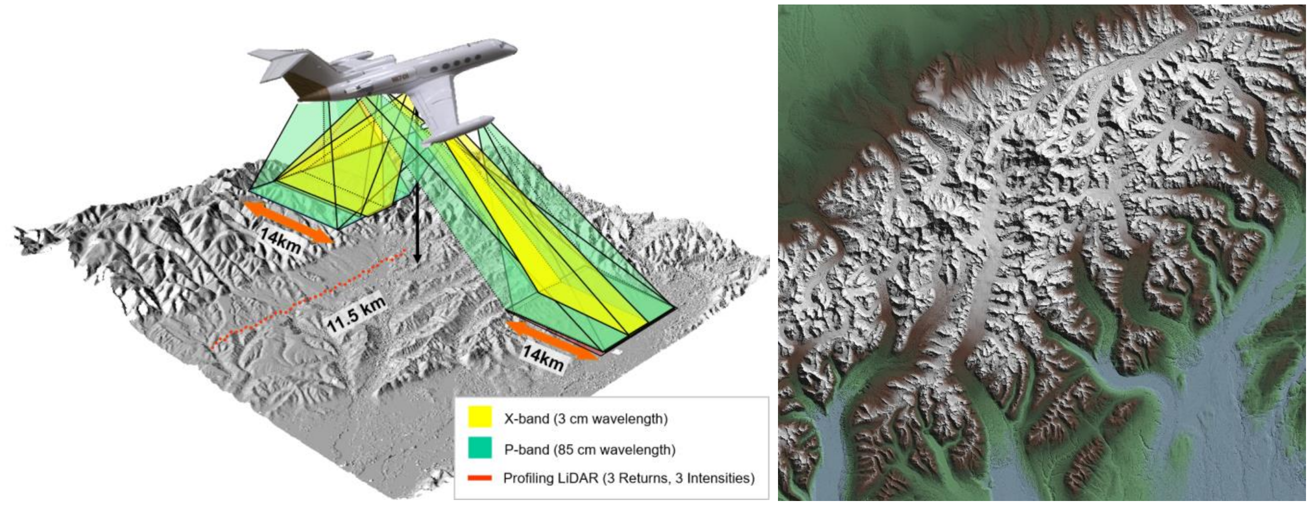


Figure 3. Left: The dual-band dual-sided InSAR system used in the Alaska statewide digital elevation mapping programme. Right: snapshot of a portion of the derived DEM, digitally delivered as part of a screening solution.

The dual-band capability was also ideal for mapping mountainous terrain. The system collected two independent "views" for every point on the ground, in each radar band. Flying successive parallel flight lines allowed the collection of overlapping data strips with four or more independent views. Each ground point was typically viewed twice from the left and twice from the right, at a steep and shallow angle to ensure highly detailed and complete datasets.

The system included a lidar profiler for on-board, high density ground control. The profiler vastly reduced the need for surveyed ground control points, reducing the time, cost, and dangers associated with field crews establishing ground control in remote and challenging areas.

3.1.2 Shallow water bathymetric mapping

In the 1990s, Fugro commercialised Airborne Lidar Bathymetry (ALB) as a part of a screening solution for mapping the coastal zone with a green laser from an aircraft vs. using sonar from a vessel. For optically clear waters, it is a much safer and cost-effective alternative to define the shoreline and shallow water depths. In 2018, Fugro and Areté Associates developed a new generation of ALB sensor called Rapid Airborne Multibeam Mapping System (RAMMS) as part of a screening solution within the GRMF delivering insights at planning and feasibility.

ALB acquisition challenges:

- Timing collection to optimize with weather (clouds/fog, melting/floating ice).
- Water unclarity and aquatic vegetation (kelp) limit data quality. Dedicated water clarity analysis is paramount for effective planning.
- Need for anti-icing/de-icing equipment on aircraft.
- Remote locations need long-range fuel tanks; safety concern in case of an issue. Lighter ALB systems such as the RAMMS can use smaller and locally available fixed-wing aircraft or uncrewed aerial systems (UAS), and can reach more remote areas with shorter dirt or gravel runways
- Hangar needed for aircraft and equipment at night.

Fugro RAMMS is a solid-state sensor, with no moving parts (eliminating the need for a massive cooling system), and therefore weighs less than 15 kg. It is easily mobilised, and delivers high-quality coastal and nearshore bathymetric datasets, with deep-channel lidar penetration (3x Secchi depth). RAMMS can be deployed on its own or combined with other remote sensing technologies to address a wide range of bathymetric, topographic, and imagery needs (including multi-/hyperspectral) from a single airborne mission (typically covering >100 km^2/day) - reducing time, risk and carbon footprint. Lastly, but importantly, this technique is non-intrusive to local marine wildlife and critical habitats.

The white ribbon data gap, particularly in the Arctic where it is the most significant, is thus being filled more efficiently (e.g. in the Canadian Arctic), and can enable our collective transition to alternative energy sources such as offshore wind and tidal energy, smart harvesting and food production from coastlines, as well as better infrastructure planning and safer navigation. Satellite imagery and water clarity analyses are used to pre-screen vast regions of the Canadian Arctic to select those that are best suited for the RAMMS lidar approach.

Figure 4. Fugro RAMMS installed on UAS.

3.1.3 Vessel-based hydrography

At the limits of ALB, acoustics take over to capture seafloor and water column data via crewed and uncrewed platforms as part of a screening solution. Vessel-based sonar remains the workforce of all hydrographic and ocean-floor mapping beyond the extinction depth of optical sensors.

As an example, since 2006 Fugro has acquired over 140,000 km^2 of survey data to the Norwegian Hydrographic Service as part of the Mareano[9] seabed mapping programme, financed by Norway's Ministry of Trade, Industry and Fisheries, and the Ministry of Environment. The high resolution seamless dataset includes bathymetry, normalised backscatter, water column imaging and gravimetry.

For survey planning and duration, hydrographic experts take several factors into consideration:

- MBES performance (including statistics from previous years vs. survey area environment)
- Sound velocity / salinity management
- *A priori* estimated error budget vs. survey specification
- Vessel workability based on weather conditions, buoy statistics and wave datasets
- Statistical ice conditions and online ice monitoring for operational decisions
- Other logistical considerations

A poor understanding (and late information) of ice condition in the survey area may:

- Impact operational decisions with respect to survey area priority
- Cause difficulties keeping straight survey lines during normal survey operations (may lead to poor sounding quality)
- Cause difficulties managing sound velocity/salinity casting
- Lead to unnecessary and unpredictable transit time between survey areas (free of ice)
- Drift ice can affect the quality of the sounding data

[9] https://www.mareano.no/en, accessed on 22 February 2022.

3.1.3.1 Arctic vessel compliance

The Polar Code[10] contains international standards on matters such as ship design, anti-pollution regimes, crew training and safety. This fosters international research and exchanges to further improve the design and construction of ships and equipment, operational, training, search and rescue procedures, and work on the environmental protection of the polar regions.

The Code brings in a requirement for Polar Ship Certificates whereby all ships transiting polar waters are classified within three categories:

- Category A ship: Ship designed for operation in polar waters *at least in medium first-year ice*, which may include old ice inclusions;
- Category B ship: Ship not included in A, designed for operation in polar waters *in at least thin first-year ice*, which may include old ice inclusions; or
- Category C ship: Ship designed to operate in open water or in *ice conditions less severe* than those included in Categories A and B.

In order for a ship to be issued with a certificate, an assessment is required. The assessment takes into account the anticipated range of operating conditions and hazards the ship may encounter in the polar waters, information on identified operational limitations, plans/procedures and additional equipment necessary to mitigate incidents with potential safety or environmental consequences. It must be noted, however, that the classification of ships under the Code does not link the ice-classes of ships with the actual ice conditions prevailing in the polar regions.

Vessel-based hydrography data acquisition challenges:

- Limited time of the year without ice and drift ice to conduct survey operations
- Long transit times for port calls, bunkering, crew changes
- Limited communication and satellite internet onboard the survey vessel
- Consideration of restricted areas and wildlife protective areas (e.g. finding suitable shelter positions for the vessel)

It is therefore very important, if using a Polar Class C vessel, to have complete understanding of expected and predicted ice conditions, and even more importantly have real-time information to make the right operational decisions to successfully manage key risks.

To summarise the experiences from the Mareano project, it is possible to undertake a large-scale successful bathymetric survey campaign within the challenging Arctic environment through the use of experienced hydrographers and marine crew, thorough survey planning and scheduling, adequate vessels and survey equipment, a deep understanding of environmental conditions and sound velocity/salinity management, as well as robust data quality assurance/control.

Finally, for coastal infrastructure applications, a combination of vessel-based MBES with a mobile lidar fitted on the vessel enables simultaneous collection of data above and below the water line, capturing

[10] https://www.imo.org/en/OurWork/Safety/Pages/polar-code.aspx, accessed on 22 February 2022.

under-tree overhang, cliff undersides, under structures, or to ensure bank overlap when water levels change.

Figure 5. Left: Example vessel used for Arctic seabed mapping. The vessel must comply with the Polar Code Regulation and Radio certification A4. Right: Current geographical boundaries of polar waters (both Arctic and Antarctic) where the Polar Code is applicable.

3.1.3.2 Ice-related geo-data

Utilising multibeam sonar, digital photogrammetry, and motion compensation technologies as part of a *Screening* solution, complex iceberg properties above and below the waterline can be digitally delivered for ice engineering, ice management, and risk mitigation. The resulting high-density 3D iceberg models enable multiple applications including impact analysis, drift prediction, and in-field ice management, among others.

