EVALUATION OF THE SNOW PENETROMETER SCOPE

Pascal Hagenmuller[1,*], Benjamin Reuter[1,2], Alec van Herwijnen[3], Victor Ramseyer[4], Justin Caillol[1]

[1] *Univ. Grenoble Alpes, Univ. de Toulouse, Météo-France, CNRS, CNRM, Centre d'Etudes de la Neige, Grenoble, France*
[2] *Météo-France, Direction des Opérations pour la Prévision, Toulouse, France*
[3] *WSL Institute for Snow and Avalanche research SLF, Davos, Switzerland*
[4] *Univ. Grenoble Alpes, INRAE, CNRS, IRD, G-INP, IGE, Grenoble, France*

ABSTRACT: Knowing snowpack stratigraphy is paramount for avalanche forecasting. In many forecasting operations the stratigraphy information comes from manual observations and traditional ramsonde measurements. However, manual assessments are inherently subjective. Ram profiles can help to estimate the amount of erodible snow or identify large weak basal snow layers but lack the resolution necessary for identifying thin or soft layers. To overcome these challenges, digital cone penetrometers such as the SnowMicroPen (SMP) offer accurate stratigraphy data but are often limited by cost and primarily used for research purposes. In contrast, the snow SCOPE developed by PropagationLabs is cheaper, seems user-friendly, swiftly recording resistance profiles, and thus presents a promising alternative. The goal of this study is to objectively evaluate the SCOPE profiles with co-located SMP and standard measurements measured throughout the Alps. Our analysis, which is based on a dedicated matching algorithm, enables us to quantify the agreement with SMP measurements regarding force and vertical positioning.

Keywords: SCOPE, penetrometer, hardness, profile, SMP, ramsonde

1. INTRODUCTION

The vertical arrangement of snow layers with varying physical properties defines the snowpack stratigraphy (Fierz et al., 2009). Knowledge of this stratigraphy is crucial for deriving snow stability, a key property to assess avalanche danger (Schweizer and Wiesinger, 2001; Techel and Pielmeier, 2014). In particular, forming a slab avalanche requires a weak layer, enabling failure initiation, and a stronger, stiffer overlying slab that allows crack propagation in the weak layer (e.g. Schweizer et al., 2003). Vertical profiles of hardness, defined as the resistance against object penetration into the snow, are thus key indicators for deriving snow stability (Pielmeier and Schneebeli, 2003; Bellaire et al., 2009; Reuter et al., 2015).

Objective measurements of snow hardness are limited, with manual observations being the primary information source for avalanche warning services. These observations, though standardized, involve subjective assessments (Fierz et al., 2009). The ramsonde (Bader and Niggli, 1939) offers more objective hardness measurements, indicating overall snowpack consolidation (Schweizer and Wiesinger, 2001), but lacks the resolution to capture thin weak layers and small hardness variations in soft snow (e.g. Hagenmuller et al., 2018a).

Various digital penetrometers have been developed to measure hardness at higher vertical and force resolutions (e.g. Dowd and Brown, 1986; Floyer and Jamieson, 2008). Among them, the SnowMicroPen (SMP) (Schneebeli and Johnson, 1998) can accurately determine the penetration resistance of fine layers (Pielmeier and Schneebeli, 2003) and has been progressively adopted by the snow and avalanche research community. However, the SMP is fragile, heavy, and costly to be routinely used in an observation network organized by avalanche warning services. In recent years, several attempts have been made to develop alternatives that are cheaper, easier to use, and with sufficient accuracy for avalanche danger assessment. The SP2 by MountainHub showed promising results, but the infrared depth sensor limited the measurement quality with low repeatability and an average depth error of around 7 cm (Hagenmuller et al., 2018a).

Lately, the company PropagationLabs has proposed a new penetrometer: SCOPE (`https://www.propagationlabs.com/specs`). SCOPE uses another technology to measure depth: the correlation of the reflectance signal along the hole created by the penetration (same measurement principle as a computer mouse) (Elder et al., 2023). This technological evolution may overcome the limitations of the SP2 series.

