ADVANCEMENTS IN THE LYTE PROBE: IMPROVING SNOW CHARACTERIZATION AND AVALANCHE WORK THROUGH MULTI-SENSOR APPROACHES

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ABSTRACT: The Lyte probe is a multi-sensored, manually-driven penetrometer/reflectometer, designed for operational snow safety and scientific research-prioritizing accuracy, portability, and durability. To assess depth accuracy, the Lyte probe was tested against a displacement tube for NIR layer placement errors and a LiDAR range finder for total depth errors. These tests revealed that the Lyte probe's layer placement is accurate to within +/- 5.2 cm and total depth estimates are accurate to within +/- 14.5 cm, with a 95% confidence level. The Lyte probe employs a novel high-impact force sensor which is estimated here to endure ~1500N of force and is still able to detect thin snow layers like buried surface hoar. Qualitative evaluations showcased the Lyte probe's ability to replicate features from hand hardness profiles, differentiating stable and unstable snowpacks. It effectively replicates SnowMicroPen measurements in shallow Arctic snow conditions. As it matures, the Lyte probe is increasingly integrated into research which is exemplified by two notable applications. In the first application, the Lyte probe was used to characterize multiple transects of snow on EastGRIP ice core site in NE Greenland during 2022. The second revolves around a statistical relationship developed to predict snow density from Lyte probe profiles in 2023. Validation across three sites-Idaho, Colorado, and Alaska-yielded predictions of bulk densities ranging from -3.8% to -11.6% of the measured values. The Lyte probe will continue to develop focusing on reducing the uncertainty in total depth and development of mobile app data acquisition.

KEYWORDS: smart probe, penetrometer, near-infrared, snow hardness, density, lyte probe

1. INTRODUCTION

Identifying snow properties and layering for avalanche work is often managed heuristically because it is difficult to comprehensively quantify. Most practitioners rely on some combination of the various snow stability tests, hand hardness profiles, and occasionally using ramsondes. Unfortunately, the hand hardness test is time consuming, subjective, and does not resolve thin layers (Höller and Fromm, 2010). Ramsondes provide some objectivity but they are heavy and also struggle to resolve soft thin layers (Pielmeier and Schneebeli, 2003). The SnowMicroPen (SMP) is a field-hardened, commercially available instrument that is able to quantify a large range of snow hardness, including thin snow layers (Schneebeli and Johnson, 1998).

Although the SMP provides high accuracy and precision, the instrument is prohibitively

* *Corresponding author address:* Micah Johnson, Adventure Data Inc, Boise, ID 83709; email: micah@adventuredata.com expensive and requires significant logistics in transporting to, in, and from the field– making it impractical for many operations and purposes.

The tools available to avalanche practitioners and snow scientists that enable fast objective measurements without limiting human-powered mobility are lacking. There have been several, strong attempts to balance these design goals. For instance, the digital resistograph was able to resolve soft thin layers but suffered from durability issues (Brown and Birkeland, 1990). Later manually-driven attempts were plagued by repeatability issues. Typically this was due to poor position sensing, such as the SABRE probe (Floyer, 2008) and the Avatech SP1/SP2 (Hagenmuller et al., 2018). Manually-driven attempts that did not suffer large errors in layer positioning often used moving parts to measure the position, like with the New Generation Rammsonde probe (Abe et al., 1999) and the 2008). modified SABRE probe (Floyer, Unfortunately, in both cases the added bulk reduced portability.

During the last 9 years, the Lyte probe has sought to fill the gap between the practicality of

hand hardness tests and the precision of the SMP. Initially, the Lyte probe only used NIR reflectance to characterize layers (Johnson et al., 2016). After additional development, a beta test was launched in 2017 in which 37 practitioners recorded nearly 5,000 measurements around the Western US. We found that to be used for avalanche work, the Lyte probe would need a force sensor, improvements in position sensing, and improved portability. Two years of development yielded the first prototypes that included this feedback. Since then the Lyte probe (Version 6) has undergone rigorous testing across many parts of the cryosphere.

