DEVELOPMENT OF A SENSOR SYSTEM TO SUPPORT AVALANCHE RISK MANAGEMENT IN ARCTIC NORWAY

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ABSTRACT: Automated measurements of snow cover properties serve as a key data source for most avalanche forecasting programs. In Longyearbyen, Svalbard, a lack of automated snow depth measurements presented a challenge to daily site-specific avalanche forecasting efforts in the initial seasons following the program's establishment in the aftermath of a fatal avalanche accident in December 2015. This work describes a snow depth sensor system in Longyearbyen as it evolved over five winters from a proof-of-concept test of communication technology to a robust snow measurement program supporting avalanche forecasters in two communities in Arctic Norway. We have focused on developing a low-cost, low-power sensor concept which measures snow depths in avalanche release areas with high temporal resolution and delivers these data to avalanche forecasters in an operational time frame. The resulting system relies on ultrasonic snow depth sensors which transmit data via a Narrow Band Internet of Things (NB-IoT) communication device to a web interface with data available in quasi real-time. Semi-regular snow depth measurements with a terrestrial laser scanner (TLS) serve to help select and iteratively update ultrasonic sensor placement while also contextualizing the ultrasonic measurements within the forecasting area's drainage-scale snow depth variability. In addition to offering an illustrative example of an effective, low-cost snow monitoring sensor concept, we provide suggestions, based on our experiences with measuring snow in Longyearbyen, for a framework by which to develop sensor-based natural hazard monitoring systems.

KEYWORDS: Sensors, risk management, terrestrial laser scanning, ground-based LiDAR, Arctic

1. INTRODUCTION

Snow avalanches have a long history of impacting human life and infrastructure in Longyearbyen, Svalbard. Most recently, naturally-released slab avalanches struck inhabited infrastructure in December 2015 and again in February 2017, resulting in two fatalities of residents in their homes and destroying fourteen residential buildings (Brattlien et al., 2016; Landrø et al., 2017; Hancock et al., 2018). In the aftermath of these events, a variety of local and national actors have worked to improve avalanche risk management in Longyearbyen through the establishment of daily avalanche forecasting routines for threatened infrastructure, installation of structural defenses in key avalanche paths, and the relocation and removal of exposed residences.

Daily avalanche forecasting for endangered infrastructure in Longyearbyen began in the immediate aftermath of the fatal December 2015 avalanche and has continued to the present day in various forms (Engeset et al., 2020). Currently, a private consulting firm contracted by the Norwegian Water Resources and Energy Directorate develops and delivers the daily avalanche forecast to local authorities. The authorities in turn use the forecast as a basis to aid decisions on possible risk mitigation measures such as area closures or building evacuations.

The present work describes the development of a snow depth sensor system to support site-specific avalanche forecasting in Longyearbyen. This system provides data on snow conditions in avalanche release areas to help reduce uncertainty and improve accuracy in the avalanche forecast. By describing the evolution of this sensor system from a research project into an operational tool, we hope to provide a foundation – in the form of practical suggestions based on our experiences – for other programs to employ similar sensor technologies to better manage risks related to natural hazards.

An extended version of this work can also be accessed online as an interactive ArcGIS StoryMap in the link given in the final section of this paper.