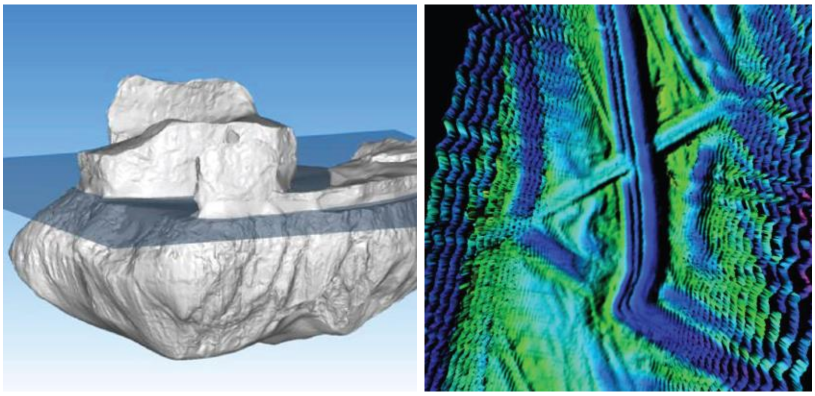


Figure 6. Examples of a 3D iceberg model (left) and an ice gouge dataset (right).

MBES (including backscatter), sub-bottom profiler, and sidescan sonar technologies are used to derive a high resolution digital elevation model of the seabed. This provides critical information about contemporary and historical ice gouging, e.g. the depth, frequency, and relative age of ice gouges to inform Arctic infrastructure design and installation.

Fugro has been undertaking a multi-year ice monitoring programme in the waters surrounding Svalbard since 2015. The subsea metocean moorings record ice draft and velocity data, with the moorings recovered annually during the open water season for servicing and data processing. The data allow an appreciation of the variability of sea ice thickness from year to year, and provide a better understanding of the operational uncertainties and risk factors associated with working in the region.

3.1.4 Satellite imagery supporting hydrography and charting

Satellite imagery has numerous valuable applications in habitat characterisation and exploration and is an integral part of the screening solution within the GRMF. In the context of baseline mapping, we also use satellite imagery to map uncharted hazards or changes from the baseline, thereby de-risking and optimising the acquisition approach by a marine vessel using MBES or by an aircraft using lidar.

Fugro, for the Norwegian Mareano programme, was able to test the Ice Pad developed by MARSAT[11]. Vessels operating at higher latitudes with very limited satellite bandwidth can download pre-processed Copernicus satellite images. These images are made available in small tiles. At first instance the image is downloaded in low resolution only, and the user can decide to download high resolution images if more detailed information is needed. In this way, the vessel receives up-to-date information, a few hours after a new satellite image becomes available.

What do we do when we have a choice between no survey and an old survey? As an example, Fugro has helped the US National Oceanic and Atmospheric Administration (NOAA) to update nautical charts off the northern coast of Unimak Island, Alaska. Located in the Bering Sea, the island supports multiple fisheries, a major transit route, and at-sea cargo transfers. Existing charts in the region do not meet current navigational needs, with data in some cases predating the 1940s. Fugro is helping NOAA address these data deficiencies with new, high resolution bathymetry over five sites totalling approximately 1700 km^2. These geo-data are used to produce new nautical charts, making marine navigation safer and more efficient.

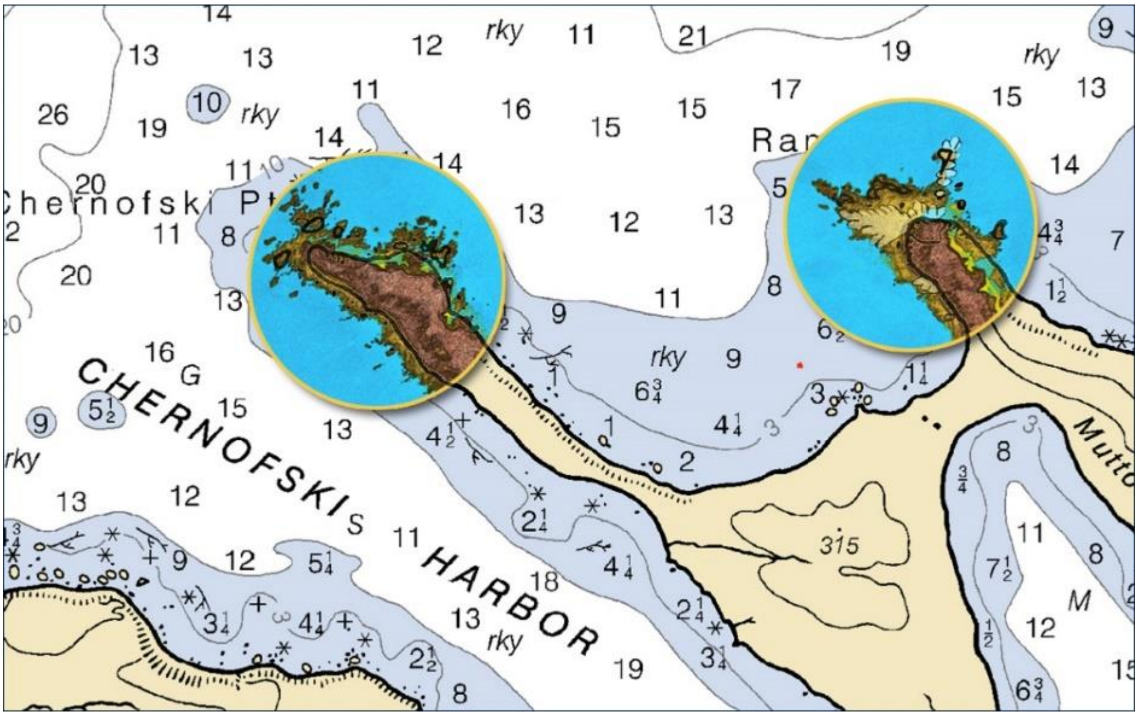
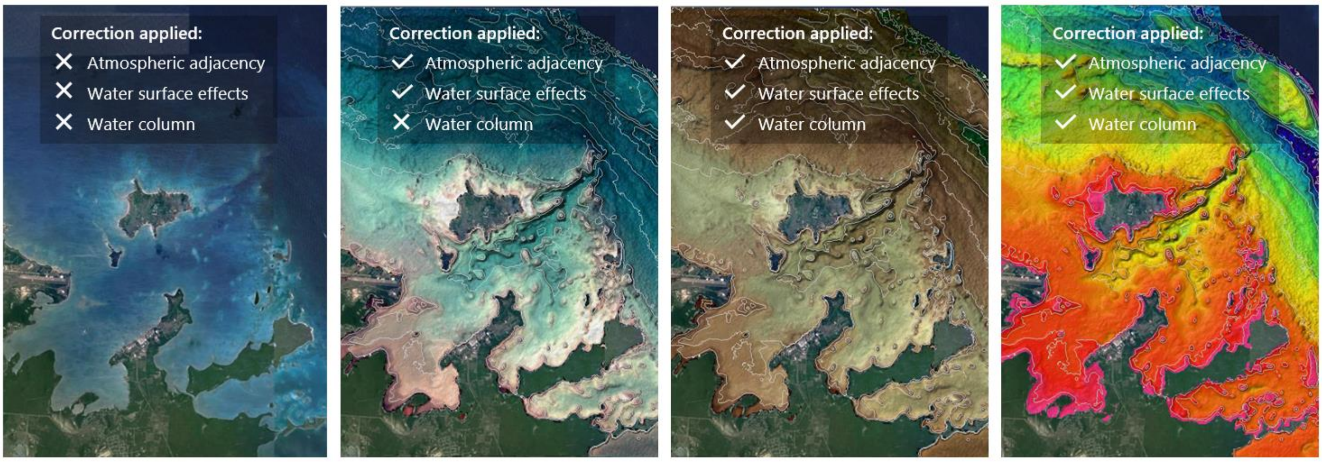


Figure 7. Fugro is using its SatRecon service to plan safe and efficient survey operations around Unimak Island, Alaska. The inset images show the difference between charted features on existing nautical charts and current seafloor morphology, made visible through advanced satellite processing algorithms.

[11] https://www.dlr.de/content/en/articles/news/2016/20160729_marsat-assisting-the-maritime-world-from-space_18791.html, accessed on 22 February 2022.

The new bathymetry was acquired from two MBES-equipped survey vessels, one focused on nearshore waters, the other on deeper waters located farther offshore. To plan the more challenging nearshore surveys, Fugro employed its SatRecon service, which combines satellite imagery and proprietary processing techniques for the identification of potential unmapped hazards such as shipwrecks and rock outcrops. It is qualitative data visualisation technique (not a bathymetric product) that is designed to make information in a satellite image or series of images more visually intuitive. In addition to improving the safety of crew, equipment and the environment, identifying these hazards also increased geo-data acquisition efficiency, allowing crews to survey the nearshore waters at a faster rate than would have otherwise been possible.

The SatRecon technology is also used in interpreting seabed bedforms and changing coastlines for Law of the Seas projects in which absolute knowledge of bathymetry is not required. The United Nations Convention on the Law of the Seas (UNCLOS) is an international agreement that defines the rights and responsibilities of nations with respect to their use of the world's ocean[12]. However, a number of potential maritime boundary segments in the Arctic Ocean remain to be delimited, creating uncertainty for the coastal countries involved. Defining the area of the Arctic seabed and subsoil in which circumpolar countries exercise sovereignty is critical to their interests in resource management, energy security and environmental protection[13].



General information, but typically not well suited for aquatic and benthic analysis.

More detailed information on geomorphologic zoning, spatial and spectral patterns of the seafloor and benthic habitats.

Very detailed information on geomorphologic zoning, spatial and spectral patterns of the seafloor and benthic habitats. Represents clear view to the surface being corrected for water column effects and perfect baseline for benthic habitat mapping.

Bathymetric information in a dense grid. Data are mapped using EOMAP's physics-based inversion algorithms.

Figure 8. From satellite imagery to seabed morphology, habitat mapping and bathymetry.

