DRONE-MOUNTED SNOW RADAR SYSTEM - QUANTITATIVE FIELD VALIDATION OF TERRESTRIAL SNOW MEASUREMENTS

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ABSTRACT:
Airborne ground-penetrating radar systems offer a secure and time-efficient method for measuring snow depth and snowpack stratigraphy in challenging terrain with potential avalanche hazard. The SnowDrone is a custom-made snow measurement system incorporating an uncrewed aerial vehicle (UAV) platform and radar payload. Specifically designed for conducting snow surveys across diverse snow cover scenarios, this system features performance attributes tailored for such missions. Here, we present the technical implementation of the complete system, coupled with validation findings from three extensive field campaigns conducted on Svalbard. Furthermore, we provide insights into snow stratigraphy measurements obtained with the SnowDrone, and *in situ* obtained snow profiles for comparative analysis. The validation is conducted by correlating the radar observations with 1673 co-located *in situ* measurements of snow depth, ranging from 5 to 200 cm, and revealing a high degree of agreement, yielding a correlation coefficient of $r = 0.938$.
The SnowDrone emerges as a reliable and effective tool for assisting with local avalanche danger assessments at the slope scale, where information on snow depths and structure is crucial.

Keywords: Snow stratigraphy, Snow depth, Radar, Drone

1. INTRODUCTION

Generally, information about snow distribution in the Arctic is sparse. New methods to retrieve accurate, but spatially representative measurements of snow depth, density and stratigraphy are highly required, especially considering the fast-changing Arctic climate, e.g., Svalbard as a hotspot, experiencing rapid environmental changes Isaksen et al. (2022).
In the context of avalanche forecasting, snow stratigraphy can have significant lateral variation Schweizer et al. (2008); thus, expanding pit-scale information to a km-scale measurement can significantly improve the understanding of the snow stratigraphy in avalanche-prone areas.
Today, ground-based snow surveys, whether conducted manually or utilizing ground penetrating radar (GPR), typically involve traversing the terrain either on foot or by snowmobile Knut Sand et al. (1998); Derksen et al. (2010); Holbrook et al. (2016). However, factors such as avalanche risk and terrain accessibility can constrain the extent of the survey area.
Utilizing drone-mounted snow-penetrating radars has seen significant developments in recent years Jenssen and Jacobsen (2020); Prager et al. (2021); Tan et al. (2021); Kolpuke et al. (2022); Valence et al. (2022).

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To enable airborne measurements of snow parameters on a km scale, some key challenges must be addressed:

- The survey altitude needs to be maximized to avoid obstacles and provide sufficient margins for terrain following in areas with significant undulation. At the same time, an adequately small radar footprint should be ensured to represent the snowpack correctly.
- The ground velocity must be as high as possible to maximize area coverage on a single charge. However, the radar measurement rate effectively limits the maximum ground velocity.

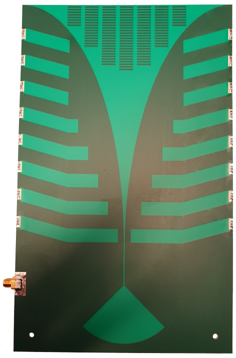
The SnowDrone is optimized for these challenges. The survey parameters in Table 3 outline the system's capabilities and the types of datasets it can produce, making the system applicable to several different applications.

2. METHODOLOGY

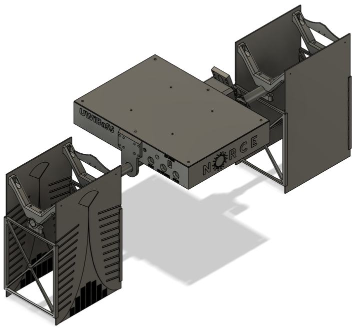
2.1 Drone and radar

The SnowDrone consists of a multi-copter drone and snow radar as payload. Both systems have undergone multiple iterations since development began in 2015. The ultra-wideband snow sounder (UWiBaSS) was initially prototyped by Professor Svein Jacobsen at UiT The Arctic University of Norway (UiT) in 2015 and developed further as part of a master thesis project Jenssen et al. (2016) led by the author under the supervision of Professor Svein Jacobsen. The project continued in a Ph.D.

program, involving further development of software and hardware. The thesis also focused on method development and processing techniques to extract snowpack parameters Jenssen (2021).



(a) Modified Vivaldi antenna element.



(b) UWiBaSS 3D model

(c) Complete radar system mounted on Cryocopter FOX.