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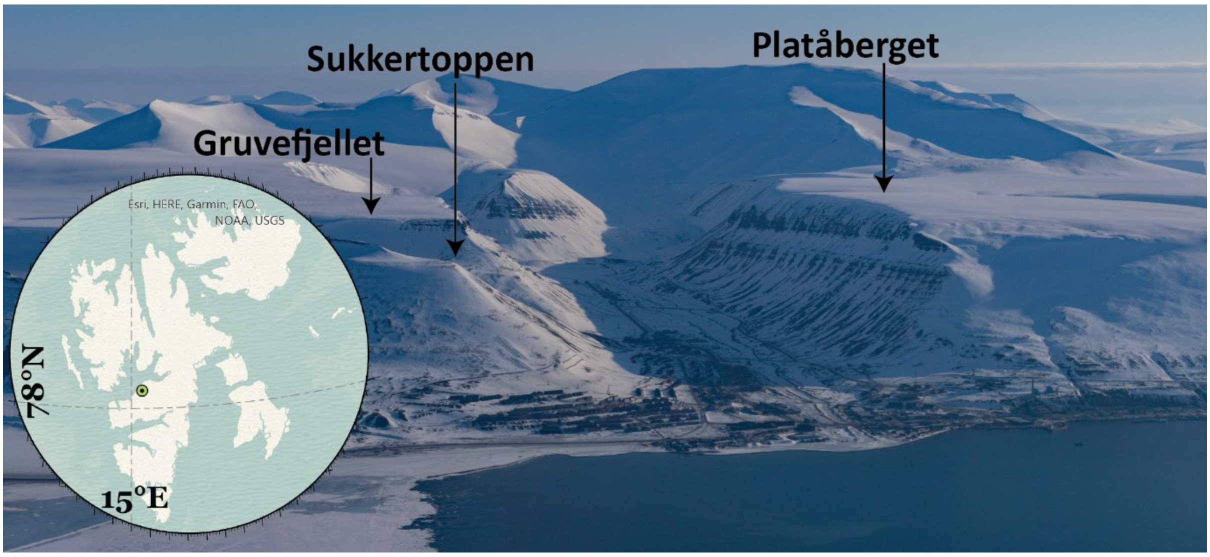

Figure 1: Longyearbyen's physical setting in Svalbard. The inset map shows Longyearbyen's location on Spitsbergen, the largest island in Svalbard. The photo, looking south over Longyearbyen, illustrates the avalanche-prone slopes on the labeled mountains surrounding the settlement.

2. PROJECT CONTEXT

The initial impetus for this project occurred when, following the 2015 and 2017 avalanche events, the University Centre in Svalbard (UNIS) received funding to install three snow monitoring stations around Longyearbyen for the 2017/2018 winter season. These stations, based on a Campbell Scientific platform and installed in avalanche release areas, would support snow research and site-specific avalanche forecasting services with measurements of various snow and meteorological parameters (Prokop et al., 2018).

Concurrently, a telecommunication company in Longyearbyen, Telenor Svalbard AS, began exploring Low Power Wide Area Networking (LPWAN) communication technology as an avenue to reduce data transmission costs. Telenor Svalbard initiated contact with UNIS and agreed to install a low-cost prototype ultrasonic snow depth sensor on the same mast as one of UNIS' snow stations (Figure 2).

The first season of automated snow measurements (2017/2018) from the initial UNIS stations successfully acquired a snow depth dataset useful for both avalanche forecasting and research (Prokop et al., 2018; Hancock et al., 2020). However, departure of key project personnel, requirements to move the sensors, and a mismatch between system requirements and available resources led us to rethink our sensor concept for the following season.

Based on positive preliminary results from the first prototype sensor, we worked over the subsequent seasons to develop the current sensor concept employed in Longyearbyen around this technology. Since 2021, this sensor work occurred as part of the research project *Risk governance of climate-related systemic risk in the Arctic* (ARCT-RISK). With Svalbard experiencing among the most dramatic climatic changes globally (e.g. Isaksen et al., 2022; Rantanen et al., 2022), ARCT-RISK treats risk management approaches tested here as a foundation for strategy development in other environments where similar climatic changes are expected to occur. This sensor work can therefore hopefully serve as a springboard for sensor-based natural hazard monitoring systems in other, lower-latitude locations.

Figure 2: Installation of the prototype sensor, seen to the right of the Campbell Scientific sensor on the mast arm, in January 2018. Telenor Svalbard AS photo.

