Measuring snow ablation rates in alpine terrain with a mobile multi-offset GPR system

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Abstract. Ground penetrating radar (GPR) has become a promising technique in the field of snow hydrological research. It is commonly used to measure snow depth, density, and water equivalent over large distances or along gridded snow courses. Having built and tested a mobile light-weight setup, we demonstrate that GPR is capable of accurately measuring snow ablation rates in complex alpine terrain. Our setup was optimized for efficient measurements and consisted of a multi-offset radar with four pairs of antennas mounted to a plastic sled, which was small enough to permit safe and convenient operations. Repeated measurements at intervals of two to seven days were taken during the 2014/15 winter season along ten profiles of 50 to 200 m length within two valleys located in the eastern Swiss Alps. Resulting GPR-based data of snow depth, density, and water equivalent as well as their respective change over time, were in good agreement with concurrent manual measurements, in particular if accurate alignment between repeated overpasses could be achieved. Corresponding root-mean-square error (RMSE) values amounted to 4.2 cm for snow depth, 17 mm for snow water equivalent, and to 22 kg/m³ for snow density, with similar RMSE values for corresponding differential data. With this performance, the presented radar setup has the potential to provide exciting new and extensive datasets to validate snowmelt models or to complement lidar-based snow surveys.

Key words: ground penetrating radar, multi-offset approach, snow ablation rates, snow hydrology

1 Introduction

Terrestrial and airborne laser scanning of snow has significantly increased our ability to understand the spatial variability of snow depth (Grünwald et al., 2010, Deems et al., 2013). However, methods to provide corresponding measurements of snow water equivalent of similar range and quality, particularly during the melt phase, are yet unavailable. Ground penetrating radar (GPR) technology allows estimating snow properties such as depth, density, and water equivalent. But most applications that cover large areas do not currently have sufficient accuracy to study spatial variability of snow density in detail and still depend on concurrent ground-based calibration data (Lundberg et al., 2010). Nevertheless, GPR has become more accessible to snow researchers and is already successfully being used in the context of snow hydrological studies for both calibration and validation purposes. GPR presents a non-destructive method and is, compared to manual measurements, very fast, which constitutes the technologies' potential for extensive surveys of snow properties.

GPR has become a frequently applied technique in glaciology (Plewes and Hubbard, 2001; Maurer, 2006; Woodward and Burke, 2007; Booth et al., 2013; Forte et al., 2013) and snow research (Bradford and Harper 2006; Gustafsson et al., 2012; Lundberg, et al., 2006; Lundberg and Thunehed, 2000; Lundberg et al., 2000; Marchand, 2003; Marshall and Koh, 2007; Sundström et al. 2013; Ulriksen, 1982; Webb, 2017; Yamamoto et al., 2004). Lundberg et al. (2010) give a valuable review on the use of GPR in snow studies carried out in Norway, Finland, and Sweden. GPR measurements in Scandinavia, for example, are routinely carried out from snowmobiles to estimate catchment-scale snow water resources (Andersen et al., 1987; Marchand et al., 2001; Marchand and Killingtveit, 2001, 2004).

Many applications of GPR to measure spatially distributed snow properties are generally conducted when dry snow conditions are present (i.e. no liquid water content). Under these

conditions, GPR-based measurements of snow depth, snow water equivalent and snow density are comparably easy to obtain and can be quite accurate (e.g. for snow water equivalent within 5 % of corresponding manual measurements according to Sand and Bruland (1998). They, as well as many others, have assumed snow density to be approximately constant along a measured profile when estimating snow water equivalent from the GPR data. Alternatively, Lundberg et al. (2006) assumed density to be linearly dependent on snow depth. However, when liquid water is present in the snowpack, data analysis methods become more complex and snow water equivalent estimations are typically more uncertain (Lundberg and Thunehed, 2000). Bradford and Harper (2006) determined the liquid water content by using the frequency shift method to estimate the complex electrical permittivity and by using the common-mid-point (CMP) method to estimate the real part of the electrical permittivity. Another approach to determine the liquid water content, proposed by Sundström et al. (2013), is based on the effective electrical conductivity obtained from the two-way-travel time, the propagation velocity, and the attenuation of a radar wave within a snowpack.