Figure 1: Vivaldi antenna system.

2.2 UWiBaSS

The UWiBaSS is a custom built radar system for drone-mounted snow measurements. The current key characteristics of the UWiBaSS system are described in Table 1. UWiBaSS has undergone testing with various antenna setups. These include the utilization of RX and TX spiral antennas Jenssen et al. (2016), a combination of Vivaldi and spiral antennas Jenssen et al. (2020), and presently, a bistatic configuration employing dual, modified Vivaldi antennas. The antenna element and complete antenna system are shown in Figure 1a.

2.3 Cryocopter FOX

The Cryocopter FOX is an X8 heavy-lift multicopter with eight motors that provide redundancy. It can be operated as a single or multi-crew system. The

Table 1: UWiBaSS key characteristics.

Attribute	**Value**
Signal generation	UWB Pseudo noise
System bandwidth	3.8 GHz (0.7 to 4.5 GHz)
Range resolution	$\approx 5\,\mathrm{cm}$
m-sequence clock frequency	12.8 GHz
Measurement rate	52 Hz (max 1 kHz)
MLBS order	9 (511 range bins)
Nominal output power	2.4 dBm
Unambiguous range in air	5.98 m
Antenna system	Bistatic dual modified Vivaldi
Directivity (2 GHz)	14 dBi
Average power consumption	$\approx 9\,\mathrm{W}$
Total Weight	$\approx 3\,\mathrm{kg}$

Fox is based on the Foxtech D130 frame, which has been modified and reinforced at several key points by Norwegian Research Centre (NORCE) engineers. The airframe primarily consists of carbon fiber and aluminum parts.
The vehicle can be transported fully assembled in a custom-made transport box. The current key characteristics of Cryocopter Fox are described in Table 2.

Table 2: Cryocopter FOX key characteristics.

Attribute	**Value**
Frame	X8
Body diameter	188 cm
Body height	79 cm
Weight (empty)	12.5 kg
Weight 4x22 Ah Battery packs	10.6 kg
Full voltage	50.4 V
Maximum take-off weight	48.7 kg
Maximum payload dimension	$\approx 45 \times 45 \times 43\,\mathrm{cm}$
Max demonstrated wind	15 m/s
Min. outside air temperature	$-30\,^{\circ}\mathrm{C}$
Throttle demand 22 m/s	$\approx 25\,\%$
Throttle demand 26 m/s	$\approx 31\,\%$
Thrust per motor	12.3 kg (2.5 kW)

2.4 Application scenarios and system performance

The performance of the complete system is under continuous development and is, thus, only correct at the time of writing. Some parameters, such as survey altitude, can be increased at the cost of signal to noise ratio (SNR) Jenssen and Jacobsen (2020), which can still be sufficient for signal detection of several (especially dry) snowpacks.
The antenna system can be set to maintain a specific angle matching the slope of the survey area. Additionally, the antenna system has active angle regulation in one axis to remove influences on the drone's attitude. The axis in question can be the roll

or pitch axis of the drone, depending on the drone flight setup. In some cases, it might be more beneficial to eliminate the movements in the roll axis while keeping the pitch angle constant, and in other cases, it could be more convenient to have active regulation of the pitch angle. The SnowDrone has surveyed mountain slopes up to 32°.

Table 3: SnowDrone typical survey parameters

Attribute	**Value**
Survey range	< 10 km
Survey ground velocity	≈ 5 to 15 m/s
Battery change time	≈ 10 min
Survey flight altitude	≈ 8 to 20 m
Nadir footprint	≈ 3 to 8 m
Max slope angle	$\approx 35°$
Max dry snow depth	≈ 5.9 m
Max wet snow depth (3% LWC)	≈ 1.5 m

3. RESULTS & DISCUSSION

In this section, we will first present the validation results for snow depth obtained from three field campaigns conducted on Svalbard as part of a project for Svalbard Integrated Arctic Earth Observing System (SIOS). The three SIOS campaigns have produced approximately 395k snow profiles with the SnowDrone. Figure 2 shows the sites for the three SIOS campaigns and what sites were surveyed for each year.