Here we show how the Lyte probe V6 resolves soft thin layers, accurately senses vertical positions, endures extreme operating conditions, and does not limit human-powered travel. Additionally, this work highlights the remaining improvements required for the Lyte probe to be used regularly in avalanche work.

2. INSTRUMENT/METHODS

The Lyte probe V6 is a lightweight, multi-sensored digital probe that can rapidly characterize various snow conditions. It is designed to be accurate for scientific and operational endeavors, durable, portable, and affordable.

2.1 Scientific and Operational Accuracy

and Precision

An important aspect of snow science and snow safety is accurately and consistently capturing snowpack layer properties. Doing so requires a sampling rate appropriate for probing speeds. Early experiments showed that users are nearly incapable of probing at velocities of > 4 m/s. We believe every layer needs a minimum of 2 points per mm. A maximum travel rate of 4 m/s through one meter of snow with a factor of safety of 2, then requires a sample rate of 16 kHz. While this often results in excess data, it ensures that under no circumstance can a layer be undersampled even for the highest possible velocities. This design choice enables high fidelity data, while also reducing user-induced variability in measurements.

Vertical location is another challenging aspect of a manually-driven penetrometry. Some techniques use moving parts to track the probe displacement, like an encoder wheel (Abe et al., 1999; Floyer, 2008). These devices, while accurate, increase probe size and mass, and increase the likelihood of durability issues in the field. Alternatively, most optical displacement sensors are not suitable for manually-driven probing. This is due to the fact that many sensors are NIR based and thus subject to surface and ambient solar conditions. Thus any proposed solution should minimize moving parts and avoid being optically based. Double integrating an accelerometer is an intuitive solution that meets these criteria and was attempted in the SABRE probe (McKenzie and Peyton, 2002). Unfortunately, the SABRE design was prone to large depth errors (Floyer, 2008) likely because the acceleration range coupled with the data logger may have produced too coarse of resolution to accurately capture typical displacements. Using lower sensing ranges could fix this issue but can expose the sensor to maxing out during the brief moments of high accelerations that occur around melt freeze crusts. The Lyte probe issue by combining a 3D solves this accelerometer with a high-resolution barometer.

Additional challenges arise in manually-driven penetrometry due to the fact that measurements begin at an unknown distance above the snow, making surface detection a critical feature of these devices. Surface detection has historically been a difficult problem for manually-driven probes (Floyer, 2008; Solbakken and Karlsnes, 2017). The Lyte probe is able to detect the surface within 1 cm using the ambient-corrected NIR reflectance, which further improves the accuracy of Lyte probe depth retrievals.

2.2 <u>Durability</u>

All known attempts to digitally measure the penetration force of snow have been done using strain gauges or load cells which are in direct contact with their sensing interface. While this is industrv standard for force sensina instrumentation, there are opposing design criteria that become apparent when applied to characterizing snow. Due to the unseen ground features under the snow, users will eventually strike an ice lens, rock, or stump unexpectedly mid measurement. We have frequently measured accelerations exceeding 16 g's with the Lyte probe when crusts are present. Assuming conservatively that our users put 10-15% of their mass (e.g. 10 kg) behind the probe while inserting through tough snow, then the Lyte probe can successfully and repeatedly sustain forces of > ~1500 N and still accurately measure forces less than 1 N. While there are certainly sensors capable of handling these large forces, the snow problem lends itself to low sensing ranges. Off the shelf force sensors typically have overforce limits of ~3X their sensing range. For example the SMP for

seasonal snow measures 0 - 50 N (SnowMicroPen, 2023) and has an overforce of 150 N (Kistler 9207, 2005). Given this, many off the shelf force sensors that are suitable for snow are not suitable for the potential forces estimated here.

The Lyte probe is capable of enduring 100X its sensing range because it employs a novel high-impact force sensor specially designed to measure snow while enduring large impact forces generated by users.

2.3 Portability

To meet the demands of human powered avalanche work, the Lyte probe is designed to be used as an adjustable ski pole. It is relatively lightweight, weighing 405 g and can extend from 1.0 m to 1.5 m. It is capable of transmitting data wirelessly to enable mobile app data acquisition, and it can be used via USB connection for research applications. The mobile app is not publicly available yet but is a part of the future work for the Lyte probe.