This study aims at evaluating the accuracy of SCOPE hardness profiles. To this end, we measured numerous co-located SCOPE and SMP profiles (Sects. 2.1). To assess the differences between profiles (1D data), we used a matching algorithm that translates differences into layer positioning and hardness differences (Sect. 2.3). We can then evaluate the repeatability of the measurements (Sect. 3.2). Assuming that the SMP profile is the reference

*Corresponding author address:
Pascal Hagenmuller, Centre d'Etudes de la Neige
38400 St Martin d'Hères, France;
tel: +33 476637901;
email: pascal.hagenmuller@meteo.fr

measurement (ground truth), we can also evaluate the accuracy of SCOPE measurements (Sect. 3.3).

2. MATERIAL AND METHOD

2.1 Test sites and snowpack properties

We conducted co-located SMP and SCOPE measurements at two different sites in the Alps:

1. The first site, hereafter called *Huez*, is located in the French Alps on a frozen post-glacial lake (Glacier de Sarenne, Lat.: 45.11493°, Lon.: 6.12811°) at 2900 m a.s.l. The snowpack was dry. The total snow height was 130 cm on the lake ice. The faceted, but well-consolidated basal layers were overlain by more recent layers consisting of small rounded grains sandwiching one thin faceted layer (Fig. 1). Around the snow pit, we measured six different groups of penetrometer profiles (Huez_1 to Huez_6). Each group was separated approximately 2 m from its closest neighbor, and the hardness profiles within one group were at a maximum of 30 cm from each other. The measurements in each group were composed of 9 measurements: 3 with one SCOPE device (hereafter called SCOPE_IGE), 3 with another SCOPE device (SCOPE_CEN), and 3 with the SMP (version 5, S/N: SM57). The profiles were measured vertically down to a depth of 120 cm.

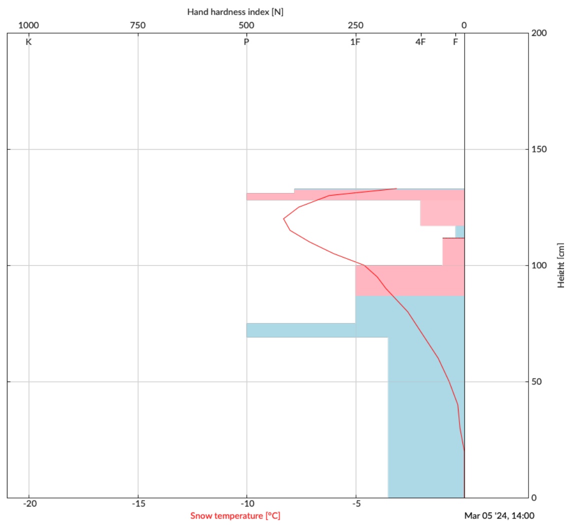

Figure 1: Main characteristics of the snowpack tested at site Huez. The coding and colors follow the international classification (Fierz et al., 2009). Image produced with `https://niviz.org`.

2. The second site, hereafter called *WFJ*, is located in the Swiss Alps at the historical WSL-SLF test site (Weissfluhjoch, Lat.: 46.82967, Lon: 9.80940) at 2535 m a.s.l on a flat terrain. The snowpack was dry. The total snow height was 206 cm on gravel rock. The snowpack hardness mainly increased with depth typically of a rather well-consolidated snowpack but also presents a few thin melt-freeze crusts (Fig. 2). One group (called WFJ) of 8 co-located SCOPE (SCOPE_SLF) and 5 SMP (version 5, S/N: S36) profiles were measured near the snowpit (within 50 cm). The profiles were measured vertically down to a depth of 120 cm.

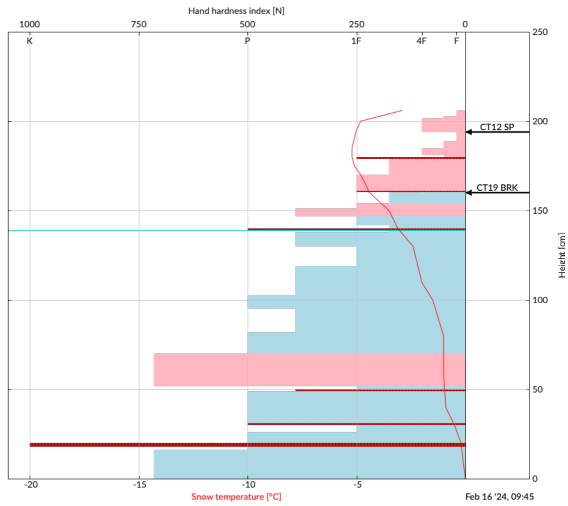

Figure 2: Main characteristics of the snowpack tested at site WFJ. The coding and colors follow the international classification (Fierz et al., 2009). Image produced with `https://niviz.org`.