In shallow water, satellite-derived bathymetry (SDB) can provide robust and accurate depth determination from multispectral satellite imagery. The main challenge of applying optical satellite imagery-based techniques in the Arctic is the availability of suitable images that are ice-free and cloud-free, usually within a narrow window from July to September/October. Additional concerns are the atmospheric correction models that are less accurate due to limited observations, and limited

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[12] https://www.thearcticinstitute.org/wp-content/uploads/2016/04/TAI-Quick-Start-to-UNCLOS.pdf, accessed on 3 February 2022

[13] Bekker, P., & van de Poll, R.. Unlocking the Arctic's Resources Equitably: Using a Law-and-Science Approach to Fix the Beaufort Sea Boundary, *The International Journal of Marine and Coastal Law*, 35(2), 163-200 (2019)

survey data available to validate with ground truthing. SDB methods that rely on physics-based modelling[14] of light penetration through the water column do not require ground truthing. Accuracies could be however improved with *in situ* control points, which are seldom available in the Arctic region. Beyond depth measurement, the SDB process delivers information on water column properties and enable benthic or geomorphologic mapping.

An EU-funded research project called 4S (Satellite Seafloor Survey Suite)[15] is developing an online cloud-based solution that leverages machine learning, data analytics and cloud processing on multispectral satellite imagery to derive bathymetry, morphology, seafloor and water column properties to de-risk marine site characterisation in shallow water, supporting hydrography, coastal resilience modelling and environmental services.

To summarise, complex coastal environments typically require more than one technology to achieve the optimum mapping solution. An integrated screening approach utilising satellite imagery, airborne lidar, SDB, ALB and MBES enables delivery of quality geo-data cost-effectively, thereby providing critical and timely inputs for risk management of the coastal zone.

3.1.5 Collect once, use many times

Having high quality 3D maps of Arctic regions and coastlines enables its use in a variety of different applications, often unforeseen in the original objectives. For example, in addition to elevation mapping, the Alaska InSAR dataset described in Section 3.1.1.2 was used for:

- *Search and rescue*: In the aftermath of a plane crash in the area, Fugro provided unscheduled emergency delivery of InSAR data to help assess avalanche danger for recovery crews. The data proved essential in assessing potential avalanche danger for recovery crews on the scene.
- *Ice thickness mapping*: While mapping in high elevations and over glaciers, Fugro determined that P-band radar could penetrate deep into snow and ice. This discovery led to a new mapping capability developed in partnership with NASA JPL and the University of Alaska Fairbanks to characterise ice type and thickness for engineering purposes, safety of offshore operations, and scientific pursuits.

There is further value that can be derived from this dataset:

- The data exist in Fugro's archive of processed data and can be used to extract intertidal topography and more defined hydrology data beyond the USGS specifications that were required for the project.
- In the glacial regions, P-band data is not needed to determine surface elevation. However, as was discovered, P-band penetrates snow and ice. The P-band data can be made available for research purposes to understand glacier thickness or to compare with other ice thickness data subsequently collected.

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[14] https://www.eomap.com/services/bathymetry/, accessed 4 February 2022

[15] https://www.fugro.com/media-centre/news/fulldetails/2021/01/11/fugro-partners-on-4s-global-satellite-observation-seafloor-mapping-innovation, accessed 4 February 2022

- When hitting metallic objects, P-band returns a different signature than X-band. The contrast between the two can identify cultural or man-made sites, such as aircraft parts in forested areas, which are undetectable if only X-band is used.

Fugro is currently working on the development of an implementation plan for the Alaska Coastal Mapping Strategy (ACMS)[16], a comprehensive shoreline mapping program that envisions seamless coastal mapping data in 2030 along Alaska's 106,000 km of shoreline. The State's coastal ecosystems are geologically complex and diverse, including glacial fjords, many active volcanoes, large deltas, inlets, bays, parks, and refuges. These coasts have a long history as places of subsistence, indigenous culture, and economic and recreational activities, but are also known for their challenging weather and ocean conditions.

Informed decisions in the coastal zone rely on accurate and up-to-date coastal mapping data; however Alaska has large gaps in its tidally referenced elevation and imagery data coverage, and a deficient geospatial positioning framework. The anticipated geospatial products of the ACMS include

- Seamless, integrated topography and nearshore bathymetry
- Orthorectified imagery
- Habitat mapping
- Linear vector collection of the shoreline
- Upgrade of spatial reference system components to support development of accurate coastal products

Multiple technologies and platforms will be needed to achieve these, including airborne (ALB, topographic mapping, imagery from crewed and autonomous platforms), vessel-based (bathymetry from crewed and uncrewed platforms) and satellite (imagery, satellite-derived bathymetry for planning and change detection).

3.2 Geological and infrastructure hazards related to degrading permafrost

Permafrost degradation has severe effects on Arctic infrastructure and foundations. Building in regions of continuous and discontinuous permafrost presents serious and unique challenges, but they are hardly new. It is the rate of environmental change that makes these issues more urgent and acute. How we address these challenges determines the integrity and longevity of Arctic assets, and the quality of life for people who live and work there at a basic level. Engineering solutions are able to mitigate the effects of degrading permafrost, but their economic cost is often high. The focus should be on quantifying the economic impacts and occurrence of permafrost-related infrastructure failure. To avoid detrimental impacts, local-scale infrastructure risk assessments should be conducted on future development projects, and mitigation measures applied.

[16] https://iocm.noaa.gov/about/documents/strategic-plans/alaska-mapping-strategy-june2020.pdf, accessed 18 February 2022

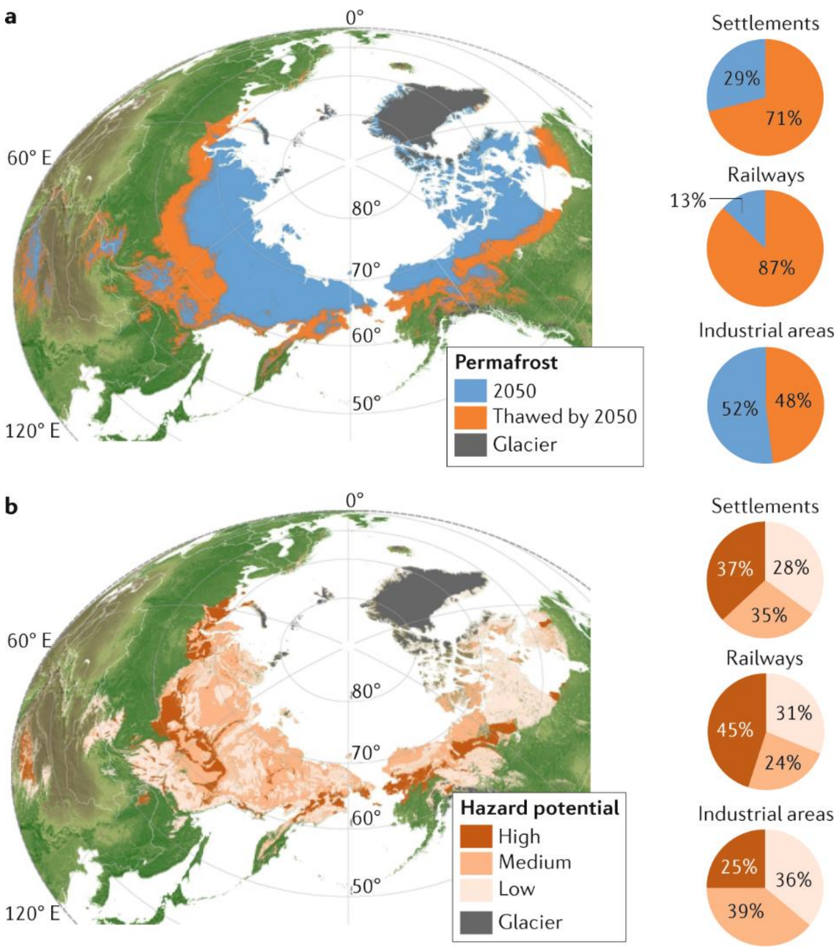

Figure 9. Circumpolar infrastructure at risk by 2050, from Hjort *et al.*[17]

Planning and construction methods in permafrost areas therefore need to include geo-data approaches that enable accurate mapping, monitoring and prediction of climate and ground conditions at high resolution across large spatial and temporal scales. Understanding the vulnerability of assets and predicting the behaviour of permafrost in the context of infrastructure development requires an interdisciplinary approach, drawing on geospatial, geophysical, geotechnical, geological and geomorphological characterisation.

3.2.1 Cone penetration in frozen soils

In Russia, up to 80% of buildings are damaged in some cities built on permafrost. Frozen soil has ice content and exhibits rheological behaviour, meaning the stress-strain behaviour and mechanical properties change with time. The failure of frozen soil under long-term loading is important for design. The long-term soil strength (the resistance of a soil to failure in response to a long-term load application) is a key parameter in the engineering of frozen ground[18].

Fugro has been doing pioneering work in Russia, both in characterising soil conditions and performing asset integrity investigations in permafrost. Here we summarise recent practical experience with cone penetrometer test (CPT) investigations at several permafrost sites in Siberia

[17] Hjort, J., Streletskiy, D., Doré, G. *et al.* Impacts of permafrost degradation on infrastructure. *Nat Rev Earth Environ* 3, 24–38 (2022).
[18] Vyalov, S.S. (1986). Rheological Fundamentals of Soil Mechanics, Volume 36, 1st Edition, *Elsevier*, ISBN: 0444600566

delivered as part of the *Site Characterisation* solution at Δ2 in the GRMF. These projects include civil works like housing, bridges and railroads as well as Russia's biggest resource development projects on the Yamal and Gydan Peninsulas such as the Yamal LNG, Arctic LNG 2, as well as a recent and notable discovery, the Kruzenshtern Gas Field.

Some of the investigations were performed in unconventional conditions such as with ice cover, in a crawl space, or from a jack-up platform. All CPT measurements used a cone equipped with a temperature sensor to confirm the sub-zero temperature of frozen soil. Stress relaxation tests were performed in ice-rich permafrost soils to investigate long-term soil strength in both compression and shear. Sampling of frozen soil using direct push techniques was achieved at some of these sites. Fugro holds the world record of penetrating frozen soils down to 62 m with CPT equipment, without pre-drilling.

