CHARACTERIZING SNOW STRATIGRAPHY: A COMPARISON OF SP2, SNOWMICROPEN, RAMSONDE AND HAND HARDNESS PROFILES

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ABSTRACT: Information on the structure of the snow cover is of great importance for operational avalanche forecasting. Manually observed snow profiles including snow hardness are therefore widely used to characterize snow stratigraphy. However, such measurements are subjective and observer dependent. While the ramsonde resistance profile provides a more objective alternative, it lacks the vertical resolution to identify thin layers which are often responsible for avalanche release. To overcome these limitations digital cone penetrometers were developed to provide accurate and objective snow cover stratigraphy data. Two well-known examples are the SnowMicroPen (SMP) and the recently developed SP2. In this study, we therefore investigate the accuracy and repeatability of various measurement methods to quantify snow stratigraphy by performing side-by-side SMP, SP2 and ramsonde measurements as well as profiles of hand hardness index and density on a level study site. Results show that the SMP provides the most repeatable and detailed measurements, while hand hardness profiles were generally very coarse but included relevant thin weak layers and crusts. SP2 profiles showed stratigraphic features similar to the SMP. However, SP2 measurements were less repeatable, resolution was coarser and shifts in the vertical resolution were observed. The strengths and limitations of the different methods are compared in view of future developments for operational avalanche forecasting.

KEYWORDS: snow cover, stratigraphy, snow penetrometer, SnowMicroPen, SP2, ramsonde, hand hardness index, snow density

1. INTRODUCTION

Characterizing snow stratigraphy is of great importance to evaluate snow stability. Information on the presence and the mechanical properties of potential weak layers and the overlying slab is of particular importance (e.g. Gaume et al., 2014, Schweizer et al., 2003). However, objective snow stratigraphy measurements are hard to come by and manual snow profiles in combination with stability tests are still the method of choice to characterize snow stratigraphy (e.g. Schweizer and Jamieson, 2001; van Herwijnen and Jamieson, 2007a; Winkler and Schweizer, 2009). The classical manual snow profile, based on the International classification for seasonal snow on the ground (Fierz et al., 2009), therefore remains highly relevant, yet its objectivity and spatial resolution are limited. An important part of the manual snow profile is the hand hardness profile, used to characterize the hardness of the layers identified in the snow cover. The hand hardness index is obtained from manual penetration tests which are observer dependent and have variable vertical resolution. However, observers usually identify the most critical thin layers relevant for snow stability assessment. Furthermore, despite being a relatively crude measurement, various studies have shown that hand hardness, and in particular differences in hand hardness index across layer boundaries, can provide an indication of potential instabilities (e.g. Schweizer and Jamieson, 2007; van Herwijnen and Jamieson, 2007b).

Vertical hardness profiles are also rather intuitive and are therefore widely used to characterize the snow cover. Over the years, various methods have thus been developed to obtain more objective snow hardness measurements. The oldest example is the Swiss ramsonde (Bader et al., 1939). This classical cone penetrometer is used e.g. by the observers of Swiss avalanche warning service to record a snow hardness profile. The ramsonde is driven into the snow by mechanical hammer blows on top of the probe. The vertical resolution of the ram profile is limited by the diameter of the measuring cone (4 cm) and is at best 1 cm. To overcome these limitations and obtain more objective measurements, at the turn of the century the SnowMicroPen (SMP) was developed (Schneebeli and Johnson, 1998, Schneebeli et al., 1999). It is a motor driven, small-cone (5 mm), digital penetrometer that measures penetration resistance at the millimeter scale. Microstructural snow parameters can be derived from SMP sig-

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nals (Johnson and Schneebeli, 1999; Löwe and van Herwijnen, 2012) and related to snow stratigraphy and stability (e.g. Pielmeier and Schneebeli, 2003, Bellaire et al., 2009, Marshall et al., 2010; Reuter et al., 2015; Schweizer and Reuter, 2015). Very recently, Avatech Inc. introduced a new hand driven digital cone penetrometer, the SP1 (Christian et al., 2014). It has a similar small diameter cone as the SMP, but lower sensor resolution (Table 1).

