Technical Project Description

Project Title: *Sikunnguaq* - "the likeness or image of ice in maps"

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a) Objectives

The following are the short-term objectives of this project:

1. develop sea ice information retrieval algorithms for satellite data for safe sea ice travel needs as identified by Inuit (ice roughness, slush, and ice thickness);
2. transfer satellite information retrieval methods to prototype image product formats representing usable information layers for map-makers in communities; and
3. produce satellite and field data related training materials and protocols to enable the extension of objectives 1 and 2 beyond the project scope, as desired by communities.

Long term objectives of this project are:

1. empower communities to utilize advanced satellite remote sensing technologies, in support of *Inuit Qaujimajatuqangit* (IQ) and currently used technologies, for safe sea ice travel; and
2. improve health, safety, climate resilience, and less search and rescue situations.

b) Rationale

In the coastal communities of the Canadian Arctic, Inuit are vulnerable to increasingly variable sea ice conditions on diurnal, seasonal, and inter-annual time scales [1]. In recent years the emergence of unpredictable features including rough ice, slush zones, and thin ice areas has caused accidents and deaths, and negatively impacted the use of sea ice as an essential platform for travel and subsistence activities [2,3]. Sea ice trails are used like roadways for accessing the land, and the underlying or adjacent ocean is a key source of traditional foods. The breakdown of sea ice in a manner that confounds traditional knowledge, and challenges the leading-edge of monitoring technologies, results in contemporary, and worsening, risks associated with travel on sea ice as critical physical infrastructure. In turn, this leads to risks to food security and well-being.

Our overarching project goal is to empower Inuit Nunangat (IN) communities to strengthen their resilience to rapid Arctic climate change, and the associated risks to their well-being and food security, by improving travel safety. Our approach involves developing new sea ice mapping techniques by combining satellite imagery with field-based drone and on-ice surveys to develop new ways to map sea ice travel hazards including rough ice, slush zones, and thin ice areas (Figure 1). New satellite technologies will allow us to better detect these hazardous features than before. If successful, a novel component of this project is the creation of routinely mapped sea ice features including thickness from synthetic aperture radar (SAR), with potential for far-reaching impacts including safety, climate research, and weather prediction. Importantly, as climate change intensifies [4], the SAR based information about sea ice will provide the appropriate spatial and temporal scales for community use and provide an alternate solution in place of *in-situ* sensor deployments and on-ice activities that have become increasingly restricted due to the presence of marginal ice travel conditions.

The scientific basis for this project is related to recent developments in satellite remote sensing technology, particularly SAR. Specifically, the RADARSAT Constellation Mission (RCM), and the pending NASA-ISRO (NISAR) mission, due for launch in early 2025, are missions that provide the

Figure 1. (Left) Travel over rough ice is damaging to snowmobiles, costly in time and fuel, and more dangerous than smooth ice (credit: Andrew Arreak). (Right) Slush under snow can trap and stall snowmobiles, leaving passengers stranded and wet, far from home (credit: David Iqqaqsaq).

potential to be used as critical input to the mapping solutions proposed here. SAR is an established remote sensing tool for operational sea ice mapping and is used extensively for ice charting agencies to support marine operations [5]. The ability of SAR to provide sea ice information at relatively high spatial scale (nominally <100m) and high temporal scales due to acquisition consistency owning to independence from cloud, weather, or daylight conditions, is well established. The advantages have led to the increased prominence of SAR in research on sea ice, in climate, atmospheric, oceanographic, and ecological contexts. SAR has been used for sea ice classification [6]; ice/open water discrimination and ice concentration [7,8]; ice and melt surface discrimination [9-11]; ice thickness proxies [12-14]; sea ice roughness at the geometric scale [15,16]; the broad-scale tracking of deformation [17]; melt onset [18]; and flooded ice (and slush) on Antarctic sea ice [19]. SAR has been demonstrated as advantageous for community-focused sea ice monitoring in safety and trafficability contexts: the combination of high-resolution remote sensing, including SAR, IQ, and on-ice measurements has been viewed by Inuit users as 'the best of both worlds' [20] when it comes to safe ice travel in Inuit Nunangat [21].