GPR technology has been used in many ways to measure snow properties. Here we focus on approaches that allow for spatially distributed measurements, in particular along line or gridded transects. To measure snowpack properties in the presence of density changes, Gustafsson et al. (2012) used an array of multiple impulse antennas of two different nominal frequencies in a row mounted on a sled, which was pulled by a snowmobile, and tested it along a 1 km line. We adopted this approach to develop a light-weight mobile GPR system that allows simultaneous estimation of snow depth, snow density, and snow water equivalent in a snow survey setting in alpine terrain. For this purpose, we built a GPR platform on a sled system with four antenna pairs. We will show how this approach represents a very efficient

Measuring snow ablation rates with a mobile multi-offset GPR system means of spatially-distributed measurements that are similarly accurate as manual measurements.

The study elaborates further on the question of whether GPR systems of this type can possibly be used to determine spatially distributed snow ablation rates in alpine terrain. To this end, we used the GPR system to retrieve snow properties along several preselected transects. Careful repetitions of these measurements along the same transects after several days of snowmelt provided both absolute values of snow depth and snow water equivalent as well as corresponding ablation rates. Complementary manual snow measurements that were taken during the field campaigns for validation purposes allowed us to demonstrate the feasibility of using mobile GPR systems to derive snow ablation rates and examine the practicalities of such measurements.

2 Methods

2.1 Study areas

Measurements were conducted in two valleys in the vicinity of Davos, Switzerland, during the winter of 2014/2015. Field sites were selected according to different requirements. The sites were selected to cover a certain range of elevations, aspects, and slope inclinations (Table 1). Further, each individual site needed to be clear of recreational as well as dangerous areas, in particular avalanche runout zones. Avoiding avalanche exposed terrain was not only for safety reasons but also because an avalanche would have interrupted the series of repeated measurements. Seven sites were located in the Monbiel valley (Figure 1 top right) between 1300 and 1400 m a.s.l. where snowmelt occurred from mid-March 2015 onwards. Starting mid-April 2015, measurements were taken in the Sertig valley (Figure 1 bottom right) between 1850 and 1950 m a.s.l. at three sites. In both valleys, our sites were mostly located

Measuring snow ablation rates with a mobile multi-offset GPR system on snow-covered alpine meadows. Table 1 details the characteristics of all transects based on a digital elevation model with 2 m grid resolution.

2.2 Measurements

A variety of procedures were applied during fieldwork at each transect. The sled was towed by two persons, one to the left and one to the right, so as to prevent stepping on the transect. The GPR assembly was moved at an average speed of approximately 0.4 m/s. For reference, we periodically positioned markers (bamboo sticks) along the transects. These reference points were also marked in the radargrams to allow exact synchronization between repeated measurements along the same transect. To this end, the positions of corresponding traces recorded at these markers were forced to match and the relative positioning accuracy of individual traces along the entire transect could be limited to ≤ 5 cm. Manual measurements of snow depth, snow water equivalent, and liquid water content (as detailed in section 2.2.2) were taken along each transect at the reference points and used for calibration and validation purposes. Subsequent overpasses followed the tracks of the sled drawn during the first acquisition and allowed accurate spatial match between multiple overpasses of the same transect. To avoid the sled from breaking through the snowpack and disturbing the snowpack below, the fieldwork was carried out when a crust had formed after cold, clear nights. Measurements at each transect were repeated three to five times depending on the remaining snow height, as well as meteorological and logistical conditions.

2.2.1 Construction and setup of the mobile GPR system

Typically, snowpack properties such as snow depth, snow water equivalent and snow density show strong lateral variations. For a given liquid water content, both snow depth and density can be independently estimated from multi-offset radar. To allow for efficient sampling we

Measuring snow ablation rates with a mobile multi-offset GPR system opted for a fixed assembly mounted to a plastic sled. At the same time, the assembly needed to be light and small enough to permit safe and convenient operations in snow-covered rugged alpine terrain. Weight could be reduced considerably by adopting an antenna setup suggested by Gustafsson et al. (2012). This design is illustrated in Figure 2 and consists of four instead of eight antennas to form four pairings, which is achieved by combining each of the transmitting with each of the receiving antennas. The downside of this approach is that each pairing has a different midpoint which needs to be synchronized in the post processing. While this is neither difficult nor computationally intensive, it does require sampling at fixed spatial intervals (as opposed to fixed temporal intervals), which necessitates an accurate spatial referencing system.