Tbl. 1: Overview of the characteristics of different snow hardness measurements methods (Pielmeier and Schneebeli, 2003; for SP2: AvaTech Inc., 2016).

	Hand	*Ram*	*SMP*	*SP2*
Weight of probe	- (none)	1 to 3 kg	7 kg	0.56 kg
Length of probe	- (depth of pit)	1 to 3 m	1.72 m	1.47 m
Vertical resolution	0.3 to 7 cm	1.5 to 5 cm	≤ 1 mm, motor with depth encoder	2 to 10 cm
Sensor range	-	-	50 N	28 N (1000 kPa)
Sensor resolution	-	-	242 per mm	3 to 7 per mm
Sensor accuracy	-	-	± 1.25 mN	± 8 mN

Lutz and Marshall (2014) showed that the SP1 measures snow hardness at the millimeter scale, yet the robustness as well as spatial and signal resolution was limited. Pilloix and Hagenmuller (2015) found large variations in the depth accuracy especially in soft snow, in part due to problems with the detection of the snow surface. Hence, the SP1 was recalled in the summer of 2015 and the improved SP2 probe became available in January 2016.

To evaluate the performance of the new SP2, during the winter of 2016 we performed side-by-side SMP, SP2 and ramsonde measurements as well as profiles of hand hardness index and density. During this evaluation period, on 24 February 2016, a firmware update was released for the SP2, altering the internal signal processing algorithm. In this study, we investigate the correlations of the different hardness measurement methods, the influence of the SP2 firmware update, the variations amongst different SP2 operators and the properties of potential weak interfaces in the SP2 measurements.

2. DATA AND METHODS

2.1 Field measurements

On five days between January and March 2016 we performed side-by-side measurements with the SMP, SP2 and ramsonde as well as profiles of hand hardness index and density. The measurements were carried out on the undisturbed, level study plot at Weissfluhjoch above Davos, Switzerland at 2540 m a.s.l. (Figure 1). On three days, we performed three to five SP2 and SMP measurements at the location of a manual snow profile with densities and ramsonde measurements. On two other days, we measured a 5 or a 10 meter transect with SMP measurements every meter and SP2 measurements every 10 to 15 cm. The distance between the SMP and SP2 measurements lines was about 20 cm. At the start of the transect we excavated a snowpit to record a manual profile including density and ramsonde hardness.

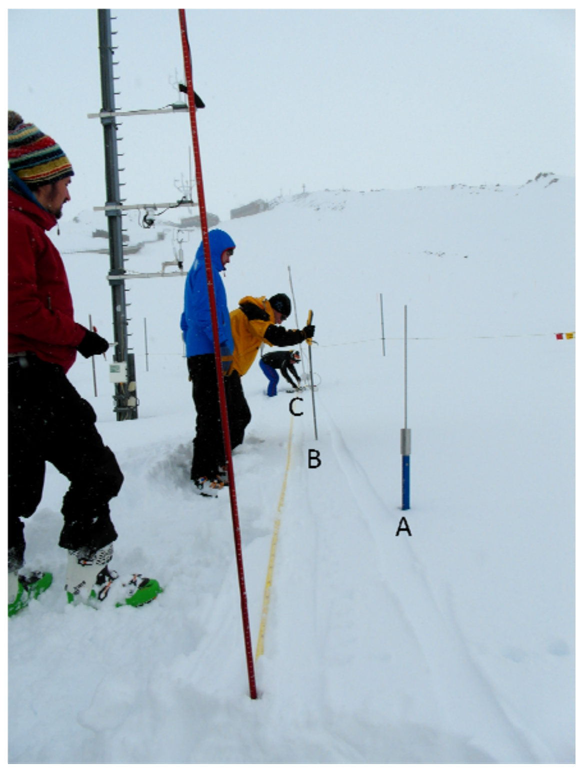

Fig. 1: Transect with side-by-side hardness measurements with the ramsonde (A) the SP2 (B) and the SMP (C) at the Weissfluhjoch study plot.