RCM is a three-satellite constellation capable of providing imagery of the entire Canadian Arctic domain every 1-2 days at 100 m spatial resolution or better. RCM operates in the C-band frequency (5.4 GHz), the same frequency as the European Space Agency's Sentinel-1 mission. RCM can image in compact polarimetric (CP) mode over a wide swath. The CP mode preserves the intensity and phase information of backscatter which enables the signal to be decomposed into its roughness and dielectric (*i.e.*, wetness and salinity) contributions [22]. While C-band backscatter has already shown promise for sea ice roughness detection [16,23], CP mode sensitivity to dielectric constant shows potential for slush detection based on the dielectric contrast between water (~80) compared to snow and ice (~3-5). CP mode data has also shown promise for the retrieval of level ice thickness between 0.1m to 0.8m based on dielectric changes from ice desalination as it grows [24]. Tasking of RCM modes, first for experimentation, and later for operational implementation, will be possible through our collaboration with the Canadian Government.

NISAR will provide the first open access SAR data stream in the lower L-band frequency (1.3 GHz). L-band SAR data from the current, restricted access, ALOS-2 mission have shown promise for the estimation of roughness and ice thickness across the 1.6m to 3.8m range [16,25]. With testing, it can be used to extend the mapping capability of RCM. Importantly, the lower frequency provides detection potential in situations where deeper radar wave penetration is necessary, such as detecting dangerous slush and thin ice areas buried under a thin snow cover. L-band has also been shown to be less impacted by surface melt and will enable detection of sea ice features into the spring period [26].

Despite successful developments in SAR for sea ice monitoring, additional work is required to reduce uncertainties and improve retrieval accuracy for specific locations and time periods. This requires a more comprehensive understanding of SAR signals from sea ice over a wide range of seasonally and regionally dependent geophysical properties and environmental conditions, along with consideration of the advantages of relatively understudied frequencies, such as the L-band frequency of NISAR. Mult-frequency SAR studies that combine the collection of SAR images with detailed *in situ* data collection, are essential. This project will address this research need by collecting the *in situ* data specific for the development of ice roughness, slush, and ice thickness retrievals for SAR data at site locations relevant to, and prescribed by, participating communities.

Given how critical C-band SAR and the RADARSAT program is for operational sea-ice monitoring and marine stakeholders in Canada, and how the field of L-band SAR is growing in prominence and data availability with NISAR (and the future European Space Agency ROSE-L mission), we are convinced that these missions will meet the objective of operational implementation beyond the formal project end-date. Using open access and free satellite data will be used to minimize barriers to knowledge mobilization. Participation by the government sector as collaborators in this project will ensure that these SAR technologies needed to fulfill the project objectives are first acquired, and that the SAR image datasets are available for implementation beyond the project scope. As recently voiced by our Inuit co-Principal Investigator (co-PI), the support of Inuit-led science programs, such as their own community Ice Travel Safety Mapping, “illustrates the incredible potential of Indigenous self-determination in cryospheric science when the scientific merit of IQ is fully recognized, when Indigenous researchers are able to access technologies and training to apply their IQ, and when non-Indigenous partners mentor and support young Indigenous scientists” [27]. As knowledge holders of the long-term record of, and local variability in, sea-ice conditions, Inuit are the “original Arctic scientists'' [28].

c) Progress to Date: Describe the results of any work completed to date. This section should also include information on any progress in the areas of capacity building, communications and/or the use of Indigenous knowledge.

This project has adopted the *Sikumiut-SmartICE Model of Community Partnership*. In this model local communities govern project activities, ensuring that *Inuit Qaujimajatuqangit* is combined with scientific expertise in map production [29]. Each participating community convenes a community management committee (CMC) that governs project activities and provides mentorship around IQ use. CMCs ensure that the sea-ice IQ we document and share is accurate, as it provides the foundation for our research strategy regardless of discipline. Involving the communities in the project substantially improves the effectiveness of, and confidence in, newly generated Ice Travel Safety Maps, as users will know they are produced with a combination of IQ, local observations, and technology operated by one of their own.