We used a MALA GPR ProEx (MALA Geoscience, Malå Sweden) system with four of their separable shielded antennas featuring a nominal frequency of 1300 MHz. The multi-offset array was mounted on a light-weight plastic sled (HDPE pulk, Snowsled, UK) with a large baseboard to form a level bottom surface, which provided the fixed antenna positions during the measurements (Figure 2). This way, the antennas were placed approximately 2 cm above the snow surface. To keep the system free from snow, all GPR components including the main unit, antennas, batteries, and cables were enveloped in a waterproofed bag provided with the pulk. Separation distances between the antenna pairs were 0.09 m, 0.32 m, 0.66 m, and 1.07 m. Traces were sampled at a frequency of 42 GHz, and individual traces were recorded every 5 cm along the transects. The trace lengths were set to 744 samples per trace. For highest positioning accuracy, we used a hip chain odometer which measures distance with a specialized thread that unwinds from a spool as the sled moves along the transect. Note that this setup was optimized to allow for accurate measurements in rather shallow snowpack. Deeper snowpack may require lower antenna frequencies, larger antenna offsets, more samples per trace, and more antenna pairings.

To test the capability of the GPR system in mountainous terrain (Figure 3), measurements along ten transects were carried out. Overpasses of exactly the same transects with the GPR were repeated several times during snowmelt periods without precipitation in between the measurements. The dates of the measurements are listed in Table 1.

2.2.2 Manual measurements

Snow water equivalent was measured with a standard Federal sampler and thus only imposed minimal disturbance of the snowpack. In some cases however, when ice layers were present in the snowpack, taking the measurements became more challenging and several attempts were necessary to extract an intact snow core. For each snow water equivalent sample, three snow depth measurements were taken at the same location as well as one and two meters away along the transect. We estimate the accuracy of these measurements to amount to ± 10 mm for snow water equivalent and to ± 1 cm for snow depth.

Measurements of the liquid water content were taken using a Denoth meter (Denoth, 1994) and a small snow sampler for concurrent snow density measurements. The Denoth meter was used to determine the relative dielectric permittivity of snow with 10 cm vertical spacing in a snow pit. Techel and Pielmeier (2011) give more details on this device and compare it to possible alternatives. Concurrent snow density measurements were taken with a small cylindrical sampler of 100 cm³ volume. Resulting liquid water content values were averaged per snow pit, with a mean value of 2.1 Vol% when further averaged over all pits. The accuracy of the resulting values is estimated to be ± 0.5 Vol%. To minimize disturbances, we limited these measurements to one vertical profile per transect and acquisition date. For each, a snow pit was dug sideways towards the center of the transect. Complementary measurements some meters away from the transect, however, showed liquid water content to be fairly constant along individual transects with a mean standard deviation between

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alternative measurements for a given transect of 0.5 Vol% only. We consequently assumed liquid water content to be constant along individual transects.

2.3 Data post processing

Information about standard procedures when analyzing GPR data are, e.g., available from Annan (2009). Below we outline post processing details specific to this study. Most GPR radargrams showed a clear signal and did not require excessive filtering. However, to improve the signal-to-noise ratio and the visibility of reflecting layers, especially of the soil surface, we applied the following processing steps to the radargrams before picking the relevant layer interfaces. We first removed any amplitudinal offset using a DC-shift filter. Second, where needed, we applied a manual y-gain filter to amplify the signal as it attenuates with increasing travel time. Figure 4 shows an exemplary GPR radargram before filtering, after filtering, and after picking. A Kirchhoff migration was further applied to all radargrams of the S3 transect in Sertig valley as this site featured some roughness elements on the ground along the transect (using a wave velocity according to respective snow pit measurements at S3). All above steps were performed using the Software ReflexW, Sandmeier Scientific Software. This software was further used to pick reflections of the layer interfaces using the phase follower utility built into ReflexW. This determines the travel time of the direct wave, which is the first radar signal reaching the receiver, and of the bottom wave, which reaches the receiver after being reflected at the bottom interface underneath the snowpack. Then, odometer data were used to shift the picks of the individual antenna pairings to refer to a common mid-point (CMP). This as well as the subsequent CMP analysis were performed in Matlab.