2.2 Data processing and statistical analysis

The different methods used to quantify the hardness have widely different vertical measurement resolutions (Table 1). For instance, in a hand hardness profile there is one hardness measure for each identified layer, while the SP2 performs one hardness measurements per mm. Since we wanted to evaluate the performance and usefulness of the SP2, we therefore converted all other hardness measurements to a mm scale. To quantify the relationship between different hardness measurements, we then used the non-parametric Pearson correlation coefficient (e.g. Walpole et al., 2002). Correlations were considered significant at the $p < 0.01$ level. The log-log scale in Figure 4 has no influence on the correlation coefficient. For snow stability assessments, information on weak layers and the overlying slabs are of great relevance. On each measurement day, we therefore manually picked the location of the most critical weak layer in the SP2 and SMP profiles, as identified by field test. This allowed us to compare mean slab and weak layer properties.

3. RESULTS

On 16 February 2016 we performed 5 SMP and SP2 measurements at the location of a manual snow profile with density and ramsonde measurements. Overall, the snowpack was characterized by a well consolidated middle part between 35 and 70 cm, with softer recent snow above and weak faceted snow below (Figure 2). While this overall shape was found in all measurements, in the SP2 profiles, the top of the well consolidated zone was shifted upwards by as much as 20 cm (arrow in Figure 2). Furthermore, since the SP2 can only measure up to a depth of 147 cm, the faceted old snow was not always measured (circle in Figure 2). The Avatech firmware update in February 2016 seemed to resolve these issues in part, as illustrated by the measurements performed on 8 March 2016, where the vertical positioning of the SP2 measurements was more in accordance with the other measurement methods (Figure 3). This is further highlighted when directly comparing SP2 and SMP hardness. While there was a significant positive correlation before and after the update, the scatter plots in Figure 4 clearly show that after

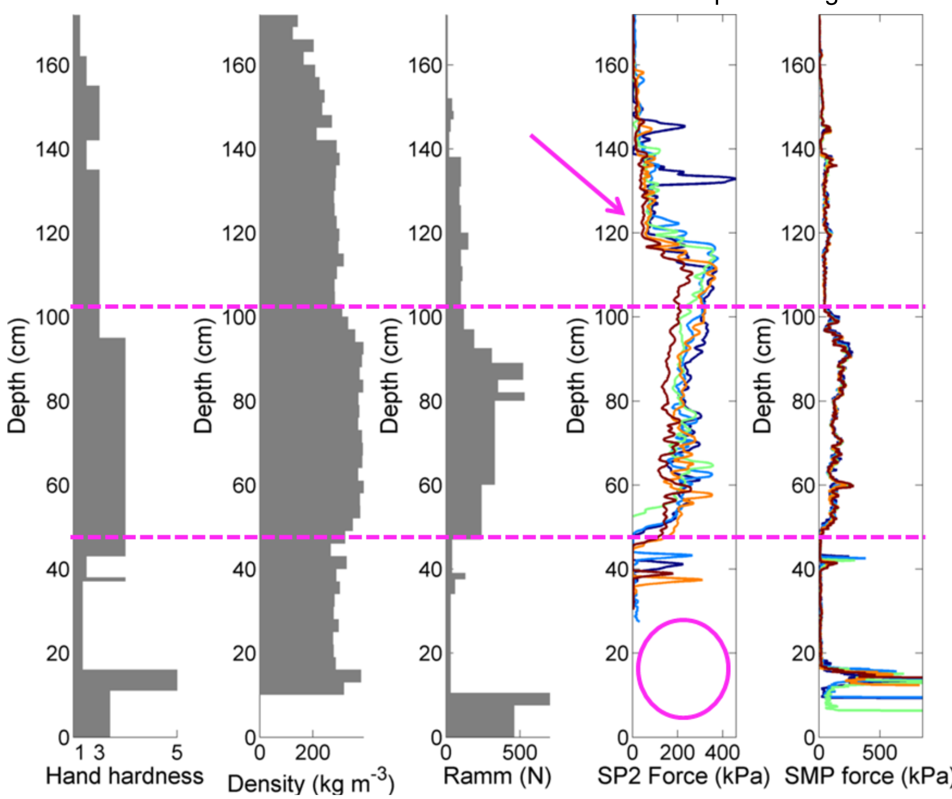

Fig. 2: Side-by-side measurements of hand hardness, density, ram hardness, SP2 and SMP hardness measurements on 16 February 2016. The pink dashed lines include the zone of the consolidated middle part and the pink arrow points to the SP2 profile with an upwards shifted start of this zone. In the pink circle SP2 measurements are missing due to the depth limit of the SP2.