Detailed project planning with SmartICE CMCs has informed the scientific research goals of this project. For this application, long-term CMCs in Mittimatalik (since 2016) and Qikiqtarjuaq (since 2018; self-named *Ikirmiut*, meaning “people of the coast”) have received information (*e.g.*, presentations, briefing notes) about the project and provided letters of support. In Iqaluktuuttiaq (Cambridge Bay), the project was presented to the municipality and the Ekaluktutiak HTO and letters of support are attached or forthcoming. In Uqsuqtuuq (Gjoa Haven), our long-term Sikumik

Qaujimajjuti Trainer and Sikunnguaq project co-PI, Leanne Beaulieu, has taken a leave of absence from SmartICE and as a result we were unable to convene a meeting of our CMC (self-named *Qiqiqtaqmiut*, meaning "people of the island") in time for this permit application. A letter of support will be requested at their next meeting in the first quarter of 2025 prior to any project fieldwork in the community.

d) Methodology

Field Research Methodology

The field research methodology is based on the need to collect *in-situ*, and drone-based, sea ice and snow thickness, roughness, and slush data, coincident to satellite data, during field campaigns in the late-winter to spring periods (mid-March to mid-May) in 2025 and 2026. Four Nunavut communities have been selected as locations associated with sea ice data collection, as dictated by the combination of community-specific needs and availability of SmartICE personnel. In each project year, there will be primary communities selected for detailed data collection involving large science teams and SmartICE personnel. There will also be secondary locations involving a smaller science team and SmartICE personnel contributing a comparatively limited, but effective, suite of *in situ* snow and sea ice variables. In 2025, the primary data collection sites will be Mittimatalik (Pond Inlet) and Qikiqtarjuaq, where detailed measurements will be made of sea ice roughness and slush, respectively. Secondary sites in 2025 will be Iqaluktuuttiaq (Cambridge Bay) and Uqsuqtuuq (Gjoa Haven). Our current plan is to retain this structure of primary and secondary sites for 2026 as well. The focus of 2025 data collection is for calibration (*i.e.*, learning), whereas in 2026 the focus is on validation and refinement.

The SmartICE CMCs, along with their partnering organizations, will inform the project team of specific field sampling areas within the pre-defined areas of interest associated with each community. *In situ* data collection will focus on snow and sea ice properties critical for interpreting C- and L-band frequency SAR backscatter, reducing uncertainties, initializing sensitivity analyses using a microwave scattering model (i.e., the SMRT model [30]), and sea ice property retrieval algorithm development. The following parameters will be measured at reference snow-pit and ice core locations at primary sites:

- snow temperature, density, and salinity, and dielectric permittivity and loss at 50 MHz (profiles with 3 cm vertical spacing);
- snow stratigraphy and grain type;
- snow grain specific surface area (SSA);
- snow wetness, if applicable;
- sea ice temperature and salinity (profiles with 5-10 cm vertical spacing);
- sea ice stratigraphy; and
- snow and sea ice thickness, with sea ice freeboard height.

Snow-pit and ice core measurements at primary sites will be collected across a range of spatial scales to address variability associated with known influences including wind (1-50 m), sea ice floe dynamics (>50 m), and precipitation (>1 km). Measurements will also be collected at scales appropriate for process scale analysis (~10 m) and satellite product development (>1 km).

On-ice electromagnetic (EM) sensors will be used at primary sites for conducting transects of snow and sea ice thickness, and for delineating flooded, *i.e.*, slush ice, areas forming in cold conditions due to heavy snow-loading and sea ice depression below the water line. An EM-31 (single frequency

EM sensor) and a GEM-2 (multi-frequency EM sensor) will be operated in transect mode to measure snow and sea ice thickness. A digital snow probe (or manual ruler, *i.e.*, metre-stick) and manual ice auger (2-inch diameter Kovacs-type) will be used to record snow thickness, sea ice thickness, and freeboard measurements at fixed intervals along each transect (for EM instrument calibration purposes). Several transects will be used to characterize "grid cells", areas of approximately 300 x 300 m, to ensure that the variability of the satellite SAR swath is captured. Additional characterization of slush areas will include slush properties (temperature, salinity, dielectric permittivity and loss at 50 MHz, and slush depth), slush state (liquid, re-frozen), and spatial extent.