2.4 Sensor Details

The Lyte probe is equipped with a flat-tipped penetrometer, a NIR receiver-emitter pair, and

Sensor	Measurement Range	Sampling Frequency
3D accel.	0-16 g	100 Hz
High res. barometer	260-1260 hPa	75 Hz
Active NIR	850 nm	16 kHz
Passive NIR	800-1100 nm	16 kHz
Force sensor	0.2 - 15 N, ~1500 N overforce	16 kHz

Table 1: Lyte probe sensors and specifications

a separate passive NIR receiver to characterize the snowpack structure. The NIR sensors are measure side-lookina uncalibrated and reflectance which is important for grain size, specific surface area, and density (Matzl and Schneebeli, 2006). The penetrometer measures penetration resistance along-axis and is calibrated against a load cell. To measure its position, the Lyte probe is equipped with a high resolution barometer and а 3-axis

accelerometer. The sensor details are provided in Table 1.

3. EVALUATION

3.1 Position Sensing Error

Determining an accurate, high resolution vertical



Figure 1: Absolute and relative layer error during regular probe insertions using a displacement calibration tube.

position for a manually-driven probe is difficult, but critical for the purposes of this device. Additionally, Morrison et al. (2008) found in interviewing avalanche professionals that a portable penetrometer would need to be able to measure its own position to at least 5 cm to meet the demands of avalanche forecasting. To determine if the Lyte probe meets this criteria, we performed two experiments. First, a displacement calibration tube was employed to examine the accuracy in the NIR placement of layers and second the total depth was compared to a LiDAR range finder.

In the first experiment, we developed a displacement calibration tube that had 10 NIR sensitive markings on the inside, each 5 cm apart. Each marking then served as a pseudo layer that could be quantitatively assessed for error in vertical position. Two types of measurements were taken using the calibration tube; regular insertions and insertions with a speed reduction mid measurement (irregular insertions). The regular dataset had a mean error of -0.5 cm with a standard deviation of 2.9 cm. The irregular dataset had a mean error of -0.6 cm with a standard deviation of 3.1 cm. In the irregular probe strikes, 12 profiles were

taken. Three of which were automatically flagged by the DAQ software for depth data quality issues and excluded from the analysis. Figure 1 and Figure 2 show the boxplots of each layer's positional error for the two datasets where layer one is the top of the tube. Using these standard deviations and a confidence interval of 95 %, the margin of error for one measurement is 5.2 cm. Looking closer, layers 1-7 (0 - 35 cm) are accurately placed within +/-5 cm which is a promising result considering the importance of layer thickness at the surface for avalanches. Additionally, the relative spacing results for laver 1. confirms that the Lyte probe's surface detection



Figure 2: Absolute and relative layer error during irregular probe insertions using a displacement calibration tube.

is identifying the start of the tube very accurately. After the 7th layer, the probe still placed layers within +/- 5 cm but had a negative bias of a few centimeters. For comparison, Hagenmuller et al. (2018) found that relative placement of layers using the Avatech SP2 was in the range of -10 cm to 22 cm shifted. This range is still true when their dataset is reduced to the 0 - 55 cm of travel being considered here. A similar trend follows in the irregular dataset shown in Figure 2. The error scatter widens further, suggesting that +/- 5 cm layer placement is still possible with increased negative biases when users are met with layers that induce a reduction in probing speed.



Figure 3: Comparison of total distance between the Lyte probe and a LiDAR range finder.

The presence of a trending bias in the absolute and relative layer spacing in Figure 1 suggests that a systematic error is present and could be resolved through design changes and in-field operations. Additionally, the minor differences between the regular and irregular probe strikes suggest that the errors induced could be due to the sudden reduction in speed and not drifting with total depth. To evaluate this, the second experiment compares the Lyte probe's total distance traveled to a LiDAR range finder mounted on the device for coincident measurements which was accurate to +/- 2.5 cm (Garmin LiDAR Lite V3, 2016).