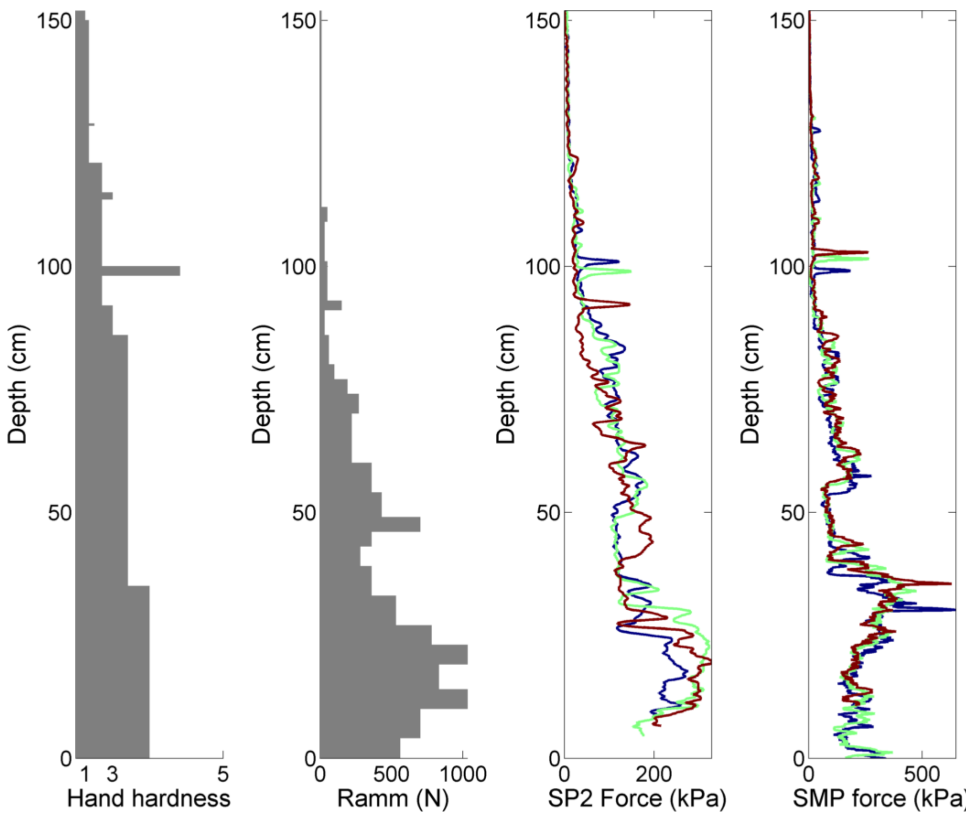

Fig. 3: Side-by-side measurements of hand, ram, SP2 and SMP hardness from 8 March 2016 (after the SP2 firmware update).