Figure 10. Differential settlement of the operational railway line near Vorkuta. 1 CPT with total length of 12 m (including 8 m of frozen soil) and 6 temperature measurements were performed at night within 3 hours. The initial hypothesis of thawing permafrost was not confirmed.

Frozen soil CPT improves data quality and variety, while also reducing safety risks, time and carbon footprint. It provides information, both on land and in the shallow nearshore, about soil strength profile, temperature, electric conductivity and salinity. This less invasive and more efficient method to determine geotechnical properties helps to reduce the number of drilled boreholes - a lot of data can be obtained in one push performed within a single working day.

Figure 11. Salekhard College built in 1970s started experiencing deformations in 2014. 3 CPTs with total length of 12 m (including 10 m of frozen soil) and 8 temperature measurements were performed in the crawl space (1.9 m) under the structure. The initial hypothesis of thawing permafrost was not confirmed[19].

Figure 12. A multistorey apartment building in Western Siberia, erected in 2017, experienced differential settlement of up to 3 mm/month. 34 CPTs with total length of 724 m (including 360 m of frozen soil) and 305 temperature measurements were performed. Soil sampling showed ice lenses up to 10 cm thick, and the cause of settlement was found to be the thawing of the ice lenses.

Figure 13. In the Arctic, where infrastructure is sparse and the outdoor work season could be just a few precious weeks, smaller, lighter and faster make a big difference.

[19] Volkov, N., Sokolov, I., & Jewell, R. (2017). Investigation by cone penetration tests of piled foundations in frozen soil maintained by thermosyphons. *American Academic Scientific Research Journal for Engineering, Technology, and Sciences*, 31(1), 40-58.

3.2.2 Geophysical investigation of frozen soils

Geophysical methods have been applied to the characterisation of permafrost for a number of years. These are mature, widely accepted methods practiced globally with the underlying physical principles being well understood by the geophysical community. When applied standalone at a regional scale, geophysics is a component of a *Screening* solution and when focussed at a site scale is part of a *Site Characterisation* solution within the GRMF, frequently accompanied by borehole drilling and probing, sampling and laboratory testing.

The geomorphology and shallow ground conditions of periglacial environments can be complex and present significant uncertainty that requires management for surface infrastructure development in Arctic regions. Within a warming climate, it is well understood that permafrost degradation may lead to significant problems associated with ground instability.

The key benefit of geophysics is the ability to screen for variations in ground conditions at an appropriate scale to minimise the overall effort required to characterise sites to levels of detail required for risk management decisions to be made. In practical terms, near-surface geophysics can be deployed as one of the key means to manage subsurface uncertainty associated with permafrost into project risk and cost reduction.

Compared to its unfrozen state, cryotic ground is generally characterised by:

- higher compressional wave seismic velocity
- higher shear wave seismic velocity
- higher surface wave seismic velocity
- higher electrical resistivity / lower electrical conductivity
- lower electromagnetic attenuation
- lower dielectric permittivity

A change to the cryotic state has very little impact on density and magnetic properties.

The physical characteristics of frozen or cryotic ground form the basis for geophysical investigation. Long-established airborne methods based on electromagnetic principles have been used for large scale assessment of the presence and extent of permafrost, whilst surface geophysical methods have been used on a more local scale to characterise periglacial environments to greater vertical and lateral resolution.

Frozen ground is more electrically resistive and has higher seismic velocities of propagation, both for body and surface waves, than unfrozen ground. In addition, frozen ground is generally more amenable to radar energy propagation than frozen ground both due to high resistivity and a contrast in the dielectric properties between water and ice. The contrast between the physical characteristics of unfrozen and cryotic ground can be best exploited by the geophysical techniques appropriate to the underlying physical principles, namely electrical resistivity tomography for resistivity, seismic methods (refraction, surface wave) for seismic velocity and ground penetrating radar to exploit favourable dielectric contrasts between water and ice.

The unique electrical, dielectric and seismic properties of frozen ground makes geophysics a potential tool for permafrost characterisation. Geophysical screening provides the geo-data to help identify variability in ground conditions to identify key risks related to permafrost prior to the commitment of further investigative effort at a site scale. At a regional scale and following appropriate desk studies, a phased site characterisation approach can be initially adopted using electromagnetic airborne methods to screen for large-scale variability in ground conditions or presence of permafrost.

At a site scale, resistivity and seismic methods should be considered as the most practical and robust approaches to determine the spatial distribution of permafrost to beyond foundation depths from the measurement of some of the specific physical ground properties at an appropriate level of detail.

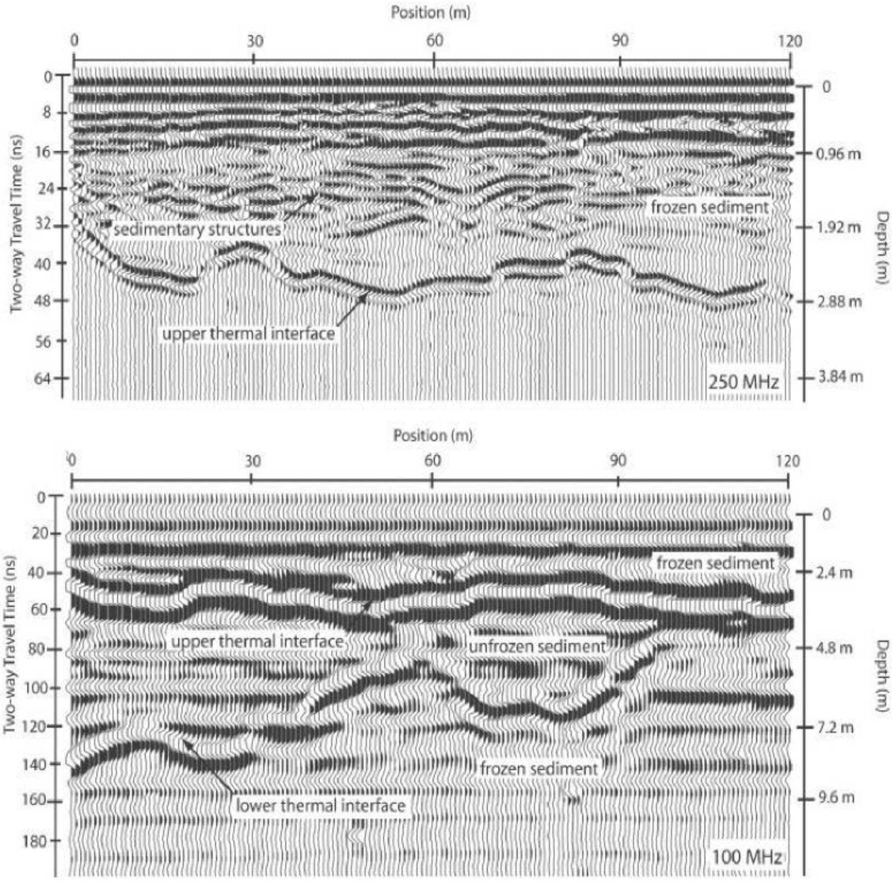

Figure 8. A multi-frequency ground penetrating radar profile in a shallow water deltaic area, Mackenzie Delta margin, Canada. The higher frequencies provide better resolution in the near surface, while the lower frequencies provide greater depth of penetration[20].

Electrical resistivity tomography can be used for general spatial mapping of frozen ground and seismic methods can be used to complement resistivity for spatial mapping but also to derive estimates of geotechnical parameters such as shear/Young's modulus and Poisson's ratio. Both methods can be applied in a repeated programme when temporal variations (e.g. permafrost degradation) need to be investigated.

Where a high level of detail of internal structure are required (e.g. to investigate ice lenses or similar), ground penetrating radar methods can be used to investigate specific cases. If boreholes are drilled to provide direct samples for geotechnical or environmental testing, then wireline logging provides a means to extract localised geotechnical and environmental properties that can be integrated with

[20] Christof Kneisel, Christian Hauck, Richard Fortier and Brian Moorman, 2008, Advances in Geophysical Methods for Permafrost Investigations, *Permafrost and Periglac. Process.* 19: 157–178 (2008)

geophysical screening information to provide a comprehensive model for the assessment and management of project risks.

Recent advances in geophysics that could be applied to mapping geotechnical properties include 3D mapping of subsurface properties to depths in excess of 100 m using ambient noise tomography such as Fugro's SWANS (surface wave ambient noise seismology) system that typically deploys 100s to 1000s of receivers delivering a 3D block of shear wave velocity as a proxy for small strain stiffness. In boreholes the development of nuclear magnetic resonance (NMR) techniques can help identify free water in largely frozen ground. For example, borehole NMR is sensitive to the nucleation of ice within soil pore spaces[21]. Seasonal dependency on surface conditions should of course be considered a primary factor for deployment of geophysics at a site scale.

3.2.3 Road construction and maintenance

Permafrost is treated as a stable base on which to build roads (and other infrastructure). However, as temperatures rise, permafrost is melting at various rates depending on location and makeup. As permafrost melts the flexible asphalt surface of the road is no longer supported, and can crack, slump, heave, or in really severe situations fall into a sinkhole. Even in less extreme environments and in contrast to most foundation engineering, linear transport infrastructure such as roads and railways will inevitably require maintenance to optimise safety, asset availability and total cost of operations. Geo-data are required to make timely risk management decisions as to when, where and how to intervene.

Road data acquisition challenges:

- Timing collection to optimize with weather
- Getting ARAN vehicles to Alaska's islands (typically on boats)
- Some roads on the mainland can only be accessed by air
- Collection on very rough terrain and gravel roads – leading to the development of the 4x4 ARAN

The Alaska road network is around 28,455 km split across different jurisdictions and road types. Alaska Department of Transportation (DOT) was concerned about locations of unstable permafrost and wanted to review the road network to more accurately quantify areas experiencing damage. Fugro has been collecting state-wide digital roadway data for Alaska DOT since 2017 as part of a structural health monitoring solution delivered at Δ6 in the GRMF to identify changes in condition and structure and identify key operational risks at a network scale. About 18,000 lane kilometres are covered using specialised Fugro ARAN vehicles.