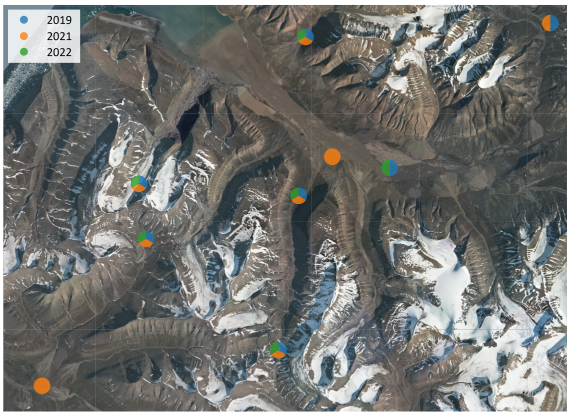


Figure 2: Survey locations for the three SIOS campaigns. Background map from TopoSvalbard, with courtesy of the Norwegian Polar Institute.

Table 4: SIOS campaigns duration and total coverage.

Year	2019	2021	2022
Campaign start	31.03	14.04	29.03
Campaign end	04.04	19.04	01.04
Total coverage	21.7 km	51.5 km	44.4 km

In situ snow depth was collected using the GPS snow probe (Magnaprobe) from Snow Hydro Sturm and Holmgren (2018). The SnowDrone performed surveys in the same area and extended the snow depth measurements several kilometres beyond the manual measurements. The collected radar data was processed in the same manner as described in Jenssen and Jacobsen (2020) and compared to *in situ* data by using inverse weighted distance interpolation with a threshold of 5m. Figure 3 shows an example radar image and *in situ* snow depth.

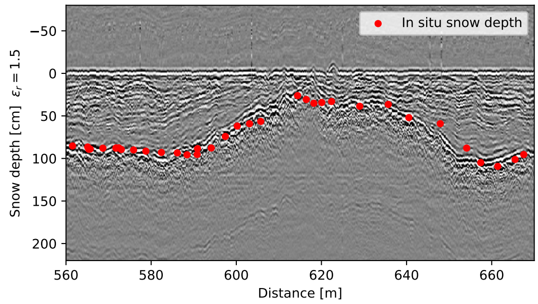


Figure 3: Example radar image and *in situ* snow depth.

The following sections present and describe the snow depth validation, snow depth distribution at repeated locations, and finally, a comparison of *in situ* snow profiles to profiles collected with the SnowDrone system.

3.1 Snow depth validation

Figure 4 shows all *in situ* measured snow depths and UWiBaSS snow depth estimates combined. Time-depth conversion was performed using bulk snow density from local snow pits. However, similar results were found using *in situ* depth measurements and polynomial fitting to estimate snow density.

Figure 4 exhibits outliers that give some insight into potential improvements to the validation process.

Most of the outliers in Figure 4 correspond to areas where the Magnaprobe did not penetrate to the bottom of the snowpack. The probable cause of this can be seen in Figure 5, where the radar profiles reveal that the Magnaprobe snow depth diverges to a prominent layer (hard/icy snow) in the snowpack.

The remaining outliers are caused by positioning discrepancies between the two datasets in dynamic terrain, where small offsets in position cause significant differences in snow depth.

3.2 Snow depth distribution

Figure 6 shows the snow depth distributions from repeated surveys over three field campaigns. Approximately 290k snow depth measurements form the

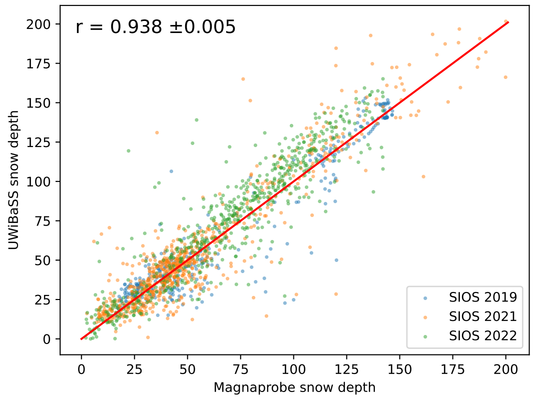


Figure 4: Spatial correlation between *in situ* and radar snow depth. $C = 0.938 \pm 0.005$, N = 1673.