We observed total displacements ranging from 30-151 cm and maximum velocities ranging from 81-360 cm/s. All measurements were taken indoors by moving the probe through the air. The Lyte probe showed a positive bias of 0.3 cm with 8.9 cm standard deviation and no obvious error associated with velocity. Using this standard deviation and a confidence interval of 95 %, the margin of error for the total depth of one measurement is 14.5 cm.

The standard deviations observed in the calibration tube and LiDAR comparisons communicate different messages about the probe accuracy. The LiDAR can introduce unrelated displacements due to the laser pointing off axis from the user slightly rotating the probe. Additionally, a brief informal experiment using the LiDAR and the calibration tube showed the LiDAR tended to underestimate the 55 cm long calibration tube

by 3-5 cm. Thus we tend to place more emphasis on the calibration tube due to the static nature of its comparison. The standard deviations from both experiments imply that to achieve a margin of error of 5 cm in total depth with a 95% confidence, users would have to take somewhere between 2 - 9 probe strikes. In the future, we will build a one meter calibration tube to further investigate and reduce this uncertainty.

3.2 Hand Hardness Comparisons

Hand hardness is the standard for avalanche assessment. The Lyte probe V6 has been evaluated in more than 22 pits ranging from Alaska, Canada, Idaho, Colorado, Greenland and Norway to ensure wide ranging conditions were tested. For brevity, only a couple profiles are shown to demonstrate comparable results are being retrieved. All hand hardness profiles were recorded before taking measurements





to avoid biasing the data. When comparing high resolution force profiles to hand hardness profiles it's important to recognize two differences. The first being that it is frequently assumed that hand hardness profiles are an accurate representation of the snowpack. At a minimum, the depth of stratigraphic intervals can vary significantly, even in a single pit. The second being that the hand is often insensitive to variations in the observer's designated layer. In force profiles, it is frequently observed that the previous snow surfaces (now buried) have mild crusts often not noted in the hand hardness profiles. Here we use the hand hardness profiles more qualitatively. We are checking for similar structure and coarse depth alignment, but expect some variation even with perfect reconstructions.



Figure 5: Comparison of the Lyte probe and a hand hardness profile from showing a stable snowpack.

During the winter of 2022, the Lyte probe was used near Kaslo B.C. right after a period of warming that destabilized the snowpack, resulting in widespread failures on buried surface hoar. The avalanche problems detailed by the local forecasters were persistent weak layer and wet loose (Legacy Archive Forecast, 2022). We performed an Extended Column Test which produced propagation after 17 taps (ECTP17). The failure occurred on buried surface hoar at ~55 cm. Figure 4 is a comparison of the Lyte probe and the hand hardness profile from that day highlighting the buried surface hoar problem.

An important but often overlooked component of evaluating high resolution profiles is whether stable snow can be distinguished from unstable snow. The detailed nature of the data often can show subtle features that lead to confusion regarding snowpack stability. For example, Figure 5 shows a classically right-side-up snowpack that was measured at Mores Creek Summit, Idaho which was well represented in the Lyte probe data.

3.3 SMP Comparison

The Lyte probe was used in Toolik, Alaska as a part of the NASA SnowEx Arctic campaign in 2023. During the campaign the probe was used coincidently with the SMP for more quantitative



Figure 6: Comparison of the Lyte probe and the SMP in shallow Arctic snow.

comparisons. A shallow snowpack in a tussock landscape (undulating Arctic grass tufts) complicates comparisons. Measurements even 15 cm apart can produce notable variations in the depth. Regardless, the Lyte probe was still able to produce similar features as the SMP in Figure 6 with slight depth variations. For both instruments, the work around Toolik produces challenging conditions to measure in. In multiple instances the SMP failed to penetrate certain layers that the Lyte probe did penetrate. And in other instances the Lyte probe did not always capture the softer surface snow features that the SMP did. Even in Figure 6 the difference in starting force can be seen in the Lyte probe.