[21] Kass, M. A., Irons, T. P., Minsley, B. J., Pastick, N. J., Brown, D. R. N., and Wylie, B. K.: In situ nuclear magnetic resonance response of permafrost and active layer soil in boreal and tundra ecosystems, *The Cryosphere*, 11, 2943–2955, https://doi.org/10.5194/tc-11-2943-2017, (2017)

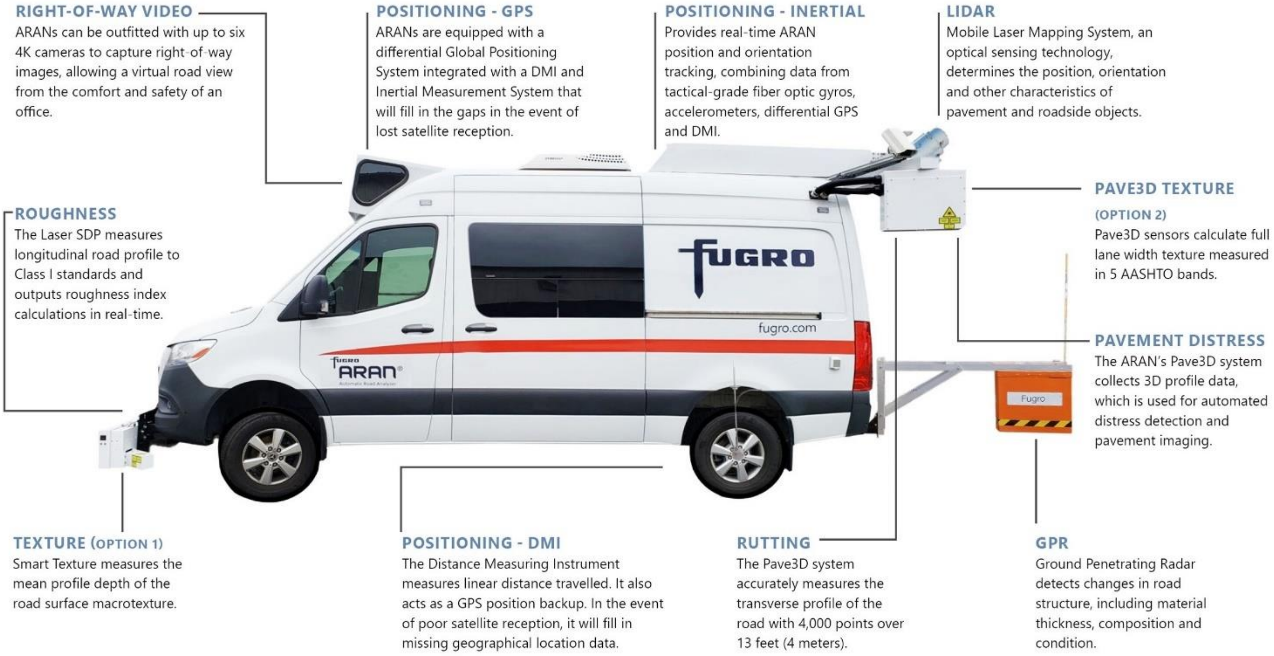

Figure 14. Fugro ARAN (Automatic Road ANalyser) technology: measured parameters.

Figure 15. Fugro ARAN enabling digital roadway over discontinuous permafrost in Alaska.

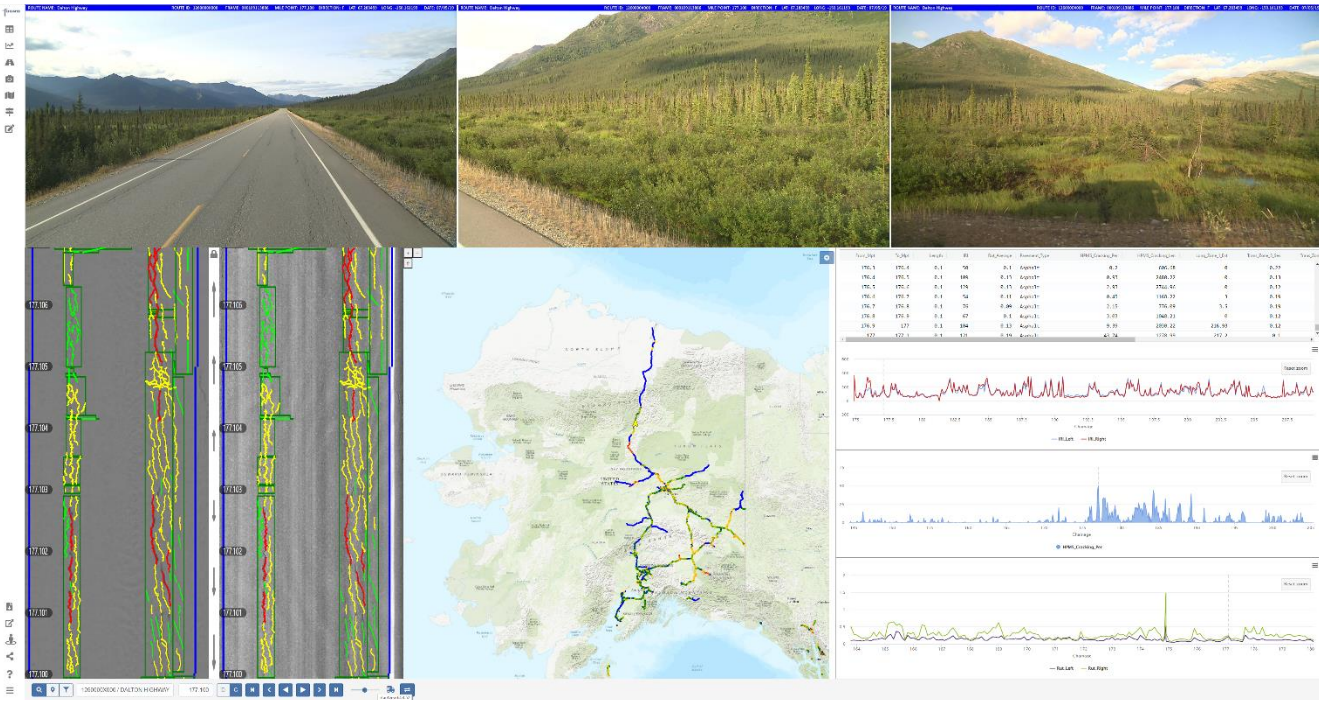

Figure 16. Fugro iVision is a web-based data analysis platform allowing access to synchronised imagery and pavement condition metrics in reports, charts, and map layers.

During Alaska's short summer season, these vehicles are driven at highway- or near-highway-speeds from communities on the North Slope to the Southeast. A wide variety of pavement condition parameters can be measured including roughness, texture, rutting, cracking, ravelling, and patching as well important information like right-of-way video. Specifically the right-of-way imagery and the downward facing 3D pavement imagery were able to locate areas of slumping or heaving along the route that didn't look like typical vehicle-related damage. Areas were also identified that had full lane patching in light trafficked zones, likely signs of thermal degradation damage. Multi-year analysis monitors the rate of change, measuring the impacts of thermal degradation over time.

These data are web-accessible to Alaska DOT engineers on demand, and provide input to solutions that prevent or delay thermal degradation of road infrastructure, thereby helping them manage Alaska's state roads efficiently.

3.2.4 Wide-area subsidence monitoring

Permafrost is a subsurface phenomenon, and cannot be directly observed from satellites. However, its impact on the surface can be measured through remote sensing methods. Synthetic Aperture Radar (SAR) satellites are especially useful in the Arctic as SAR imaging is independent of solar and weather conditions. The ground layer above the permafrost, which thaws in summer and refreezes in winter, can induce spatially variable mm- to cm-level heave and subsidence, which can induce slope instability, affect infrastructure and thus the socioeconomic development of the area.

Such ground dynamics in permafrost landscapes can be measured over large and hard-to-access areas using spaceborne repeat-pass Interferometric SAR (InSAR)[22]. Over broad Arctic areas, the accuracy of the InSAR technique can however be limited by challenges such as decorrelation due to cryoturbation of the surface or snow cover, strong phase gradients that cause unwrapping errors, as well as temporal decorrelation. Some of these may be circumvented by focusing on smaller areas, using only the SAR images acquired during the thawing season, or through using long-wavelength e.g. L-Band SAR[23,24].

The European Ground Motion Service (EGMS) aims to provide consistent, regular, standardised, harmonised and reliable information on natural and anthropogenic ground motion phenomena over Europe and across national borders, with millimetric accuracy using Copernicus Sentinel-1 data[25]. Several Copernicus Participating States in the Arctic, including Norway[26] and Sweden[27], have already or are in the process of implementing national ground motion services.

InSAR is thus complementary to more accurate but sparse traditional *in situ* measurements such as those described earlier in this Section, and together can provide deeper insights into the dynamics of permafrost systems and changes in permafrost conditions[28].

3.3 Geo-data management and liberation

As described in the previous sections, scientists and engineers can access a wide range of geo-data for managing land and resources, building and maintaining infrastructure, and modelling and forecasting environmental change in the Arctic. But what about non-technical professionals? Can geo-data be liberated beyond the confines of highly specialised skillsets to benefit the average citizen?

Efforts, such the Arctic Spatial Data Infrastructure[29], are being made towards providing open access to a coherent and authoritative Arctic reference map and thematic Arctic geo-data. Broadening access to geo-data provides a foundation for self-service analytics among an extensive variety of users, which is vital to a sustainable future. Take coastal mapping: across the globe, government agencies collect and publish authoritative data depicting low-lying communities prone to sea-level rise and storms. Experts within these agencies use the data to perform various analyses, such as damage estimates, risk-level determinations and coastal resilience strategies. Easy access to this expert analysis would also benefit non-governmental users, helping individuals and business owners make informed decisions in support of a safe and liveable world.