2.2 Penetrometers

The operation scheme of the SMP and the SCOPE probe is shown in Fig. 3. The nominal specifications of the penetrometers are summarized in Tab. 1. Note that these specifications are nominal, and it is unclear how they were evaluated or theoretically derived from the specifications of individual sensors.

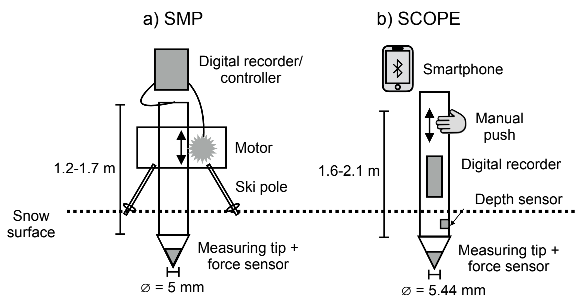

Figure 3: Operation scheme of the penetrometers used in this study: (a) SMP and (b) SCOPE. The scheme is not to scale.

2.3 Matching algorithm

To compare two profiles, we need to explicitly identify and associate layers that occupy the same positions in the layer sequence. This procedure is called layer mapping or matching. We followed the work of

Parameter	SMP	SCOPE
Measurable depth (m)	0-1.25 (2.2)	0.2[1]-1.6 (2.1)
Penetration speed (mm/s)	20	1000
Depth resolution (mm)	0.004	1
Layer resolution (mm)	0.5	1.5
Depth accuracy	1-5[1] mm	2.3% (<5%)
Stress range (kPa)	0-2000	3-550
Stress resolution (kPa)	0.5	3
Stress accuracy (kPa)	1-5[1]	3
Weight (kg)	7	0.28

Table 1: Nominal technical specifications of the SMP and SCOPE. SMP datasheet is extracted from `https://www.wsl.ch/de/services-produkte/snowmicropen-smp5-version/`. SCOPE datasheet is extracted from `https://www.propagationlabs.com/specs`.
[1]Estimation by the authors.

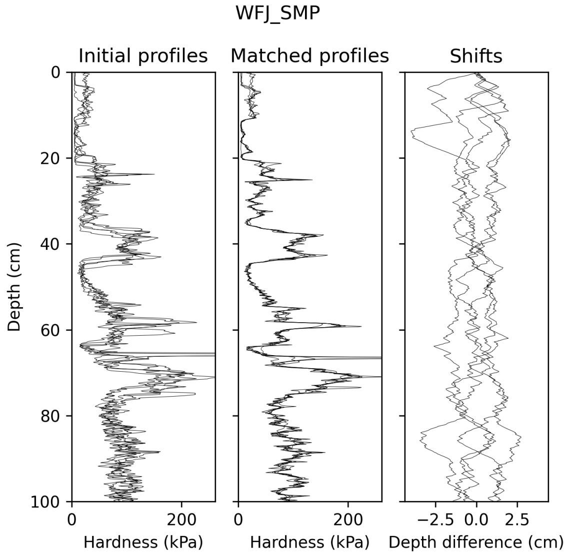

Figure 5: Matching of the five SMP profiles of the group *WFJ*. The initial profiles do not perfectly overlap (left panel). By slightly shifting the layers (right panel) by -2 to 2 cm, we clearly reduce the hardness variability at a given depth (center panel). The residual hardness variability is related to the spatial variability of the snowpack and the force sensor repeatability. The depth shifts are related to the spatial variability and the repeatability of the depth sensing.

(Hagenmuller and Pilloix, 2016) and (Schaller et al., 2016) to achieve this. We adjusted the layer thicknesses such that the root mean square difference in hardness between the profiles becomes minimal. Layer thickness adjustments are constrained within -50% to +100% to prevent significant depth shifts. Dynamic Time Warping (Sakoe and Chiba, 1978) is employed to solve this optimization problem. An example of such a mapping between two illustrative profiles is depicted in Fig. 4.