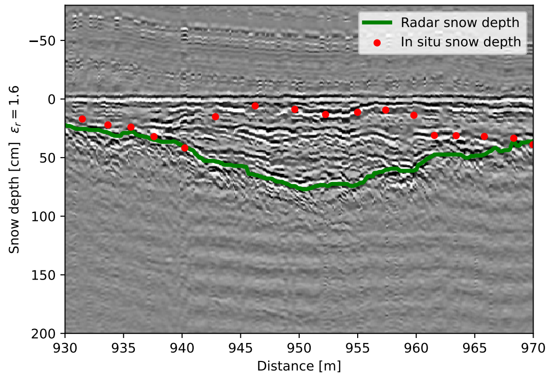
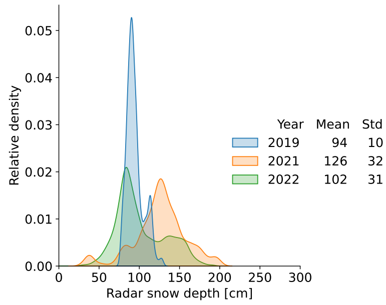
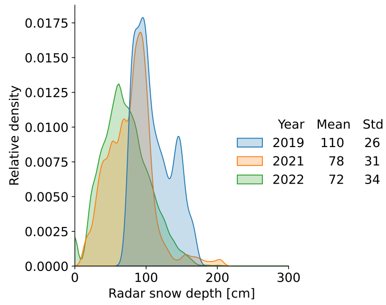


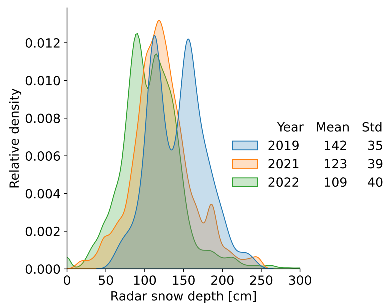
Figure 5: Example of Magnaprobe not penetrating prominent layers found in radar profile.



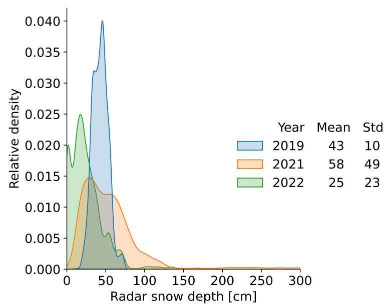
(a) Longyearbreen



(b) Fardalen



(c) Gangskaret



(d) Todalen

Figure 6: Snow depth distributions on repeated locations over three field campaigns.

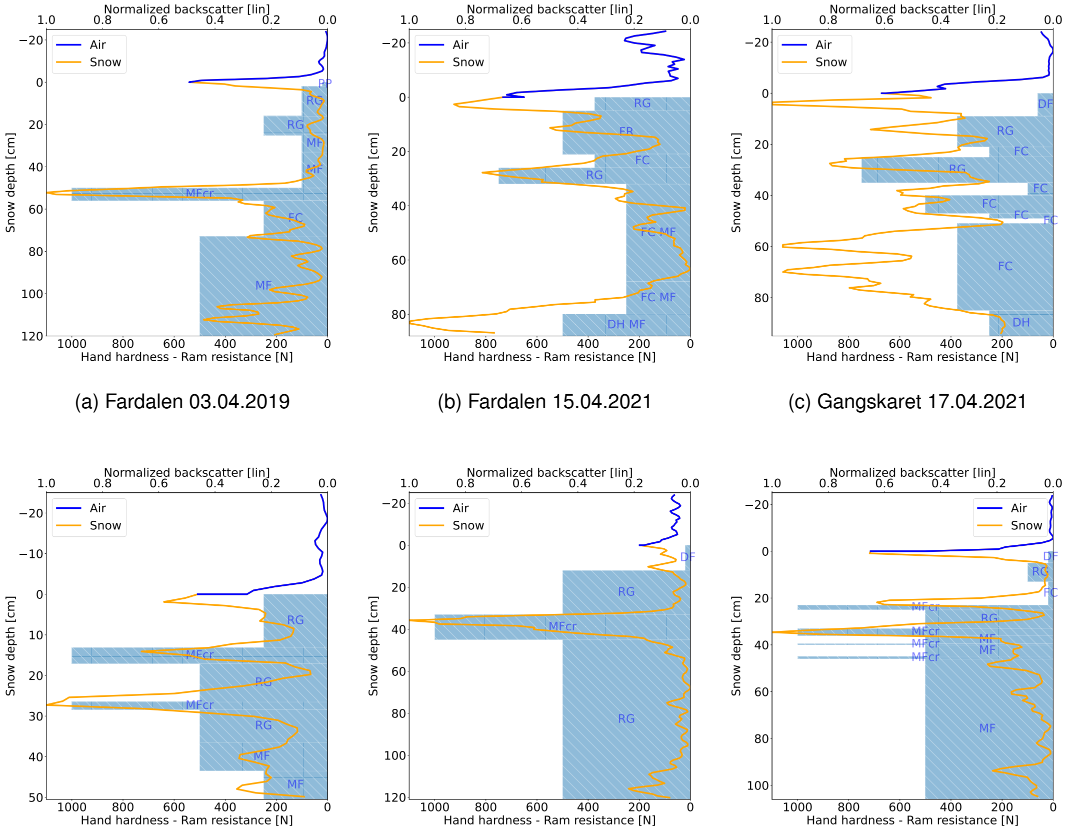
basis for these distributions. Todalen and Longyearbreen exhibit greater variation in snow distribution from year to year compared to Gangskared and Fardalen. This could be due to the altitude difference and closer vicinity to the ocean, where there may be a more maritime climate. Gangskaret also exhibits more snow in general compared to other sites. The snow surveys from Longyearbreen are taken from the glacier itself and are in a different category than the other sites. Other factors, such as topography and, therefore, orientation to the dominant wind direction and distance from the ocean, are driving factors for these distributions.