[22] Rouyet, L., Lauknes, T. R., Christiansen, H. H., Strand, S. M., & Larsen, Y. (2019). Seasonal dynamics of a permafrost landscape, Adventdalen, Svalbard, investigated by InSAR. *Remote Sensing of Environment*, 231, 111236.
[23] Daout, S., Doin, M. P., Peltzer, G., Socquet, A., & Lasserre, C. (2017). Large-scale InSAR monitoring of permafrost freeze-thaw cycles on the Tibetan Plateau. *Geophysical Research Letters*, 44(2), 901-909.
[24] Abe, T., Iwahana, G., Efremov, P.V. et al. Surface displacement revealed by L-band InSAR analysis in the Mayya area, Central Yakutia, underlain by continuous permafrost. *Earth Planets Space* 72, 138 (2020). https://doi.org/10.1186/s40623-020-01266-3.
[25] https://land.copernicus.eu/pan-european/european-ground-motion-service, accessed on 22 February 2022.
[26] https://insar.ngu.no/, accessed on 22 February 2022.
[27] https://insar.rymdstyrelsen.se/, accessed on 22 February 2022.
[28] Liu, L., Zhang, T., & Wahr, J. (2010). InSAR measurements of surface deformation over permafrost on the North Slope of Alaska. *Journal of Geophysical Research: Earth Surface*, 115(F3).
[29] https://arctic-sdi.org/, accessed on 3 March 2022.

Geo-data supports faster, more-informed decision-making by experts; associated GIS tools make this information more valuable by offering the general public greater transparency in the decision-making process and a deeper understanding of how the science impacts them directly. Geo-data can be liberated for public consumption through a variety of platforms, from simple Esri StoryMaps that guide non-technical users through expert analysis, to immersive platforms such as Fugro SIMmetry that enable advanced queries and 4D visualisations.

Here are some start-to-finish tips for building a comprehensive geo-data programme that also implements user-friendly tools for non-technical users – applicable both in the Arctic and elsewhere:

- *Create a plan*. The process of acquiring and serving geo-data for managing risk can be complex. Involve stakeholders from the beginning; understand their needs and key uncertainties so they can be guided toward a clear set of project specifications before any data are procured.
- *Educate users on accuracy*. Detecting small changes and performing critical analysis requires mapping-grade accuracy. There is a big difference between relative accuracy and absolute accuracy; make sure the stakeholders understand the difference.
- *Elevate interoperability*. When investing in enterprise software, one should look for solutions that utilise open standards. Geo-data must work across multiple platforms, which is why organisations like the Open Geospatial Consortium (OGC) were founded.
- *Move to the cloud*. Geospatial data can be cumbersome and hard to manage. Imagery, lidar point clouds, and 3D geo-data, in general, can take up a lot of network space. Rather than storing it on an a hard drive or ailing server, one should consider streaming it from "the cloud." Cloud providers such as Amazon Web Services and Microsoft Azure have made massive strides in bringing down the costs to store, serve and protect data.
- *Make it accessible*. Further to the last point, providing on-demand, easy access to geo-data allows organisations to improve outreach campaigns and develop communication channels with the public. Geo-data funded by the public sector are prime candidates for the "map once use many times" paradigm. Accessibility increases awareness, stimulates partnership and is imperative to delivering best value to the public.
- *Simplify the complex*. Interpreting geo-data can be complicated, and in many cases, requires a sophisticated supercomputer or distributed processing network. For instance, deriving a seamless coastal dataset, may rely on vessel-based sonar, drone-based lidar, and aerial imagery. The burden on the end-user is minimised by understanding their needs and creating GIS tools that allow quick manipulation, analysis and communication of these integrated geo-data.
- *Pay attention to security*. Even though one would want geo-data to be as free and open as possible, data rights and licensing considerations may also need to be considered. Robust user management, credentialing and encryption processes are important to ensure that the data remains in the right hands.

4. Geo-data initiatives supporting Arctic activities

4.1 Remote and autonomous operations

A remote operations centre (ROC) provides a centralised hub allowing experts to control equipment and vessels, and manage operations remotely enhancing the way projects are undertaken. ROCs enable transferring personnel from hazardous offshore environments to a safe and centralised onshore environment. The experts located at the ROC can conduct the same tasks onshore as required onboard a survey vessel, enabling access to a broader range of expertise, 24/7 monitoring and support and data through a secure web interface. Managing and maintaining connectivity is critical to remote operations - the connections are ensured to provide the highest possible uptime reducing latency and improving throughput.

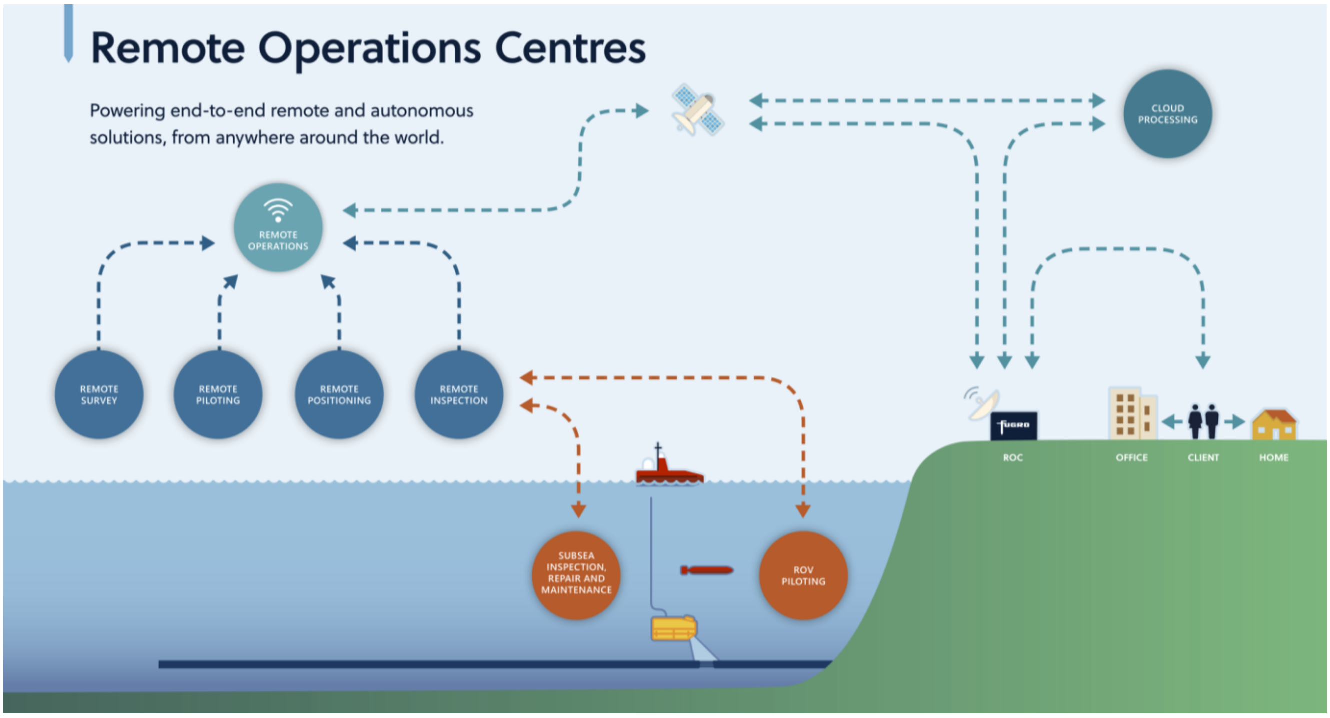

Figure 17. Overview of how Fugro ROCs support remote and autonomous solutions globally.

The key benefits can therefore be summarised as:

- Improved safety through elimination of personnel from hazardous environments
- High-quality data processed and available several days faster than traditional approaches, ensured by 24/7 availability of scalable expertise and in-house remote data processing capabilities
- Optimised operational efficiency due to operations being managed remotely with reduced logistics
- Sustainable operations with significantly reduced fuel consumption

Additionally, the deployment of uncrewed vessels and platforms further reduce/eliminate the requirement for personnel offshore for various screening and survey activities. Fugro uses its global network of ROCs to support multiple projects with diverse operations and requirements.

4.1.1 Uncrewed vessels

Uncrewed surface vessels (USV) can enable fast and continuous screening and insight delivery on coastlines, oceans and marine environments, while also reducing inefficiencies in data collection due to weather conditions, and exposure risks of surveyors in remote and harsh Arctic environments through reduced acquisition time and remote operations.