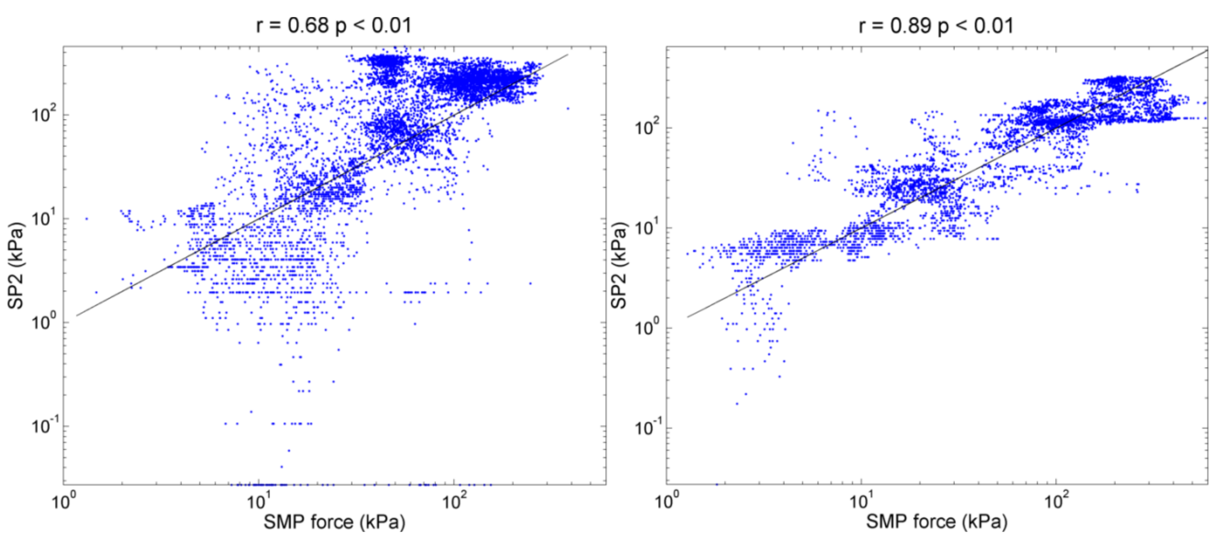

Fig. 4: Correlation analysis of SP2 and SMP hardness for all side-by-side SP2 and SMP hardness measurements before the SP2 firmware update (left) and after the firmware update (right).

the firmware update the correlation improved over the entire range of hardness values, with correlation coefficients of 0.68 before and 0.89 after the firmware update. SP2 and SMP measurements positively correlated with the traditional methods (Figure 5).