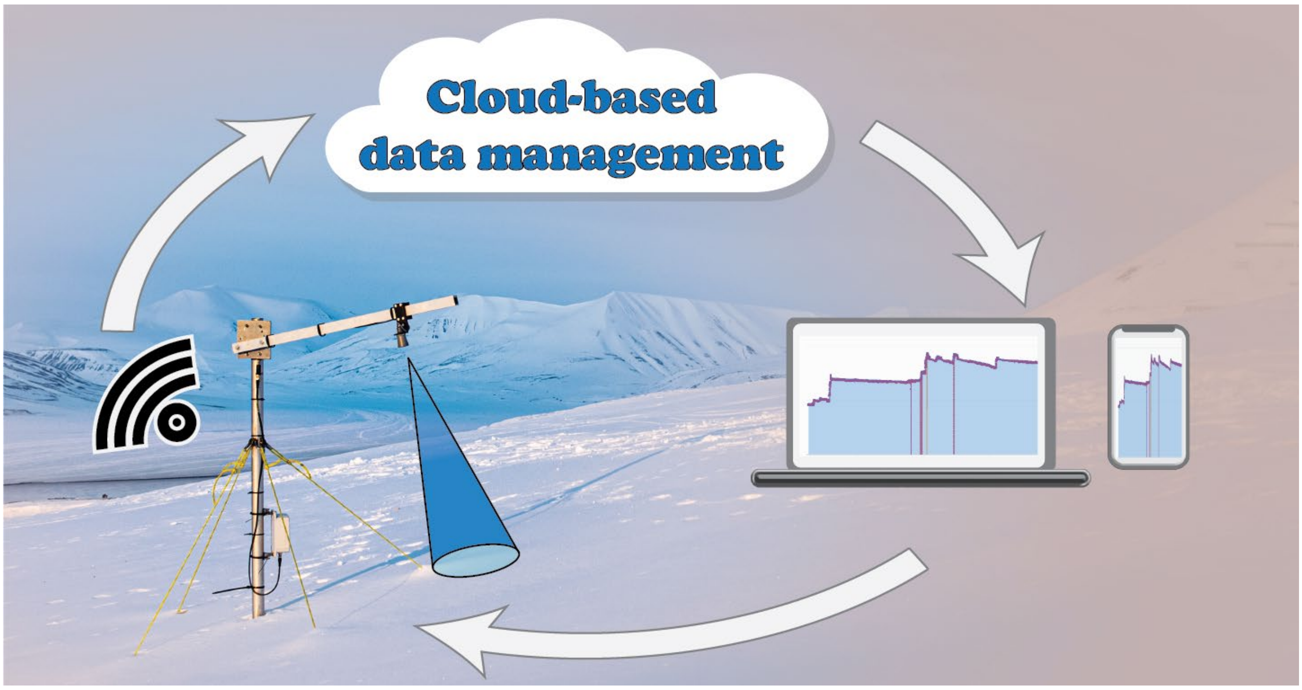

Figure 3: Diagram representing the general sensor concept employed for the ultrasonic snow depth sensors described in this work.

3. THE CURRENT SENSOR SYSTEM

When employing sensors as a tool in the risk management of natural hazards, we propose seeking a sensor concept which:

- Will measure a parameter relevant for the natural hazard in question;
- Can measure this parameter at the most optimal location; and
- Will deliver the measured data to users in an operational timeframe.

To satisfy these requirements in the context of avalanche forecasting in Longyearbyen, we have developed a sensor system reliant primarily on ultrasonic snow depth measurements and Narrow Band Internet of Things (NB-IoT) communication (Figure 3). We chose to employ ultrasonic snow depth sensors as the basis for this sensor system because 1) snow depth changes in avalanche release areas serve as a critical avalanche forecasting parameter (e.g. Schweizer et al., 2009), and 2) we could easily modify available low-cost ultrasonic sensors to interface with our communication technology and suit our low power requirements. Semi-regular, terrestrial laser scanning (TLS) supplements the automated, point-scale data from the ultrasonic sensors with spatially distributed snow depth measurements.

The current sensor configuration transmits data via Narrow Band Internet of Things (NB-IoT) technology to a cloud-based data management system from which users can access the data in real-time via a data visualization portal (Figure 3). Data managers can also communicate with the sensor itself to, for example, change the time interval between measurements or troubleshoot sensor failures from the office.