Additional data collected at primary sites include drone surveys of 4-8, 300 x 300 m, locations with cameras, for deriving surface roughness using photogrammetric techniques. Vertical profiles of air, snow, sea ice, and upper ocean temperature, will be provided by sea ice buoys (SmartBUOY) fixed in the sea ice at locations determined by CMCs. These sensors each provide temperature readings from 60 thermistors, which can be used to understand vertical temperature variations with time, to derive layer thicknesses (snow, sea ice), and to understand atmosphere-ocean energy exchanges with the snow and sea ice volume (e.g., surface melt and bottom melt). Small, battery operated, profiling CTDs (conductivity, temperature, depth) will be lowered and raised through a 9 cm diameter hole in the sea ice to measure the temperature and salinity of the water column. Meteorological data will also be obtained from Environment and Climate Change Canada maintained weather stations in proximity of study communities.

At secondary sites the smaller research teams will follow a simplified field sampling strategy compared to that of the primary sites. Ice monitoring surveys will be conducted along transects and within the coverage of coincident satellite SAR data collections. These surveys will use current SmartICE equipment (EM-31 ice thickness sensor, auger), so that the total thickness measurements can be combined with snow thickness measurements to provide snow and sea ice thickness. Surface roughness will be measured using drone surveys of 2-3, 300 x 300 m, locations at each secondary site. A simplified snow-pit and ice core sampling scheme will enable collection of the following variables at 100-200 m intervals along a transect line:

- snow temperature, density, and salinity (profiles with 5 cm vertical spacing);
- snow stratigraphy and grain type;
- sea ice temperature and salinity (profiles with 10 cm vertical spacing);
- sea ice stratigraphy; and
- snow and sea ice thickness, with sea ice freeboard height.

At secondary sites, small, battery operated, profiling CTDs will be lowered and raised through a 9 cm diameter hole in the sea ice to measure the temperature and salinity of the water column. Meteorological data will also be obtained from Environment and Climate Change Canada maintained weather stations in proximity of study communities.

Data Analysis

Data analysis will take place from May 2025 to the project end-date of April 2027. The collected field data will provide geophysical and EM data for constraining uncertainties in satellite signals and optimizing SAR modes for estimation of continuous variables roughness and thickness, and for detecting slush zones. *In-situ* measurements provide essential detail on confounding variables on SAR measured backscatter, such as the occurrence of ice lenses, and enable us to identify the expected radar penetration depth at the radar frequencies of interest. The SAR signature controlling properties of snow and sea ice are scale-dependent, such that effective understanding requires combining radar wavelength scale (cm-scale) measurements, such as those from snow-pits and ice cores, with geometric scale (m- to km-scale) measurements, such as those from drone photos and transects.

Data will be used for development of satellite-based roughness and slush retrieval algorithms following a calibration/validation (cal/val) approach. This analytical framework includes methods for modeling the EM behavior of snow and sea ice for conducting sensitivity analyses [30], and for upscaling from the *in-situ* to SAR scale [31]. Surface roughness models will be developed for RCM and NISAR, individually or combined, and optical Multi-angle Imaging SpectroRadiometer (MISR) will be investigated for minimizing estimation errors [32,33]. RCM and NISAR backscatter intensity, and the RCM CP mode, will be used to identify high-dielectric surface and sub-nivean slush zones. Additionally, state of the art machine learning techniques may offer ways to provide the communities with enhanced resolution roughness and slush maps over areas of interest.