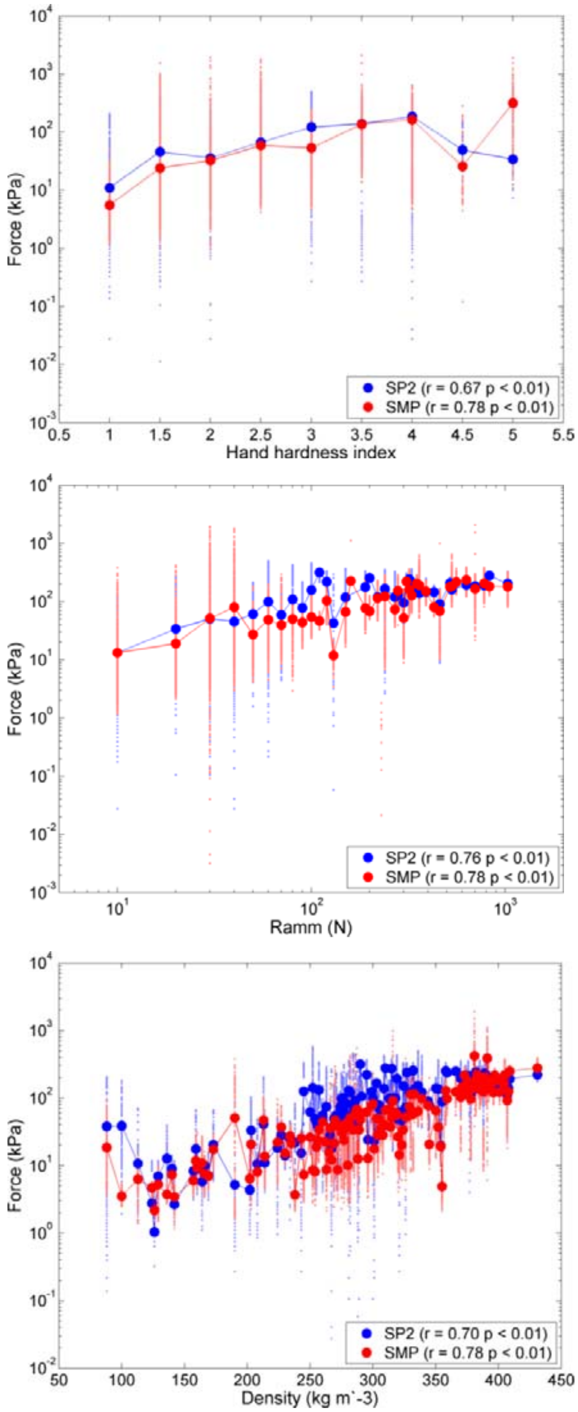

Fig. 5: Correlation analysis of SP2 and SMP hardness with hand and ram hardness and density measurements of all profiles from the winter 2016.

The correlations are not very strong, which is due to the fact that hand hardness, ramsonde and density measurements are relatively crude compared to the small cone penetrometer measurements. Nevertheless, the SMP correlated better with the traditional methods than the SP2 (compare r values in Figure 5).

Parallel transects of SMP and SP2, with closely spaced side-by-side measurements, illustrate the small-scale variability of the snowpack. The horizontal variability is much lower in SMP measurements than in SP2 measurements (Figure 6).

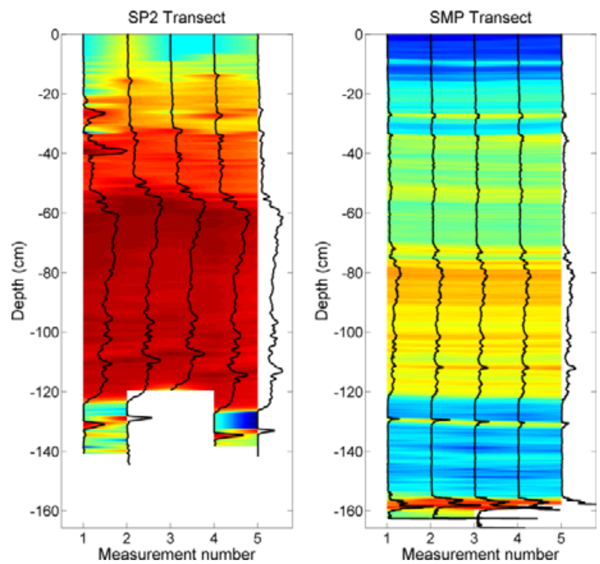

Fig. 6: Interpolated transects of five parallel SP2 and SMP measurements from 16 February 2016. The colors represent hardness with blue for soft layers and red for hard layers.

On similar but longer transects, measured on 17 February and 8 March 2016, the SP2 probe was handled systematically by 5 to 10 different operators on a line up to 10 m. There was no significant operator bias evident in the SP2 data (not shown), even for operators whom had never used the SP2 probe before. This suggests that the measurements obtained with the SP2 probe are not user dependent.

To evaluate the reliability of SP2 and SMP measurements for snow instability assessment, we compared mean weak layer and slab properties for the manually picked layers from each of the five days. Since the SMP measurements showed very little variability (Figure 6), we chose the mean SMP property of all measurements of one day as reference to normalize the individual weak layer hardness and slab thickness values. Overall, the SMP measurements show a much lower variability in weak layer and slab properties than the SP2 measurements (Figures 7 and 8).

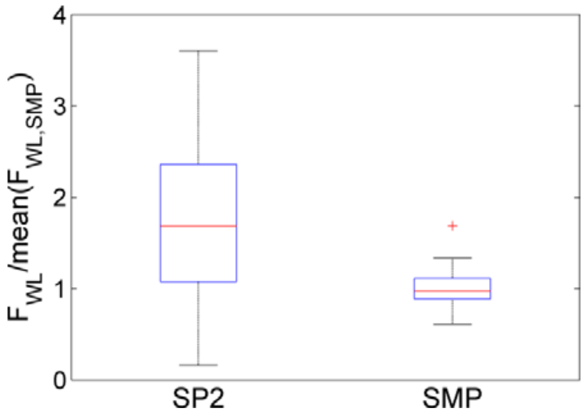

Fig. 7: Normalized SP2 and SMP weak layer hardness (F_{WL}). The values were normalized by the mean weak layer hardness for each day (mean($F_{WL,SMP}$)). The blue boxes span the inter-quartile range from 1st to 3rd quartile with the red horizontal line showing the median. The black whiskers show the range of observed values that fall within 1.5 times the interquartile range and the red crosses are outliers above or below it.