We have iteratively improved this sensor design based on our experiences from each successive winter season. We emphasized a low-power design which could easily measure and transmit data throughout the winter season without the possibility for solar recharge during the three months (November-January) of polar darkness in Svalbard. Here, paring a low-power ultrasonic sensor with efficient data transmission via NB-IoT significantly reduced power consumption compared to more traditional snow measuring stations. The current sensor design uses just 0.6 Joules to conduct and transmit a snow depth measurement over the network, corresponding to 11 years of year-round measurement with 15-minute sampling intervals and the standard battery configuration.

We also sought a design which allowed for easy installation, maintenance, and replacement to improve user-friendliness in the field. This has included experimentation with various mast constructions, sensor mounting strategies, and sensor housings and configurations. While early prototypes combined the ultrasonic sensor and the communication device in a single boxlike housing, the current generation's ultrasonic sensor connects to a separate housing containing the communication device via a standard cable and connector (M12). In addition to allowing for a full redesign of the hardware platform which helped to eliminate measurement instabilities and improved power efficiency, any sensor using standard communication protocols can now connect to the communication device, increasing the system's flexibility.

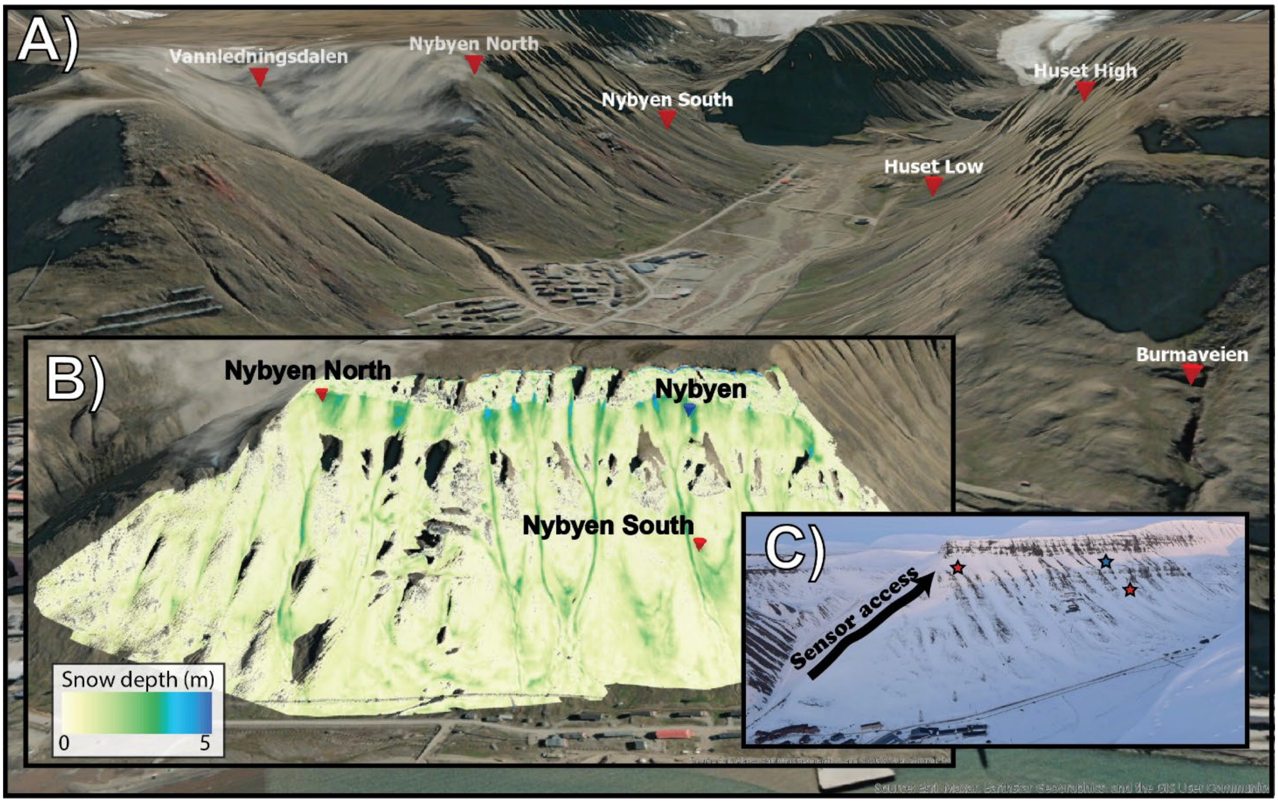

Figure 4: Panel A shows the current sensor locations near Longyearbyen, visualized looking south. Panel B shows the original (Nybyen, blue marker) and the current (Nybyen North and Nybyen South, red markers) station locations and TLS-derived snow depths from March 2017 on Gruvefjellet's western aspect. Panel C illustrates the sensor placements and the "safe" sensor access route to Nybyen North.

3.1 Sensor placement

The current sensor network consists of six stations in the vicinity of Longyearbyen (Figure 4A). Five of these stations consist of the standard ultrasonic sensor configuration displayed in Figure 3, while the Vannledningsdalen station consists of Snow Pack Analyser SPA-2 from Sommer Messtechnik.