To match a group of several profiles, we used an iterative methodology proposed by Petitjean et al. (2011): the profiles are iteratively matched to the mean of the matched profiles. We called this approach auto-matching. Details of the approach applied to snow profiles can be found in (Hagenmuller and Pilloix, 2016; Hagenmuller et al., 2018b; Viallon-Galinier et al., 2020).

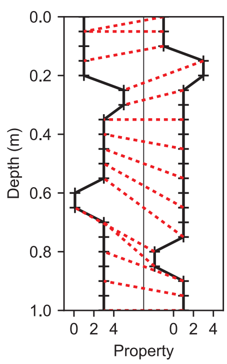

Figure 4: Mapping between two profiles. The profiles are depicted in black, with red dotted lines indicating the mapping, linking corresponding points between the profiles. For example, the weak layer at a depth of 0.6 m in the first profile (left) accurately matches the weak layer at a depth of 0.8 m in the second profile (right). Figure from (Hagenmuller et al., 2018b).

3. RESULTS

3.1 Illustration of the methodology

For each group of measurements, we repeated the same analysis. First we re-interpolated the hardness profiles on a regular depth grid with a 1 mm step down to 100 cm depth. Then, we auto-matched all the profiles of one group and one instrument (Fig. 5). If the measurements were perfectly repeatable (perfect instrument and absolutely no spatial variability), all profiles measured with one instrument would overlap directly. This is not the case (Fig. 5, left). The vertical shifts required to match the profiles (Fig. 5, right panel) and the residual hardness variability (Fig. 5, center panel) are indicators of the repeatability of the measurements, which is related to the snowpack spatial variability and instrumental repeatability.
The average of the matched profiles (Fig. 5, center panel) represents the set of measurements and can be further used to compare the instruments in one measurement group. To this end, we assumed that the representative SMP profile is the reference profile and matched the representative SCOPE profile to it (Fig. 6). The residual hardness difference and the depth shifts are indicators of the SCOPE instrument accuracy.

3.2 SCOPE and SMP repeatability

Repeatability quantifies the instrument's ability to produce the same hardness profile value when multiple consecutive measurements are carried out on

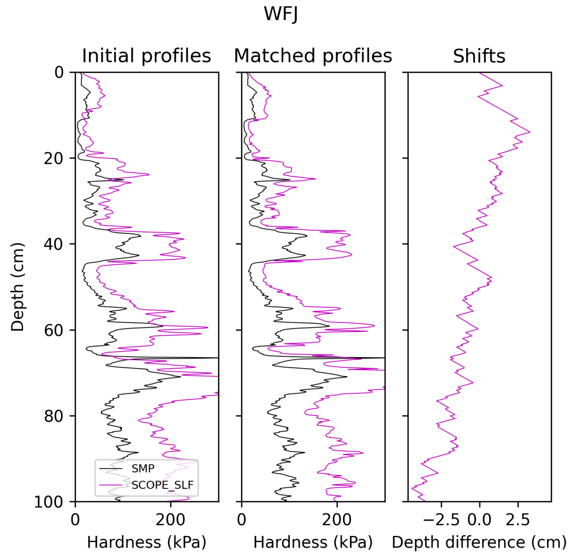

Figure 6: Matching of the representative SCOPE profile to the SMP profile, on measurement group *WFJ*.

the same snowpack. The repeatability of each instrument per measurement group is shown in Fig. 7. For instance, the relative hardness difference for the SMP data on WFJ ranged between -40% and 40% and its depth difference ranged between -4 and +4 cm. That means that within one measurement group, the SMP hardness deviated at a maximum of 40% from its average (averaging among the measurement set of one group), and the position of the layers deviated by +/- 4 cm. These numbers describe what can also be seen in Fig. 2. The associated standard deviations help quantify this repeatability. Overall, the repeatability of layer positioning and hardness were similar between the instruments and the measurement groups. The standard deviation of the relative hardness differences was 12% for the SMP and 11% for the SCOPE. The standard deviation of depth differences was 1 cm for the SMP and 1.3 cm for the SCOPE.