Procedures for analyzing CMP data are described in detail e.g. in Gustafsson et al. (2012). However, some processing details specific to our set up are detailed below. Since the

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antennas were very close above the snow surface at all times, the direct wave and the surface wave are assumed to be identical in this work. This implies that the direct wave velocity cannot be assumed to be 0.3 m/ns as usual, but instead depends on material properties of the base of the sled (baseboard, air, bag, plastic shell), as well as of the top snow surface. While the former are constant, the latter are not. The direct wave velocity is needed to determine the two-way travel time (t_{snow}) from the picks. Even if the calculation of the two-way travel time is insensitive to potential errors in the direct wave velocity due to variable effects from the snow surface, we have adopted the approach to determine the direct wave velocity for every GPR transect individually by optimizing the fit to complementary snow depth and snow water equivalent data collected along each transect. To this end, the travel time of the direct wave (t_{dir}) is determined as:

$$t_{dir} = t_{snow} - t_{diff} = \frac{d_{snow}}{v_{snow}} - t_{diff} \quad (1)$$

where t_{diff} results from the picks, d_{snow} is the travel distance of the bottom wave (available through antenna offset and observed snow depth), and v_{snow} is the radar velocity through snow (available through observed snow density and liquid water content). This way, estimates of t_{dir} are available for each antenna offset and each set of snow observations (depth, density, liquid water content). To arrive at one direct wave velocity per offset, t_{dir} estimates from multiple observations along the transect were averaged. The above procedure can be extended by including liquid water content as part of the optimization. In this case the liquid water content is iteratively adjusted to minimize the root-mean-square error between observed and calculated snow data (c.f. Table 2). In this work, we used the extended calibration approach.

Following the results of extensive field tests (Koch et al., 2014), we chose to estimate dielectric properties based on parameterizations from Tiuri et al. (1984), in particular for

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determining the real part of the complex dielectric permittivity of wet snow ϵ_s' from liquid water content θ and the dry snow density ρ :

$$\epsilon_d' = 1 + 1.7\rho + 0.7\rho^2 \quad (2)$$

$$\epsilon_s' = (0.1\theta + 0.8\theta^2)\epsilon_w' + \epsilon_d' \quad (3)$$

where ϵ_d' is the real part of the complex dielectric permittivity for dry snow and $\epsilon_w' = 87.9$ is the real part of the complex dielectric permittivity of water.

Raw density estimates resulting from the CMP analyses were smoothened along each transect by applying a running mean filter with a window size of +/- 5 m. The CMP analyses were updated thereafter to reflect the revised density transects.

2.4 Alternative data analysis using a single-offset

To quantify the advantages of using a multi-offset radar, we ran a separate data analysis for all transects and acquisition dates using only data from one of the four antenna pairs (i.e. the pair with 0.66 m separation distance). To this end, snow depth was directly inferred from the two-way travel time using v_{snow} according to observed snow density and liquid water content. Multiple observations per transect were averaged, consequently snow density and liquid water content were assumed to be constant along each transect.

3 Results

At all transects, snow water equivalent decreased with time between any series of consecutive overpasses. Subsequent measurements of snow water equivalent profiles show mostly similar spatial patterns, which means that local minima in snow depth and snow water equivalent often remained in place during the entire melting period. Finding spatially uniform snow ablation patterns is not unexpected considering studies such as Egli et al. (2012).

Figure 5 (left panel) presents GPR-based snow depth estimates along transect S3 in the Sertig valley at all sampling dates. The GPR data is in very good agreement with the manual snow measurements (corresponding dots). The root-mean-square error (RMSE) evaluated over all reference points along transect S3 is 2.4 cm for snow depth and 12 mm for snow water equivalent. These values are on the order of the accuracy at which these properties can be determined with manual measurements. Calculating ablation rates by subtracting subsequent acquisitions could also be tested against observations, as the manual measurements were conducted at fixed positions. For these differential measurements of snow depth and of snow water equivalent the RMSE is 2.2 cm and 24 mm, respectively.