The availability of a TLS system at UNIS has allowed us to employ established techniques for measuring spatially-distributed snow depths with TLS (Prokop, 2008; Deems et al., 2013) to help select and repeatedly update sensor placement. We chose the sites of the original three stations using TLS data in combination with existing knowledge of avalanche hazard in the area (see Prokop et al., 2018). High spatial resolution snow depth maps derived from TLS data allowed us to select locations with snow accumulations representative of the release areas, but not so much snow as to bury the sensors themselves.

Decreasing sensor cost as we transitioned to the NB-IoT sensors in subsequent seasons allowed us to add stations for improved spatial coverage and to provide redundancy in the event of a sensor failure. We continued to rely on TLS data and avalanche hazard information including hazard maps and manual observations taken by local observers to update and select new station locations. Practical considerations related to the season-by-season construction of long-term, structural protection measures on Sukkertoppen and general station accessibility have also influenced site selection. For 2022/2023 we removed the sensors on Sukkertoppen due to structural measure completion, but added the Vannledningsdalen and Burmaveien sensors to monitor snow depths in slushflow release areas.

Sensor placements and TLS-derived snow depth data from Gruvefjellet (Figure 4B) help visualize these considerations. The initial "Nybyen" station was well-situated to capture snow accumulation in the release areas on Gruvefjellet where falling cornices can trigger slab avalanches (Hancock et al., 2020). However, avalanche hazard limited access to this sensor throughout much of the winter. While the installation of "Nybyen South" lower in the avalanche path improved sensor accessibility, data from this sensor were less representative of the upper release areas directly under the cornices. We therefore placed "Nybyen North" in an area more representative of the upper release areas, but in a more accessible location (Figure 4C). The new stations thus improve 1) spatial coverage by doubling measurement sites, 2) station accessibility while still providing data from relevant areas, and 3) the reliability of the system by providing redundant data from Gruvefjellet should one sensor be destroyed or malfunction.