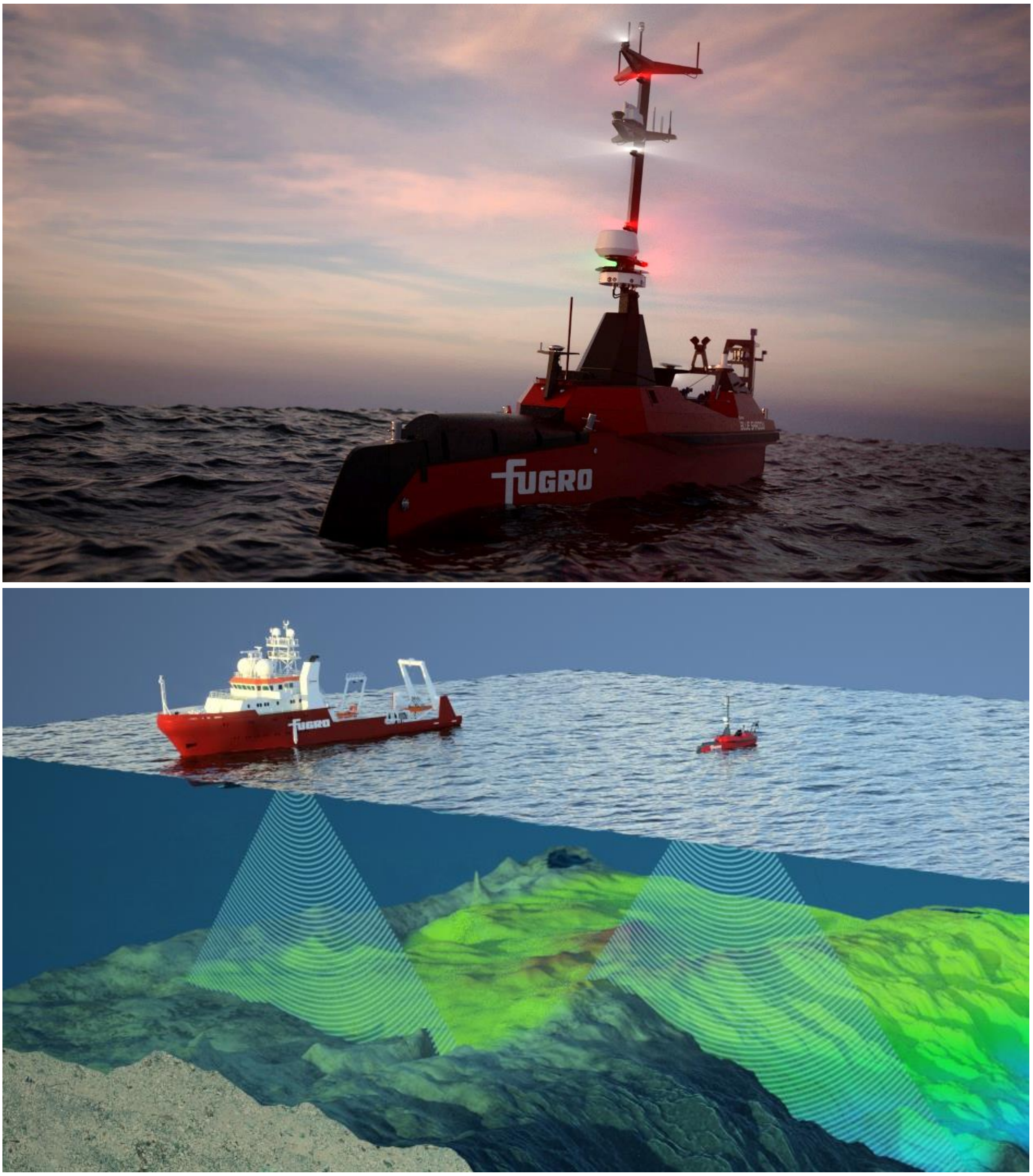

Figure 18. Top: The Blue Shadow USV. Bottom: USV as a force multiplier alongside a Polar Code certified parent ship.

Fugro's Blue Shadow is a USV with advanced level of autonomy, designed for the remote acquisition of hydrographic data. It operates as a force multiplier alongside a traditional crewed hydrographic survey vessel to improve data acquisition efficiencies by up to 50%. It includes advanced situational awareness and collision avoidance technologies, maximising efficiency and achieving optimum coverage. It is capable of operating continuously for 7 days uninterrupted at survey speed (6 to 8 knots). It enables up to 90% reduction in operational greenhouse gas emissions.

The Blue Shadow is the first of many USVs that aim to cover bathymetric scope ranging from coastal waters to the deep oceans. Further additions to the Fugro USV family over the next two years are expected to operate for several weeks on end, enabling e.g. trans-Atlantic surveys.

4.2 Ocean science initiatives

Knowledge of the depth and shape of the ocean floor is vital to answering a broad range of Arctic climate and environmental questions, such as on the declining cryosphere and the geological history of the Arctic Basin. Bathymetry provides the geospatial context for such studies, and has an effect on processes such as ocean current pathways and, consequently, heat distribution, sea-ice decline, the effect of inflowing warm waters on tidewater glaciers, and the stability of marine-based ice streams and outlet glaciers grounded on the seabed[30]. As touched upon in the previous sections, bathymetric data from large parts of the Arctic Ocean are not available or very sparse owing to logistical (and sometimes political) challenges.

The Arctic Council[31] is an intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States, Indigenous peoples and inhabitants on common Arctic challenges such as sustainable development and environmental protection. Recognising the need to work together closely, the 8 involved Arctic states cooperate on a wide range of issues including ocean-related, such as marine pollution, sustainable shipping practices, search and rescue operations, marine cooperation and risk management[32]. It is of vital importance to ensure continuing cooperation at this level despite possible political challenges[33].

Another international initiative, the General Bathymetric Chart of the Oceans (GEBCO), operates under the joint auspices of the International Hydrographic Organisation (IHO) and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organisation (IOC-UNESCO), and aims to provide the most authoritative publicly-available bathymetry of the world's oceans[34]. Additionally, the IHO's Arctic Regional Hydrographic Commission (ARHC)[35] contributes to improving hydrographic awareness, nautical charting and marine environmental protection in the Arctic.

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[30] Jakobsson, M., Mayer, L.A., Bringensparr, C. *et al.* The International Bathymetric Chart of the Arctic Ocean Version 4.0. *Sci Data* 7, 176 (2020).
[31] https://arctic-council.org/, accessed on 1 March 2022.
[32] https://arctic-council.org/explore/topics/ocean/, accessed on 1 March 2022.
[33] https://www.arctictoday.com/russias-invasion-of-ukraine-will-have-spillover-effects-in-the-arctic/, accessed on 3 March 2022.
[34] https://www.gebco.net/about_us/overview/, accessed on 1 March 2022.
[35] https://iho.int/en/arctic-rhc, accessed on 1 March 2022.

4.2.1 Seabed 2030

In 2016, Fugro envisioned a supercharged crowdsourced bathymetry program to support the global ocean mapping initiative, The Nippon Foundation GEBCO Seabed 2030 Project. This is a collaborative project between The Nippon Foundation and GEBCO to inspire the complete mapping of the world's ocean by 2030 and to compile all bathymetric data into the freely available GEBCO ocean map. The innovative approach involves using remote command and control technologies to collect valuable bathymetry data during transits to projects. Since 2017, Fugro vessels have generated more than 2 million km^2 of high-resolution bathymetry for the project, an area equivalent to the size of Mexico. These are 100% in-kind contributions to Seabed 2030, and serve as an example for similar engagement by others in the maritime industry.

The Seabed 2030 Arctic and North Pacific Ocean Regional Centre[36] plays an important role as the regional focal point for data compilation and co-ordination activities for Seabed 2030 in the Arctic and Northern Pacific Ocean region, compiling the International Bathymetric Chart of the Arctic Ocean (IBCAO) and convening the relevant stakeholders.

4.2.2 The United Nations Decade of Ocean Science for Sustainable Development

Fugro has accepted an invitation from the IOC-UNESCO to join the Ocean Decade Alliance. Comprising an eminent network of global leaders and institutions, the Alliance aims to catalyse support for the United Nations Decade of Ocean Science for Sustainable Development 2021-2030 (the 'Ocean Decade') through targeted resource mobilisation, networking and influence.

The agreement includes significant in-kind support from Fugro via loan of experts to the IOC-Secretariat in Paris for establishing and administering two key ocean science working groups. The first of these groups is an Ocean Decade Data Coordination Platform to provide a global, cross-sectoral convening framework for the creation of a "digital ecosystem" to share, manage and distribute ocean data and interoperable marine science. The second group will comprise global private-sector stakeholders who collect or own ocean science data, and who are willing to make these data publicly accessible in support of the Ocean Decade. This group will provide a global, cross-discipline and cross-data type convening framework for the development of equitable mechanisms to accelerate public access to privately held ocean science data.

As a member of the Alliance, Fugro will collaborate and coordinate with other Alliance members in leveraging existing commitments to raise awareness about Ocean Decade objectives and activities worldwide; create a platform for demonstrating the role and power of science in providing solutions for ocean sustainability; and establish a broad international network that stimulates additional actions and commitments in the framework of the Ocean Decade across all levels of society.

Specific to the Arctic, the Ocean Decade endorses the ArcticNet Core Research Program[37] and the Navigating the New Arctic (NNA) Action[38].

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[36] https://seabed2030.org/centers/arctic-and-north-pacific-ocean-regional-center, accessed on 1 March 2022.
[37] https://www.oceandecade.org/news/arcticnet-core-research-program-2022-24/, accessed on 1 March 2022
[38] https://www.oceandecade.org/actions/navigating-the-new-arctic/, accessed on 1 March 2022

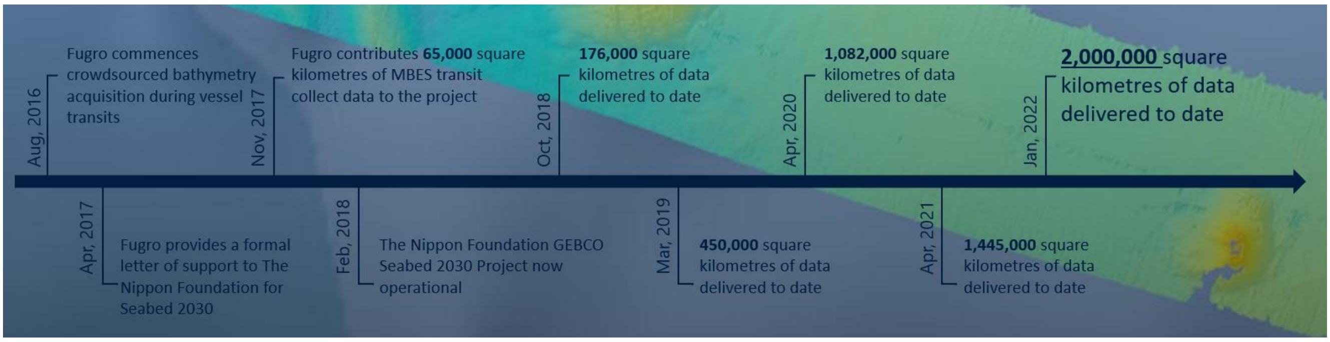

Figure 19. A timeline of recent social commitments and achievements by Fugro in the hydrography realm.