Additionally, processing the S3 radargrams using Kirchhoff migration did reveal some additional fine-structured details in the resulting profiles (Figure 5, right panel). Note, however, that these details were only partly maintained over consecutive acquisitions, which questions whether the migration actually corrected for uneven subsurface features below the snow, just introduced additional noise, or both.

After using Kirchhoff migration, corresponding RMSE were slightly deteriorated with values of 2.3 cm for snow depth, 19 mm for snow water equivalent, 2.6 cm for differential snow depth, and 30 mm for differential snow water equivalent. These findings suggested that migration did not improve the results, and therefore we did not include migration in post-processing.

Further examples of consecutive GPR acquisitions are presented in Figure 6, however these are for the resulting snow water equivalent profiles along transects S2 and M1. Similar to the snow depth profiles in Figure 5, but more prominently seen in the snow water equivalent profiles presented in Figure 6, there are some deviating features from the common signature along the profile, e.g. in S2 (Figure 6, left panel) for the acquisition on April-16 between the 10 and the 25-m mark. These deviations might simply stem from wrong interpretations within

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individual radargrams, but they might also result from a short deviation from the exact trajectory of the transect.

Validation data for all transects are presented in Table 2 and visualized in Figure 7. The RMSE for snow depth using all transects in both valleys is 4.2 cm and 17 mm for snow water equivalent, 4.2 cm for differential snow depth (Figure 7, left), and 34 mm for differential snow water equivalent (Figure 7, right). These RMSE values were considerably degraded due to transect S1. This particular transect covered some very steep sections in which it was difficult to control the sled in order to follow the given trajectory. We therefore assume that misalignment between consecutive GPR acquisitions have caused a considerably worse validation performance compared to all other transects. Removing S1 from the summary statistics results in vastly improved performance for snow water equivalent (Figure 7).

Overall, we note that differential snow depth and differential snow water equivalent could be measured to a RMSE as low as 3.8 cm and 21 mm, respectively, provided that the experimental conditions allowed exact alignment of repeated GPR acquisitions.

Further examination of individual outliers revealed another source of experimental error. Manually measured and GPR-based data of S3 were found to be in excellent agreement with the exception of one individual point, encircled in Figure 8. In this example, manual observations of differential snow depth were significantly lower than corresponding GPR estimates. Figure 8 (right panel) suggests that it is in fact the manual observation that is questionable, not the GPR data, and it appears as if the last reading of snow depth on April-24 at the third marker point was in error, possibly due to an ice layer. In assessing the accuracy of GPR systems, errors in the validation data therefore also have to be considered, and GPR systems may in fact produce more reliable snow depth estimates compared to traditional probing in certain instances.

Also the GPR-based snow density estimates were validated against manual snow measurements (Figure 9, right panel). GPR data were in good agreement with observations with a RMSE of 22 kg/m^3 for data from all transects in both valleys. A break-down into RMSE values for individual transects is available from Table 2, showing only small differences between RMSE values but with a tendency to larger errors for the Sertig valley transects (S1, S2, S3).

Finally, we compared results for the multi-offset radar with an analysis purposely downgraded to mimic results for a corresponding single-offset radar. Figure 10 presents snow depth, density, and water equivalent estimates for transects M4 and S2 and both GPR scenarios. For transect M4 the multi-offset radar provides vastly improved results for snow density and water equivalent with RMSE values as low as 5 kg/m^3 and 6 mm , respectively. However, transect S2 represents an example where only density estimates benefit from using a multi-offset setup. Aggregating the results over all transects and acquisitions dates, RMSE values for snow depth were not affected, RMSE values for snow water equivalent were improved by 19% (17 mm for multi-offset radar vs. 21 mm for single-offset radar), and RMSE values for snow density were improved by a factor of 2 (22 kg/m^3 for multi-offset radar vs. 45 kg/m^3 for single-offset radar).