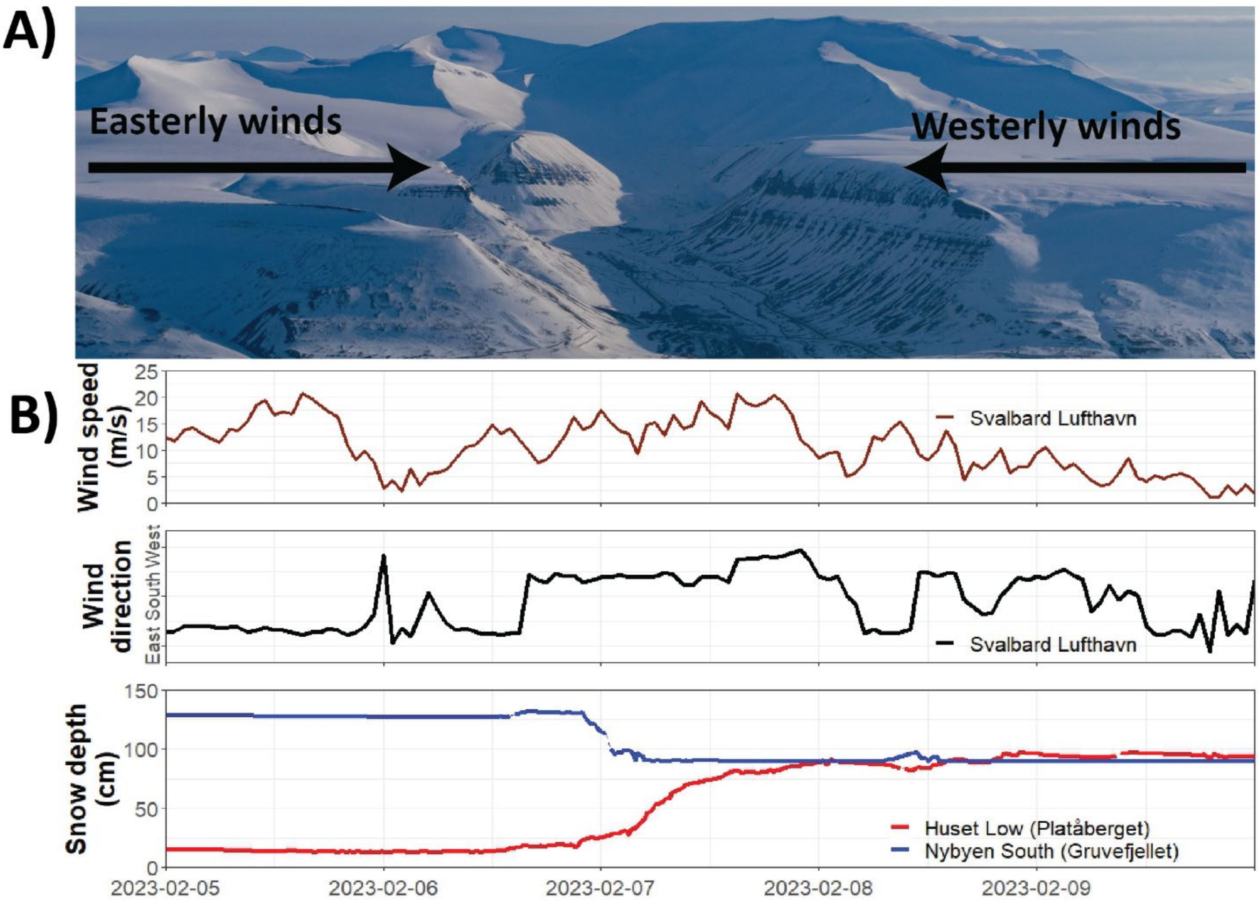

Figure 5: Panel A displays the relevant wind directions over Longyearbyen's topography. Panel B shows selected wind speed, wind direction, and representative snow depth data from early February 2023.

3.2 <u>Case study</u>

Prevailing winds near Longyearbyen typically blow from the east, but low-pressure systems off the western coast of the island often generate westerly winds during winter storms (e.g. Wickström et al., 2020). Previous research has demonstrated the clear control wind direction has on snow accumulation patterns in this valley (Eckerstorfer and Christiansen, 2011; Vogel et al., 2012; Hancock et al., 2020), with the release areas on Gruvefjellet receiving snow loading from easterly winds and the Platåberget slopes accumulating snow under westerly winds (Figure 5A). However, operational avalanche forecasting for Longyearbyen cannot rely on the primary observational techniques employed in these studies (e.g. post-event observation, timelapse cameras, and TLS-based snow measurements), especially during storms with limited visibility.

A winter storm in early February 2023 represented by the select data (Figure 5B) brought snowfall, strong winds from varying directions, and reduced visibility due to blowing snow to Longyearbyen. The period began under relatively strong easterly winds on 2023-02-05. Winds decreased throughout the evening of 2023-02-05, and it began to snow around midday on 2023-02-06. Shortly after, winds abruptly shifted from easterly to westerly and increased in strength while snowfall continued. Westerly winds remained strong throughout the day on 2023-02-07, before decreasing on 2023-02-08.