3.3 Comparison with vertical in-situ snow profiles

Snow profiles are generated from the radar images by averaging a small section (10-20 traces, $\approx$ 1 to 2 m) close to the location of the manual snow profile. In some cases, the selected sections are moved a few meters to areas where the snow depths in the two profiles more closely match. This improves the comparison between the radar and *in situ* snow profiles. The averaged profiles are then normalized and plotted on a linear scale. Hence, only relative change in the snowpack is evaluated.

The registered hand hardness is translated to the Swiss Ramsonde ram resistance Fierz et al. (2009) to compare the backscatter on a force scale.

The comparison between the radar and *in situ* snow



(a) Fardalen 03.04.2019

(b) Fardalen 15.04.2021

(c) Gangskaret 17.04.2021

(d) Gangskaret 30.03.2022

(e) Longyearbreen 31.03.2022

(f) Fardalen 01.04.2022

Figure 7: Snow profile comparison.

profiles is shown in Figure 7. The first peak at 0 cm depth corresponds to the air-snow interface. This interface is a prominent reflection in the radar profile and, naturally, not in the *in situ* profile. The most prominent layers correspond well to the radar profile. Hard layers are detected for several grain types, such as rounded grains (RG), faceted crystals (FC), and melt-freeze crust (MFcr). The radar waveform is reflected on boundaries of change in the dielectric constant. Hence, we expect to have reflections on changes in snow density Tiuri et al. (1984), which is related to snow hardness Geldsetzer and Jamieson (2000). Figure 7e has a thick MFcr layer in the middle of an otherwise relatively homogeneous snowpack. This layer stems from a rain-on-snow event during a snow season with otherwise stable sub-zero temperatures. Figure 7c shows a complex snow profile with weak layers between relatively compact ones. Very thin crusts (Figure 7f) are not clearly detected. The same goes for small changes in hardness such as the RG layer in Figure 7a.

4. CONCLUSION

The SnowDrone system has been presented, consisting of the latest version of the UWiBaSS and Cryocopter FOX. The final validation results from the SIOS campaigns are presented, and the snow distributions for each year on repeated sites are shown. The validation results with $r = 0.938$ are similar or better compared to other published work Prager et al. (2021); Tan et al. (2021); however, the SnowDrone system excels at survey parameters such as maximum range due to the high allowed ground speed, survey altitude, and the capability to perform surveys in sloped terrain. Snow depth distributions for repeated sites are presented. This result will be further investigated, with topography included in the analysis to study the influence of microtopography. Finally, we compared manual snow profiles from various locations to radar profiles, we found a clear agreement. However, interpreting radar profiles may require additional training for end users such as avalanche professionals. To expand on this work, we could calibrate and evaluate absolute backscatter values and collect detailed density profiles to improve the stratigraphy comparison. This method could offer a deeper understanding of snow layering and enhance comparisons between spatially or temporally separated snowpacks.

Inherently from the data, we can generate snow profiles along the flight paths at predetermined inter-

vals. This will provide insight into the lateral variation of the snow stratigraphy. Analyzing this data will require more effort by the operator compared to traditional snow profiles, but it could provide crucial information about lateral variation in snow stratigraphy (slope stability), beyond pit observations.
The SnowDrone emerges as a reliable and effective tool for assisting with local avalanche danger assessments at the slope scale, where information on snow depths and structure is crucial.

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