4 Discussion

Our results show that the GPR system tested in this work was capable of measuring snow depth, snow water equivalent, and snow density in very good agreement with concurrent manual measurements. Direct comparison between GPR-based and manual observations resulted in an overall RMSE of 4.2 cm , 17 mm , and 22 kg/m^3 for snow depth, snow water equivalent, and snow density, respectively. Any mismatches could have resulted from errors in the GPR-based estimates, from errors in the manual observations, and from errors in the

spatial alignment between measurement locations, or in all of these. Probing errors do occur, e.g. if an ice layer is hit instead of the ground (Figure 8), or if soft ground is penetrated. Misalignment errors were reported for profile S1, which resulted in considerably worse RMSE values especially for differential snow water equivalent (Table 2). Considering all sources of mismatch, we may infer that the accuracy of the GPR-based estimates of snow depth and snow water equivalent is not substantially different from those of manual measurements taken in a field survey setting. A similar GPR setup has been tested by Bühler et al. (2015), but over a much more extended range of snow depths ranging from 0.7 to 2.7 m. They also found GPR and concurrent manual snow depth estimates to match very well, i.e. with an R^2 of 0.96 and RMSE of 7 cm. The above findings are particularly noteworthy given that all campaigns have been done during the snow melt period where liquid water was present in the snowpack. Many previous applications of GPR have reported difficulties or reduced accuracy under melting snow conditions.

Several aspects may have helped to increase the reliability of our system under these conditions. Gustafsson et al. (2012) calibrate their system by lifting the antennas by a known distance above the snow surface and assume a wave velocity of 0.3 m/ns through air. Our procedure may be more time consuming as it requires complementary snow pit measurements, but allows us to determine the direct wave velocity *in situ* (i.e. while the systems is on the snow surface). At the same time the manual measurements allow us to infer a representative liquid water content that certainly helps to improve GPR-based snow density estimates. In our analysis, the liquid water content was assumed to be constant along a given transect. For the relatively short profiles investigated here (48 to 206 m), this simplified approach seemed to be feasible. However, for the use of GPR along longer transects, the lines should be broken into shorter segments of constant liquid water content. In this case, a set of roughly ten snow depth and three snow water equivalent manual measurements is suggested

Measuring snow ablation rates with a mobile multi-offset GPR system to complement each of those segments for calibration and validation purposes. Note that in the two investigated areas the underlying ground surface was mainly alpine meadows. For this case, we assumed that a few post processing steps were sufficient to analyze the radargrams. Also using migration technique did not improve the results, but might become necessary over more rugged terrain.

Compared to manual measurements, the multi-offset radar setup used in this study was able to a) record snow depth, density, and snow water equivalent simultaneously, b) perform observations substantially faster and more efficiently than manual methods, even if the time for data post processing is included. Essentially, it can record data along transects at a spatial resolution that may be practically unavailable with manual measurement techniques. Using a multi-offset radar particularly provided spatially distributed snow density estimates, which are often unavailable when using single-offset radar systems. As a consequence GPR-based snow water equivalent estimates were considerably improved over corresponding results for a single-offset system.

Improving our ability to accurately measure spatial distributions of snow density will allow advancing current procedures to derive spatial snow water equivalent maps from airborne lidar surveys. Raleigh and Small (2017) highlighted the importance of accurate density measurements to improve physically based snow models increasingly being used to convert airborne snow depth into water equivalent (Painter et al., 2016). Also, a set of transects representing the physiographic range of the surveyed area could allow for a local, detailed, and observation-based density parameterization to accurately convert snow depth into corresponding snow water equivalent maps.

Interestingly and novel to our knowledge, root-mean-square error values for differential acquisitions of snow ablation rates were similar to those determined for respective absolute acquisitions of snow depth and snow water equivalent. We can therefore infer that GPR

Measuring snow ablation rates with a mobile multi-offset GPR system systems can in fact be used to measure snow ablation rates in alpine terrain. For differential acquisitions, however, the accurate spatial alignment of repeated overpasses is a key to arrive at accurate ablation rates. This requires either very precise geolocation methods or homogeneous snow properties so that misalignments are less problematic. Using fixed marker points in combination with an odometer may work well for relatively short transects and in the context of studies like this. Alternatively, using a GPS-based geolocation method and mitigating misalignment problems by way of spatial averaging might constitute a solution towards operational or large-scale applications of GPR systems like the one presented here. Furthermore, reducing the weight and size of the GPR system helped to precisely maneuver the sled through alpine terrain, even under challenging conditions such as steep slopes (Figure 3).