Snow depths measured at sensors placed on opposing slopes in Longyearbyen (Huset Low on Platåberget and Nybyen South on Gruvefjellet – see Figure 4A for sensor placement) reflect these meteorological conditions (Figure 5B). Snow began to accumulate on both sides of the valley midday on 2023-02-06 under light winds. Later that evening when the winds abruptly shifted to westerly and gained strength, however, snow depths on Platåberget's leeward slopes increased dramatically, while windward slopes on Gruvefjellet experienced snow depth erosion. Snow continued to accumulate on Platåberget throughout the day on 2023-02-07 before the storm tapered off.

These data illustrate the utility of the sensor system for monitoring snow accumulation under challenging forecasting conditions while also showing the sensor network captures expected variability in snow accumulation in real-time. This allows forecasters to better trust these data as a basis for risk management decisions, especially during periods of increased uncertainty when limited visibility prevents direct visual observation of starting zones by local observers.

3.3 System flexibility

Technological advancements, increasing financial and/or labor resources, and, over longer time perspectives, climatic changes can prompt adjustments to a sensor system. Sensor systems should furthermore be able to adapt to a variety of locations and/or risk pictures. We have therefore specifically tested this system's capacity to incorporate different sensors or effectively function in other settings.

Figure 6. The SPA-2 and SNOdar in position in Vannledningsdalen.

We used Longyearbyen's well-documented exposure to slushflow hazard (e.g. Hestnes et al., 2016) as a basis for incorporating different sensors into the network. Since ultrasonic snow depth sensors do not provide information on the presence of liquid water content in the snowpack, we wanted to test other sensor types as a potential basis for slushflow risk assessments. We thus installed the SPA-2 from Sommer Messtechnik in the Vannledningsdalen slushflow release (see Figure 4A) to monitor liquid water content (LWC) in the snowpack as well as snow depth (Figure 6). We also installed a SNOdar sensor from Sensor Logic on the SPA-2 mast to compare snow depth measurements from this technology and explore the possibilities for obtaining other snow cover data with this device. While we experienced mixed results in terms of LWC measurement quality from the SPA-2, stable data delivery from both the SPA-2 and the SNOdar throughout the season served as proof-of-concept of the communication technology's flexibility to transmit data from other, more complex sensors.

Many operational risk management programs will not have access to the expensive TLS technology we used in this work. Here, unmanned aerial vehicle (UAV)-based data acquisition techniques can offer a relatively low-cost alternative to gather spatially distributed snow depth data (e.g. Revuelto et al., 2021). Although we did not employ UAV-derived snow depth data as a basis for sensor placement in this work, concurrent UAV – TLS data acquisitions have previously yielded usable and comparable snow depth maps on Gruvefjellet (raw UAV data: Hann, 2022). Substituting snow depth maps generated with UAV rather than TLS data can therefore substantially reduce the financial costs of implementing the sensor placement workflow described in this work.

To test this sensor concept in a different location, we established a similar sensor network in Honningsvåg in the Nordkapp region of northern Norway. Located near the northernmost extension of the Norwegian mainland, Nordkapp's generally treeless terrain and maritime snow climate represented a logical next step for sensor system testing. As in Longyearbyen, we installed six ultrasonic sensors in avalanche release areas threatening infrastructure in the fall of 2020. TLS work from February 2021 (Figure 7) constituted validation data for the ultrasonic measurements and provided a foundation to optimize sensor placement for the 2022/2023 season. Perhaps most importantly, however, the TLS-derived snow depth map served as a visualization aid which helped communicate to the local authorities how the point-scale ultrasonic measurements represent the overall slope-scale snow depth spatial variability. We found that helping the risk owners better interpret the ultrasonic measurements increased the overall effectiveness of the sensor system in the broader risk management process.

Figure 7: The TLS scanning the slopes above Honningsvåg in February 2021. Four ultrasonic sensors are located on the slopes visible in this photo.