3.3 SCOPE accuracy

Accuracy quantifies how close a measured value is to the true or expected value. Considering the SMP profiles as a reference measurement, we evaluated the accuracy of the SCOPE measurements (Fig. 8). For instance, the relative hardness difference of the representative SCOPE profile on WFJ ranged between 0% and 250% and its depth difference ranged between -3 and +3 cm. These numbers describe what can also be seen in Fig. 2: the SCOPE hardness profile was biased compared to the SMP profile, but the layers were correctly located at the same depth. We observed that the accuracy depended on the SCOPE device. SCOPE_SLF overestimated the hardness by 100% on average, but the layer position is correct at +/- 2 cm. SCOPE_IGE only overestimated hardness by about 30% and correctly located the layers by +/- 2 cm. SCOPE_CEN only overestimated hardness similarly to SCOPE_IGE but systematically underestimated the layer depth by -6 cm. Overall, the SCOPE devices measured hardness with a root mean square relative error of 75% and a positive bias of 39%. They measured the depth of the layers with a root mean square error of 6 cm and a negative bias of -4 cm.

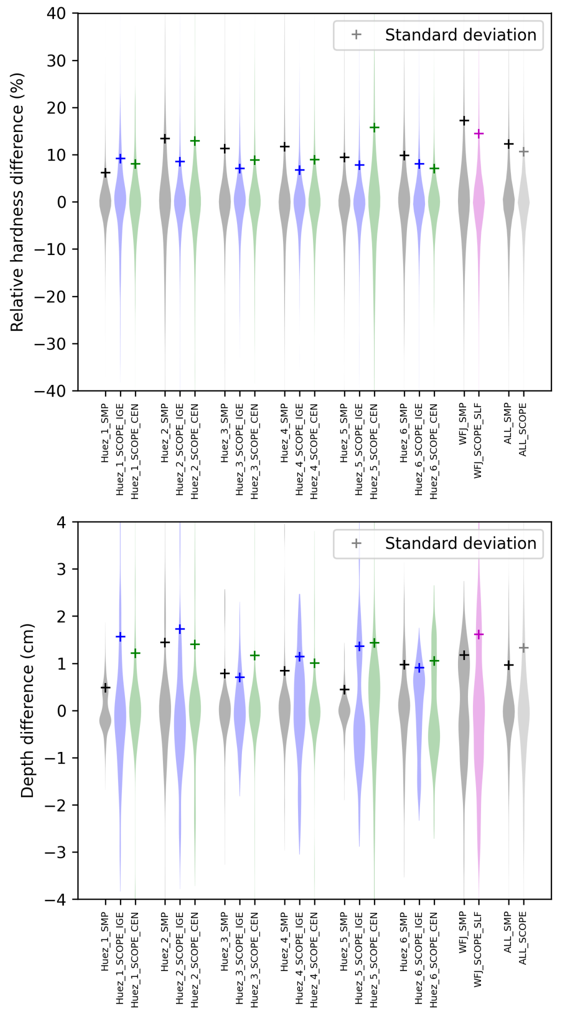

Figure 7: Repeatability of the measurements in terms of relative stress difference ($100 * \frac{\sigma-\sigma_{avg}}{\sigma_{avg}}$) (top) and depth differences (bottom). The violin plot depicts distributions of the differences using density curves. The width of each curve corresponds with the approximate frequency of data points in each region. The standard deviation of the distributions is also shown in the figure. The repeatability is shown for each instrument and measurement group as well as the overall measurements (label "ALL").

4. DISCUSSION AND CONCLUSION

We measured 67 co-located SMP and SCOPE profiles at two different sites. Using a matching algorithm, we quantified the repeatability and accuracy of SCOPE on this data.
The repeatability of SCOPE was in the same order of magnitude as the SMP: relative hardness variabil-