Finally, the snowpack should remain as undisturbed as possible between surveys to allow meaningful differential measurements. Surveying in the mornings on a hard snow surface which might be unavailable under different climatic conditions helped us to minimize the impact of the sled. It would have not permitted high impact activities, such as the use of a snowmobile for towing the GPR over longer distances.

5 Conclusions

Large scale remote sensing techniques to deliver snow properties depend on reference measurements or on model output which on their part also require validation measurements. However, manual point measurements covering whole catchments may often be unavailable and unaffordable, especially for a series of consecutive survey dates. GPR surveys with mobile setups enable measuring large quantities of snow depth, snow water equivalent, and snow density simultaneously. This technology is therefore particularly valuable for research-oriented or application-driven measurements of snow water resources. While extended

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datasets of accurate and collocated measurements of snow depth and snow water equivalent are valuable in itself, they have an even greater potential if acquired in parallel with airborne lidar surveys. Even if GPR-based measurements cannot provide full coverage over extended areas, GPR-based data from sites which represent the physiographic range of the surveyed area allow improving and training existing methods to convert lidar-based snow depth into snow water equivalent in a fully-distributed manner.

The setup presented here was optimized for efficient measurements in alpine terrain. To this end, a multi-channel radar with four antenna offsets was mounted on a plastic sled, which was small enough to permit safe and convenient operations. This allowed us to take continuous measurements of the above snow properties along line transects at a speed of roughly 25 meters per minute (excluding concurrent manual measurements).

Continuous CMP profiling allowed to arrive at snow depth, water equivalent, and density estimates without requiring bulk assumptions about the relationship between these properties. We have shown that these GPR measurements can be as accurate as equivalent manual measurements in a field survey setting, in particular if the ground surface below the snow represents a good reflector and is considerably smooth.

Further field tests could demonstrate that the GPR system was even capable of measuring snow ablation rates. To our knowledge, this is one of the first studies to demonstrate an appropriate non-destructive mobile multi-offset GPR setup which is agile and light enough to deliver such accurate estimates of snow properties. For that purpose, acquisitions were conducted repeatedly along the same transects over the course of several days to weeks. The accuracy of such differential measurements was similar to those of absolute measurements. However, the accurate spatial alignment of repeated overpasses was found to be a key to arrive at accurate ablation rates. The practicalities to achieve this were challenging and

Measuring snow ablation rates with a mobile multi-offset GPR system eventually not yet suited for operational or large-sale applications, but certainly feasible for research purposes.

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Table 1. Characteristics of transects in this study. TM1: 09 March 2015, TM2: 11 March 2015, TM3: 18 March 2015, TM4: 21 March 2015, TS1: 08 April 2015, TS2: 13 April 2015, TS3: 16 April 2015, TS4: 21 April 2015, TS5: 24 April 2015.

Site name	Valley	Mean elevation [m a.s.l.]	Mean slope [°]	Main aspect	Length [m]	Dates of measurements
M1	Monbiel	1342	10	SE	87	TM1, TM3, TM4
M2	Monbiel	1337	7	SE	48	TM1, TM3, TM4
M3	Monbiel	1359	9	SW	206	TM1, TM3, TM4
M4	Monbiel	1363	11	W	133	TM1, TM3, TM4
M5	Monbiel	1374	12	SW	103	TM1, TM3, TM4
M6	Monbiel	1361	8	S	165	TM2, TM3, TM4
M7	Monbiel	1354	4	S	174	TM2, TM3, TM4
S1	Sertig	1893	9	E	137	TS1, TS2, TS3, TS4, TS5
S2	Sertig	1903	10	NE	63	TS1, TS2, TS3, TS4, TS5
S3	Sertig	1857	2	S	118	TS1, TS2, TS3, TS4, TS5

Table 2. Root-mean-square error (RMSE) and mean error (ME) of snow depth, differential snow depth, snow water equivalent, differential snow water equivalent, snow density, and liquid water content for each transect.