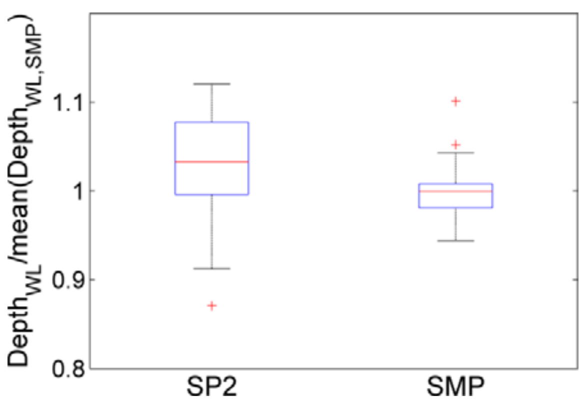

Fig. 8: Normalized SP2 and SMP weak layer depth ($Depth_{WL}$). The values were normalized by the mean SMP weak layer depth for each day (mean($Depth_{WL,SMP}$)).

4. DISCUSSION AND CONCLUSIONS

For decades now, snow scientists have invested much effort to develop methods to objectively measure snow hardness, as it provides an intuitive measure to interpret snow stratigraphy. Very recently, the SP2 was developed by Avatech, a hand drive digital penetrometer which allows to obtain high resolution hardness measurements of the snow cover. To evaluate the performance of the SP2, we compared it to measurements obtained with traditional techniques (hand hardness, ramsonde and density), as well as with the SMP.

Our results show that the SMP is the most precise instrument to measure snow hardness, which is not surprising given that it is driven by a motor and is equipped with a very sensitive sensor. Side-by-side SMP measurements exhibited very little variations. Much larger variations were observed in side-by-side SP2 measurements. One major issue with the SP2 is the inaccurate depth measurement, which can lead to shifts in the force signal of up to 20 cm, relative to the SMP and manual snow measurements. These findings are in line with Hagenmuller and Pilloix (2016). However, after a major firmware update on 24 February 2016 these issues were partly improved. A user bias in the SP2 measurements was not evident.

When comparing SP2 and SMP measurements with hand and ram hardness and density, both had similar positive correlations. This is in part attributed to the fact that the much higher resolution measurements of the SP2 and SMP are compared to relatively low resolution manual measurements. To perform a more in-depth analysis, a reliable layer matching algorithm would be required (Hagenmuller, 2016; Hagenmuller and Pilloix, 2016).

In view of these results and the requirements of professional avalanche forecasting operations we consider the traditional and modern methods to characterize snow stratigraphy. For operational use, instruments need to be on the one hand robust and suitable for field use by different operators in winter mountain conditions. In this area, the SP2 is clearly better suited than the SMP. Nevertheless, signal resolution and accurate positioning of measurements are important as well, especially when evaluating relevant snowpack parameters for stability assessments. In this area, the SMP clearly outperforms the SP2. A future operational snow probe should be able to combine both these aspects and deliver data that can be interpreted in terms of snowpack stability. The dramatic influence of the SP2 firmware update clearly shows, that a robust state of the development is necessary, before avalanche practitioners can consider using such a device operationally.

In general, snowpack stratigraphy assessments with a modern, automated probe would support avalanche forecasting, as it would allow to quantitatively and objectively determine relevant features for snowpack stability and could potentially offer a faster interpretation than traditional methods.

However, since this is not an easy task, the hand hardness profile by trained observers will likely continue to be used, since its practical strengths (flexibility and identification of relevant features) still outweigh its limitations (subjectivity and limited spatial resolution). Yet, the quality of hand hardness measurements is obviously not comparable with the SMP and SP2 data, and future efforts will have to be made to improve the interpretation of digital cone penetrometer data with regards to snow instability.

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