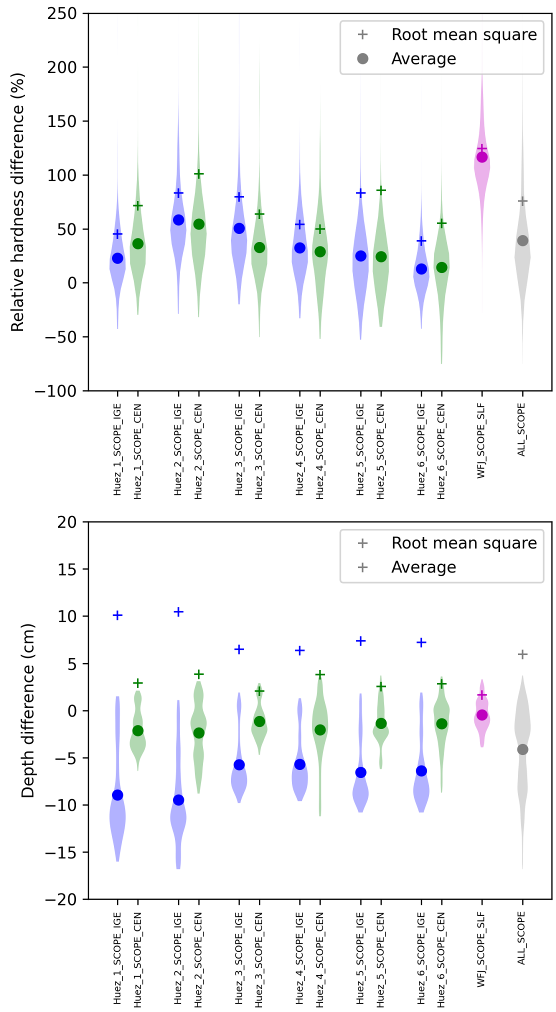

Figure 8: Accuracy of the SCOPE measurements in terms of relative stress difference (top) and depth differences (bottom). We assume that the SMP profile is the ground truth. Same legend as Fig 7.

ity of around 11-12% and depth variability of around 1-1.3 cm (Fig. 7). If we assume that the SMP is the reference, the repeatability of the SMP measurements characterizes the spatial variability of the snowpack within one measurement group. Therefore, we cannot distinguish the SCOPE repeatability from the snowpack spatial variability. In other words, SCOPE produced the same hardness profile when measuring the same snowpack, within the uncertainty related to the spatial variability at the snow pit scale. However, it has to be noted that achieving high repeatability becomes more complicated when the resolution increases. We recall that we re-interpolated the SMP and SCOPE profile at a resolution of 1 mm and that the nominal layer resolution of the SMP and SCOPE are 0.5 mm and 1.5 mm, respectively.

We evaluated the SCOPE's accuracy: relative error of hardness of about 75% with a positive bias, error on depth around 6 cm with a bias of -4 cm (Fig. 8). We observed very different biases between the SCOPE devices. In particular, SCOPE_SLF measured hardnesses around twice as high as the SMP. This observation highlights the sensitivity to the initial calibration of the device. We recall that we assumed the SMP as the ground truth, which also may be questionable without a routine calibration procedure. It remains unclear whether the SMP force sensing system may deviate in time. Overall, SCOPE correctly reproduced the shape of the hardness profile (e.g. Fig. 6). In our opinion, this capacity is the one that avalanche professionals mainly use. They aim to detect weak layers with a hardness resolution close to the hand hardness resolution but objectively and quickly and at a higher vertical resolution. The quantification of the propensity of the snowpack to avalanche is estimated from the complete stratigraphy profile and with dedicated stability tests, but not from the hardness profile itself. However, it has been shown that an accurate hardness profile contains sufficient information to reproduce stability tests or to be correlated to instability signs (e.g. Reuter et al., 2015). Besides, for hydrological applications, density profiles can be directly inferred from accurate hardness profiles (Proksch et al., 2015). Knowing the SCOPE accuracy, these methodologies calibrated on SMP data appear not transferable to SCOPE data. However, they are also not transferable between different SMP devices in some cases and must be re-calibrated anyway (Calonne et al., 2020).

This study also points out the absence of any routine calibration procedure for digital penetrometers, including the SMP. We implicitly assume that the manufacturer's calibration holds for the instrument's lifetime. In soil mechanics, cone penetration testing is a standard tool, and it inspired the use of penetrometers in the snow and avalanche community. In this domain, Scholey (2024) concluded that "Without a high degree of rigor to the requirements of the method of calibration of cones, there is a risk of unacceptable uncertainty in cone penetration results" and proposed guidelines to achieve this. Besides, in the snow research community, it is standard to calibrate reflectance instruments such as DUFISSS or IceCube before any measurement (Gallet et al., 2009). Calibration of dynamical cone penetration tests in a material so variable as snow is not an easy task. However, one may need to imagine partial calibration tests based on static calibrated weight measurements.

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