4.3 Support to Arctic navigation

4.3.1 Satellite data

Through the use of high-revisit, high resolution and high coverage satellites it is possible to contribute to Arctic navigation and to the development and risk management of new routes. These scientific methodologies, which leverage the use of satellite radar technology (e.g. the Italian COSMO-SkyMed and its Second Generation constellations), together with other datasets such as the ESA Copernicus Sentinel-1 data, consist of monitoring the route ahead of the ship, reporting the status of the ice, the presence of other ships (cooperative and non-cooperative) and documenting the ship "blue navigation" remotely. The methodology also includes satellite communications to solve communication issues at higher latitudes, in order to enable the exchange of coordinates and some limited information about the detected sea ice.

4.3.2 Improved positioning

Operating in rough waters and in areas far away from other infrastructure and resources, like in the Arctic, requires accurate and reliable positioning to manage operational risks ensure safe operations. The standard method of Global Navigation Satellite System (GNSS) correction data delivery is by broadcast over the Fugro network of L-Band geostationary communication satellites. This is an extremely reliable and robust system, but geostationary satellites, located above the equator, have a coverage footprint which is limited to around 70°N using standard spot-beam antennas.

Fugro high-performance satellite navigation augmentation services can be delivered beyond these coverage limits. The combination of a unique purpose-made L-Band antenna for low elevation satellites (AD-493 receives corrections up to 75°N) and the Fugro NTRIP (Network Transport of RTCM over Internet Protocol) solution delivered over VSAT (very-small-aperture terminal) ensures the right corrections for maintaining reliable and safe operations in the Arctic.

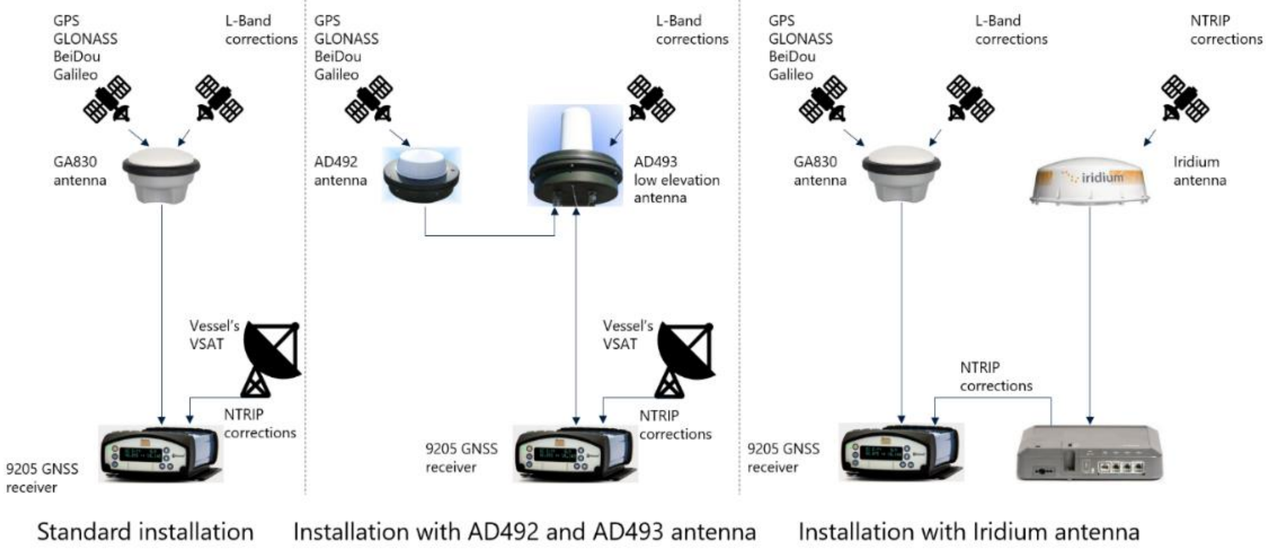

Figure 20. Fugro high-performance satellite navigation augmentation services.

4.4 Emergency mapping services

Satellite data are increasingly used to support emergency management worldwide. Owing to the amount and variety of earth observation satellites available nowadays, large programmes such as ArcSAR[39], the Copernicus Emergency Mapping Services (EU) and the International Charter[40] are able to ensure a quick reaction on a global scale in case of major events. The high availability of the satellite platforms increases the possibility to obtain timely data over the area affected by a disaster, and the programmes guarantee high quality and rapid production of specific cartography products supporting the damage assessment and impact analysis. The Arctic being very complex environment in terms of climate, morphology and remoteness), near-real time satellite observations are particularly precious to support field teams during operations in case of disasters or major events.

In addition to supporting rescue and recovery operations, emergency mapping services have built interesting statistics of the types of events occurring worldwide. In particular, in recent years the Arctic region has dealt with floods due to the glaciers melting in the Scandinavian peaks. Although in principle this is natural behaviour, the fact that it occurs at different times of the year, or very quickly, is an anomaly that causes damage and indicates how rapidly our climate is changing. Even more illustrative has been the involvement of these monitoring programmes in case of wildfire events, e.g. in Greenland in 2017 and 2019. These lasted several days, caused by the extremely dry condition of an area that is normally expected to be wet even in the summer.

4.5 Environmental monitoring services

The Arctic region, as discussed earlier, is undergoing an environmental revolution. The effects of climate change in this area are disruptive: thawing permafrost is damaging infrastructure but also opening new opportunities in term of resource exploitation and new navigation routes. These activities carry with them the risk of further compromising the environment and creating further perils

[39] https://arcsar.eu/, accessed 22 February 2022
[40] https://emergency.copernicus.eu/mapping/ems/copernicus-emergency-management-service-and-international-charter-space-disasters-join-forces, accessed 22 February 2022

for people and territory in general, in terms of safety and security. Furthermore, anthropisation of the area brings with it pollution issues, impacting the Arctic land and marine ecosystem.

Satellite technology supports the growing need for screening and monitoring the region by integrating data of different types such as images, Automatic Identification System (AIS) data, and *in situ* data. Through the application of technology such as automated analysis and artificial intelligence, early warnings are generated with respect to critical changes e.g. vessels outside the usual routes, sizable changes in earthworks associated with infrastructure construction activities or exploitation of new resources, anomalous movements of vehicles or vessels, as well as oil spills and leakage of pollutants in the marine environment. Satellite earth observation, through programmes such as ARCOS[41], is therefore a unique information source on activities and phenomena supporting decision makers such as environmental agencies and emergency first responders in Arctic countries for planning actions (and reactions) to protect the environment and population. The European Commission's Joint Research Centre has provided a detailed study of Europe's space capabilities for the benefit of the Arctic[42].

5. Summary

For the rapidly changing and dynamic Arctic region, epistemic uncertainty (i.e. uncertainty arising from insufficient data, information and knowledge) is a principal source of risk for stakeholders involved in the development and management of built and natural assets in the land and marine environments. It follows that reducing uncertainty delivers better risk management and a greater probability of achieving stakeholder objectives.

Present and future challenges and opportunities at all scales in the Arctic region will require effective risk management, with decisions on project feasibility, sustainable design as well as appropriate maintenance practices dependent upon the risk tolerance of a broad spectrum of stakeholders. Risk reduction will involve either lowering the probability of occurrence of a hazard, or mitigating its consequences. Insights and subsequent decisions around risk will need to be founded on robust, reliable and relevant geo-data acquired from technology enablers such as those discussed in this white paper.

Geospatial and geophysical technology enablers will help deliver value-adding insights not only about the present state and condition of natural and built assets, but also to build reliable, predictive behavioural models for timely and effective intervention. The Geo-Risk Management Framework (GRMF) provides a pragmatic starting point to apply a consulting mindset to identify key uncertainties for stakeholders, a means to ask the right questions around risk and then to provide appropriate risk management solutions built from the right technology components and expertise to deliver insights and value at the right time.

[41] https://arcos-project.eu/dashboard, accessed on 22 February 2022

[42] Boniface, K., Gioia, C., Pozzoli, L., Diehl, T., Dobricic, S., Fortuny Guasch, J., Van Wimersma Greidanus, H., Kliment, T., Kucera, J., Janssens-Maenhout, G., Soille, P., Strobl, P. and Wilson, J., Europe`s Space capabilities for the benefit of the Arctic, EUR 30162 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-18118-7, doi:10.2760/641049, JRC118965.

There is no single magic tool to address all environmental, cost and safety constraints of acquiring appropriate geo-data in the Arctic. Efficient execution will require many tools in the toolbox – handheld, vessel-borne, airborne or spaceborne, crewed or uncrewed, active or passive. And crucially, it will require expert knowledge to optimise what works where. Proper geo-data management and liberation frameworks can enable self-service analytics by non-technical end-users looking to reduce uncertainty and manage risks in day-to-day work and life decision-making, facilitating knowledge sharing while also addressing community interests and concerns.

Lastly, but importantly, better collaboration and communication among all stakeholders across disciplines – scientists, inhabitants, local authorities, industry and governments – are needed to effectively mitigate the effects of the Arctic's changing environment.

About the Authors

Dr. Pooja Mahapatra is passionate about applying geospatial technology towards solving real-world challenges. Since 2019, she has worked on commercialising cutting-edge Fugro innovations. Through Fugro, she is an active member of the Disaster Resilience Working Group of the WGIC. From 2016 to 2019, she led the global geospatial technology deployment efforts at Shell, contributing to digital transformation and measurable improvements in efficiency and safety. She holds a PhD in satellite remote sensing from Delft University of Technology.

Dr. Rod Eddies is Solution Director for Fugro's Land Site Characterisation business and, based in the French Alps, has enjoyed a career spanning more than 30 years in exploration and site characterisation relating to major infrastructure. Along with Ray Wood, Rod is one of the principal architects of Fugro's Geo-Risk Management Framework.