4. PRACTICAL SUGGESTIONS

The lessons we have learned in the six winter seasons of snow sensor work can help illustrate a best-practice approach to developing a sensor system suitable for monitoring natural hazards in a risk management context. Based on our experiences with measuring snow depth in Longyearbyen and Honningsvåg during the ARCT-RISK project, we suggest a best-practice approach to developing a sensor system will:

Choose sensor technologies and an overall sensor concept based on a physical understanding of the natural hazard and a realistic assessment of available labor and financial resources. Sensors should employ a measuring principle which addresses a key physical parameter governing the natural hazard in question, with parameter selection based on the current process understanding. Sensor system development should take the best available sensor technology into account while designing around resource constraints which may restrict implementation of the absolute ideal sensor solution.

Strive to minimize the financial cost and power usage of the system; e.g. employ low-cost, low-power solutions when available. Low-cost sensor concepts promote the installation of more sensors which in turn increases the spatial coverage of a sensor system while also permitting installation in locations where sensor destruction can occur. Low-power sensors limit maintenance time and costs, allow for sensor placement in locations with limited access or power supply, and help increase the temporal resolution of data delivery.

Employ a variety of data sources, including local knowledge, to choose optimal sensor locations. As sensor placement plays a critical role in the overall performance of a sensor system, resource expenditure in the planning phase will help ensure system viability. Integrating local knowledge of historic natural hazard occurrence and location accessibility with information sources of increased spatial coverage such as satellite-, drone-, or TLS-based data products will provide a strong foundation on which to base sensor placement decisions.

Ensure redundancy and reliability in the system. Sensor system design should account for a variety of unforeseen and challenging circumstances through sensor redundancy (e.g. multiple sensors acquiring similar information), well-defined plans for both routine and emergency maintenance tasks, and modern data security protocols.

Include flexibility to adapt to new sensor technologies and/or a changing risk picture as a central principle in the overall sensor system design. Flexibility will increase system longevity and robustness by allowing for adaptation to new sensor technologies or to incorporate sensors which measure a different parameter given a shift in the natural hazard to be monitored. Climatic changes can rapidly alter an area's overall risk picture and require sensor systems which can fluidly adjust sensor technology and measurement locations to best manage climate-related risks.

5. CONCLUDING REMARKS

This paper has described the development of an ultrasonic snow depth sensor system in Longyearbyen, Svalbard. The current system relies on a low-cost, low-power sensor concept which has allowed us to install more sensors and thus achieve better spatial coverage relative to more expensive sensor solutions, while NB-IoT communication provides near real-time data availability to risk managers. Relying on spatially-distributed snow depth measurements from a TLS in combination with local knowledge of avalanche hazard and terrain accessibility has helped with the optimization of station placement. Recent integration of other sensor types and implementation of a similar system on the Norwegian mainland demonstrates the system's flexibility and applicability to other locations.

We have nevertheless experienced limitations with this system including ultrasonic sensor failure due to corrosion, difficulties achieving accurate measurements during blowing snow events, occasional network outages, and physical destruction of the masts through snow creep and during storms. While the present system mitigates the impacts of these limitations on overall system efficacy by installing pairs of sensors on individual slopes for redundancy, future work should include robust measurement validation and comparison alongside other snow depth measurements from a quality-controlled standardized station (e.g. following World Meteorological Organization standards). Improvements to the mast solution should strive to improve station longevity while maintaining the current system's ease of installation.

We have presented our experiences with the development of this system as a potential foundation for risk managers to consider when designing sensor systems to monitor processes related to snow avalanches and other natural hazards. We further advocate approaching sensor system development from a risk-based perspective where data from sensors are incorporated into a broader framework for assessing, evaluating, managing, and communicating about risk. The Canadian Avalanche Association's (2016) guidelines provide such a framework for an avalanche-specific context, and more generic frameworks can be applied to a range of natural hazards and climate-related risks (IRGC, 2017, SO 2018;). Addressing sensor system development within a broader risk-based framework helps ensure the acquired data contribute to effective risk assessment and risk treatment strategies and that the system will align with overall program objectives.

INTERACTIVE VERSION

An extended, interactive version of this work is available as an ArcGIS StoryMap at the following link:

https://storymaps.arcgis.com/stories/a761694548c64004a1bd9a9bf042ef58

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