4. APPLICATIONS

4.1 Spatial Characterization

Understanding the avalanche problems found in a pit at slope and mountain scale is in part what has driven the development of so many devices. Here we demonstrate the Lyte probe's ability



Figure 7: Force profiles (contours in Newtons) from Lyte probe strikes at 10 m intervals perpendicular to the prevailing wind direction at the EastGRIP ice core site in NE Greenland (elevation 2700 m) taken May 2022.

to help with characterizing snow spatially. Figure 7 shows force values as a function of depth and horizontal distance from a transect taken during the summer season at the EastGRIP ice core site in NE Greenland. This transect is perpendicular to the prevailing wind direction, taking only one hour of data collection time. It is clear from these data that the Lyte probe can quickly and accurately characterize spatial heterogeneity in a snow field.

4.2 Density

Many snow professionals are in pursuit of measuring density. Whether to quantify loading for avalanches or water content in our mountain snowpacks, density is an important parameter in understanding how snow behaves. During the winter of 2023 an experiment was designed to determine if the Lyte probe could expand the utility of a single density profile collected from a pit. At Mores Creek Summit Idaho on January 19th 2023, a single pit and a single profile were used to generate a relationship to density. That relationship was then used to predict the data collected at a pit ~300 m higher in elevation and on a different aspect. The results were quite accurate with the Lyte probe computing a bulk density 5.2 % lower than the measured. That same relationship was then applied in Grand Mesa Colorado on February 13th-14th, and again in Toolik Alaska on March 11th. Table 2

summarizes how accurately the relationship captures the bulk density with low bias. To further highlight the suitability of the relationship,

Pit	Date	Bulk	MAE
Mores Calibration	Jan. 19	0%	5.9%
Mores Validation	Jan. 19	-5.2%	8.1%
Grand Mesa pit 1	Feb. 13	-10.7%	12.1%
Grand Mesa pit 2	Feb. 14	-11.6%	26.4%
Toolik Site A739	Mar. 11	-7.3%	15.3%
Toolik Site N730	Mar 11	-3.8%	13.7%

Table 2: Bulk density errors and mean absolute layer by layer errors of the Lyte probe derived densities measured during 2023.

the mean of the absolute errors from a layer by layer comparison still shows some successful predictions occurred but that there is room for improvement for other more demanding applications (e.g. Radar response modeling in snow). The entire dataset is shown in Figure 8.



 $\rho_{\rm E}=36.529*{\rm Log(F)}+57.916*{\rm Log(NIR)}-0.774*{\rm Depth}-522.150$

Figure 8: Comparison of the Lyte probe derived and measured densities from Idaho, Colorado and Alaska during the 2022/2023 winter.

5. CONCLUSION

The Lyte probe represents a recent effort to produce a snow probe that provides repeatable, accurate measurements of snow properties in a portable, manually-driven, multi-use sonde. It features an absolute depth sensing capability

based on the combination of а 3D accelerometer and high-resolution barometer, actuated by a NIR surface detection algorithm. Vertical layers can be detected with absolute accuracy to +/-5 cm for the majority of the profile while total depth accuracy is +/-14.5 cm. Depth accuracy appears to deteriorate at the bottom of each profile due to either a systematic error and/or rapid decelerations, which is to be investigated further. To compensate for this, users can take between 2-9 measurements to get a 5 cm margin of error throughout the snowpack.

Snow properties are sampled through a combination of a novel high-impact force sensor at the probe tip and side-looking NIR sensors just above the probe tip. This combination of sensors provides rapid, accurate assessments of snow hardness, snow structure, and snow density as a function of depth.

The Lyte probe has been successfully tested in mid-latitude and Arctic conditions. It is able to withstand impact forces of up to ~1500 N while still resolving thin snow problems like buried surface hoar. It is able to retrieve similar results shown in hand hardness profiles, distinguishing unstable and stable snowpacks. Additionally, field tests in parallel with the SnowMicroPen are very favorable even in complicated Arctic conditions.

Future work for the Lyte probe includes: further assessment of total depth, development of mobile app-based operational data collection, further development of open-source including science-oriented software development of operational snow property retrievals, and further improvement of probe profile and ergonomics based on user feedback. We are excited by the prospects that the Lyte probe has opened up for easy, rapid, accurate, spatially-distributed snow property measurements. We invite all motivated partners on this journey.

CONFLICT OF INTEREST

The corresponding author is the inventor and proprietor of the Lyte probe. The two co-authors were not supported nor did they benefit fiscally from their involvement in this work.

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