	RMSE (ME) snow depth [cm]	RMSE (ME) differential snow depth [cm]	RMSE (ME) snow water equivalent [mm]	RMSE (ME) differential snow water equivalent [mm]	RMSE (ME) snow density [kg/m ³]	RMSE (ME) liquid water content [Vol%]
M1	3.5 (-0.2)	3.5 (-0.1)	13 (2)	21 (18)	21 (2)	0.2 (-0.1)
M2	2.6 (0.5)	2.2 (0.7)	7 (2)	15 (-1)	14 (4)	0.3 (0.1)
M3	3.0 (-0.4)	4.6 (-1.6)	11 (-1)	13 (-1)	19 (1)	0.2 (-0.1)
M4	2.9 (0.0)	1.5 (0.1)	12 (1)	11 (-2)	18 (1)	0.4 (-0.1)
M5	5.2 (-1.4)	5.8 (-0.4)	13 (-4)	14 (-5)	18 (-1)	0.0 (0.0)
M6	3.2 (0.2)	3.4 (-0.1)	14 (3)	23 (4)	17 (2)	0.2 (0.0)
M7	5.1 (0.5)	4.5 (2.4)	16 (-2)	16 (-6)	19 (-6)	0.8 (0.3)
S1	5.0 (-0.9)	5.4 (-0.2)	21 (-2)	62 (38)	24 (-9)	0.8 (0.3)
S2	6.0 (1.4)	4.6 (-2.5)	31 (14)	31 (23)	28 (11)	0.9 (0.5)
S3	2.4 (0.1)	2.2 (-0.2)	12 (-1)	24 (-1)	27 (-2)	0.7 (-0.4)

Figure 1: Topographic maps of Monbiel (top right) and Sertig (bottom right) valleys with sites indicated in red. Both valleys are located in the eastern Swiss Alps, the Monbiel valley being east-west orientated and 550 m lower than the south-north orientated Sertig valley. Reproduced by permission of swisstopo (JA100118). pixmaps© 2016 swisstopo (5704 000 000).

Figure 2: Setup illustration of the shifted CMP approach as topview (bottom) and picture taken in the field (top). T and R denote transmitting and receiving antennas on the sled, where arrows indicate the midpoint of each individual antenna pairing on a reflecting target. Antennas, main unit, user interface, batteries, and cables are placed on the sled's baseboard and enveloped in a waterproofed bag inside the plastic sled. An odometer is attached to the rear end of the sled. While we used the MALA hip-chain odometer, image and sketch show a regular odometer wheel for better illustration.

Figure 3: Fieldwork using GPR in steep alpine terrain (left) and (right) fieldwork at the third overpass of a transect in Monbiel valley. Flags mark points of manual measurements of snow depth and snow water equivalent for validation/calibration purposes, and serve as reference points for the synchronization of subsequent overpasses.

Figure 4: Radargram of transect M4 passed over on 09 March 2015, raw (top), after filtering (middle), and after filtering including green picks (bottom).

Figure 5: Snow depth of five overpasses along transect S3 without using migration (left panel) and with using Kirchhoff migration (right panel). Circles denote manual measurements at the reference points.

Figure 6: Snow water equivalent of three overpasses along transect S2 (left panel) and transect M1 (right panel). Circles denote manual measurements at the reference points.

Figure 7: Relation between radar and manual measurements of differential snow depth (left) and differential snow water equivalent (right) using all transects. The RMSE values for the relation between radar and manual measurements using all transects except for S1 are given in brackets.

Figure 8: Relation between radar and manual measurements of differential snow depth at transect S3 (left panel), where an obvious error (encircled) could be attributed to a probing error during the last acquisition on 24 April 2015 (right panel).

Figure 9: Relation between radar and manual measurements of snow water equivalent (left panel) and snow density (right panel) using all transects.

Figure 10: Snow depth, snow water equivalent, and snow density along transect M4 passed over on 18 March 2015 (left panels) and along transect S2 passed over on 21 April 2015 (right panels). The top panels result from the method presented here, using all antennas of the multi-channel system. For comparison, the bottom panels show the results of using only a single antenna pair under the assumption of a constant snow density along each transect.