The data products roughness and slush (and, if feasible, ice thickness) will need to be incorporated into the SmartICE Ice Travel Safety Maps, the need for which was first recognized by CMCs. They identified that the ice charts produced by the CIS are primarily designed to support shipping and ice-breaking and are generated at temporal and spatial scales inconsistent with on-ice travel. These novel community-scale maps are being co-designed by the SmartICE *Sikumik Qaujimajjuti* program led by co-PI Wilson. These maps, the CMCs argue, would help reduce travel risks, especially for younger Inuit with less on-the-land experience. They also insist that local Inuktitut terminology for sea-ice conditions be used on the maps, together with their mapped knowledge of persistent ice hazards and safe areas (e.g., protection from winds; distribution of cabins for safe-havens, etc.). The training curriculum has been co-developed over the past 3 years with operational Ice Travel Safety Maps now being delivered in three IN communities over the past 2 years (two of which are our project communities Mittimatalik and Uqsuqtuuq).

Given the project goal of incorporating data products into SmartICE Ice Travel Safety Maps, an important part of the data analysis phase will be the conversion of retrieved variables roughness, slush, and thickness into data layers that meet the requirements for operational use in Ice Travel Safety Maps. We will develop and pilot the implementation of a framework for routine delivery of sea ice information in useable formats for extension beyond the project scope. The framework will facilitate the direct flow of input satellite and ancillary information to output maps products (*i.e.*, digital and hard copy) that are routinely updated and delivered to mappers and other Inuit sea ice users as determined by SmartICE and the CMCs. The operational delivery of map products will benefit from UCL group expertise in delivering national satellite data capability via their work at the Centre for Polar Observation and Modelling (CPOM) in the UK. This know-how to automatically download and process large satellite data into sharable and usable streams of information (*i.e.*, via website platforms) will be shared with partnering groups in Canada so that the full prototype framework will be operated on Canadian servers by SmartICE to support mapping for all communities in IN.

Training Materials

SmartICE provides opportunities and pathways for young Inuit women and men to augment their IQ and ice expertise with new technical skills for the wellbeing of their communities. Its *Pilimmaksaqniq Sikulirijimik* program, meaning “training to be a worker who deals with ice”, trains and employs Inuit as *sikulirijit* [34]. The program encompasses a broad range of soft and hard skills and reflects Inuit ways of knowing and learning. It was co-designed with Inuit educational experts and community ice users to provide the technical knowledge and skills that *sikulirijit* require to successfully run SmartICE monitoring and mapping systems, and to interpret and share the ice information they collect with their community. One key component of the program is its delivery by Inuit trainers, who foster a culturally contextualized learning environment, and the other is that IQ is the foundation for the training content and learning approach.

As part of this project, training specialists and SmartICE co-PIs Arreak and Davidge will work with other experts in the project team to create the training curriculum for the operation and troubleshooting of new sensors (GEM-2, drone) and data collections (snow pit, ice core). Delivery of training will take place in project communities by SmartICE during the 2025 ice season, in preparation for validation data collection during the 2026 ice season. It is anticipated that *sikulirijit* will be collecting these new data, as required for community Ice Travel Safety Map creation purposes, independently, beyond the project scope.

e) Data management

For decades scientists came to Inuit communities to collect their IQ and monitor their environment, without Inuit ever hearing from the scientists again, learning about what was studied, being acknowledged for their contributions, benefiting, or having access to the data. Today, having access to their data is a right, and it's about maintaining power and decision-making for their community. The Government of Canada IN policy describes that "Equity does not denote sameness of treatment, but rather fairness and justice in process and results. Achieving equity involves removing barriers, correcting conditions of disadvantage, and introducing special measures to accommodate differences with the goal of establishing a level playing field for all" [35]. How can the *Sikunnguaq* project work with our project communities and funders so that the data being collected can be shared in a way that is socially responsible and acknowledges and respects Indigenous knowledge and ownership? For the project funder, how can data sharing support Inuit self-determination and equity, empower Inuit community-based monitoring, and provide long-term benefits that give back to Inuit communities and maintain their access and control? In a parallel funded project, SmartICE, together with several CMCs, funders, and invited experts will be navigating an Indigenous data sharing framework. We intend to apply what is learned from this initiative to establish a data sharing framework for *Sikunnguaq*. PI Scharien and co-PI Wilson are leading this data sharing framework development.

Scientific data will take three forms: field data; satellite data; and output data layers for travel safety maps. Where appropriate, they will be managed according to the "FAIR Guiding Principles for scientific data management and stewardship" in Scientific Data, which meets the principles of findability, accessibility, interoperability, and reusability (FAIR). They will be submitted with metadata to the World Data Center for Marine Environmental Sciences PANGAEA data repository maintained by the Alfred Wegener Institute (AWI), where they will receive a Digital Object Identifier (DOI). Data will be stored at the earliest opportunity after processing and quality check, and will be made publicly available after finalization of analyses, interpretation and publication by ourselves. Thorough testing and validation of derived products are planned and results from these tests will be documented and uncertainties will be fully integrated into products available via download. Where appropriate data will also be deposited with the UK Polar Data Centre at the British Antarctic Survey (BAS) and the Polar Data Catalogue in Canada.

Further considerations include uploading *in-situ* data to SmartICE data servers and, pending agreement with communities, placing them on the online and freely available SIKU (The Indigenous Knowledge Social Network) platform developed by the Arctic Eider Society (AES). Printed maps and their hard and soft copies will be provided to the communities and stored in the community with the CMC and proper procedures will be followed to request agreement for external dissemination. Travel safety maps will benefit from direct assessment from Inuit experts on the ground and inclusion of IQ but will be provided with the warnings that travel on ice remains a high-risk activity and usual precautions must be taken.

f) Research outputs

A variety of research output formats are needed to meet the range of accessibility needs of IN communities, requiring us to discuss with each CMC how best and how often to communicate results. Forms may include videos, newsletters, community meetings, or Facebook posts, all of which SmartICE has experience in producing and sharing in IN. Formats may also vary by community demographic: Elders preferring written (translated) text in the form of newsletters and younger generations preferring digital media. We will present the project developments at regional trade shows hosted by Indigenous organizations and regional community forums. The latter will be important for demonstrating and sharing the technology and its results with other interested communities and Indigenous organizations.

The main research outputs, representing our operational solutions for IN communities to overcome risks for the coming decades, will be the data layers that are operationally integrated into the Ice Travel Safety Maps. Production of these maps in their current format is already successful in participating communities and will be expanded through this project. The maps are made at spatial scales that reflect local travel patterns and are produced on a schedule consistent with local sea ice dynamics and information needs. IN communities will also be able to access in near real-time these new map products through the Indigenous Knowledge Social Network platform (SIKU). Revolutionary developments in cell phone coverage (e.g. Starlink), and Wifi means that users are able to access information fast and in real time, during route planning, or even on snowmobile trips or in cabins.

Research outputs also include publication of extended abstracts for annual conferences that provide progress reports on the overall project. These summaries will be used to communicate project developments and progress to the funders and to professional organizations at their national conferences. Dissemination of project results to the broader research community involves traditional formats including the publication of at least three, peer-reviewed, journal articles on sea ice information retrieval methods, along with published datasets. These journal articles will all be led by early career researchers and will include project team members in participating communities. The project leadership intends to publish an article outlining the framework for the implementation of operational solutions for at-risk communities facing unprecedented environmental changes, with the intention of extending the developed methods and learned experiences to the broader academic community.

Research outputs also include best practices for utilizing SAR data that are shared with project collaborators and, by extension, the general public. For example, our results will reach the general public through government collaborators at the Canadian Ice Service (CIS) and other departments within Environment and Climate Change Canada (ECCC). ECCC is mandated to provide weather, climate, and safety information (e.g., storm warnings, ice hazard charts) for public benefit. ECCC's reach also extends internationally through co-operative activities such as involvement of CIS in the International Ice Charting Working Group. ECCC and CIS will benefit from improved methods for using SAR to enhance its numerical sea ice and weather prediction capabilities [36] and producing ice charts for safe navigation [37]. They will benefit from the sea ice and SAR research in this project as it helps them to overcome environmental effects and ice properties [38-40] that compromise the ice charting process.

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