Innovative devices for the SWE estimation at the basin scale: a field study in the Western Alps.

Bal G.[1,2] , Bevilacqua I.[3] , Cremonese E.[4], Dellavedova P.[1], Diotri F.[1], Ferraris S.[3],
Frigo B.[1, 5 *], Godio A.[2], Letey S.[4], Morra di Cella U.[4], Pogliotti P.[4], Previati M.[3] , Rege R.[2] .
1 Fondazione Montagna Sicura, Courmayeur (AO), Italy.
2 DITAG – Politecnico di Torino, Torino, Italy
3 DEIAFA – Università di Torino, Torino, Italy
4 ARPA – Valle d'Aosta, Aosta, Italy
5 DISTR – Politecnico di Torino, Torino, Italy

ABSTRACT: The first results of the "SnowRKnown" project (supported by Fondazione CRT), which investigates the Snow Water Equivalent (SWE) at the basin scale with innovative devices, are presented. The estimation of the SWE, the product between the height of the snow cover and the ratio between snow and water densities, is usually based on punctual measures with traditional techniques (excavation of snow trenches and vertical density profiles). These techniques are time consuming and require a large employment of human resources when applied to alpine basins of several square kilometres area. Instead the use of electromagnetic devices, the Ground Penetrating Radar (GPR), the Time Domain Reflectometry (TDR) and Water Content Reflectometry (WCR) can lead to faster estimated of desired snow properties. We performed two campaigns (during April 2008 and April 2009) to a portion of the Breuil-Cervinia basin (Valtournenche, Aosta Valley). For each device, the methodology of the survey is described within data acquisition, their processing and the results.

KEYWORDS: Snow Water Equivalent, Ground Penetrating Radar (GPR), Time Domain Reflectometry (TDR), Water Content Reflectometry (WCR), Spatial Variability.

1 INTRODUCTION

The snow plays a very significant role in mountain hydrology and snow-engineering. The Snow Water Equivalent (SWE) is one of the most important factor in mountain hydrology and snow-melt discharge modelling for water management, irrigation, energy production and tourism. SWE is defined as the product between the height of the snow cover, and the ratio of snow and water densities. It is usually estimated by punctual measures with a traditional technique: manual excavation of snow trenches with the survey of vertical density profiles. Due to the spatial variability of snow cover properties, the traditional technique is time consuming and requires a large employment of human resources, when applied to alpine basins of several square kilometres.

One year ago, thanks to the collaboration of Fondazione Montagna Sicura, DITAG - Politecnico di Torino, DEIAFA - Università degli Studi di Torino and ARPA Valle d'Aosta and with the financial support of Fondazione CRT, the project "SnowRknown" started. The aim of the project is the application of innovative devices to survey the thickness and the ameliorate the spatial distribution of obtained data reducing time and human resources.

The electromagnetic devices used are the Ground Penetrating Radar (GPR), the Time Domain Reflectometry (TDR) and the Water Content Reflectometry (WCR). E.m. measures are coupled with the classical manual technique in order to validate the e.m. estimation of snow properties.

To check the effectiveness of the e.m. devices, a portion of the Breuil-Cervinia basin (Valtournenche, Aosta Valley, Italy) has been chosen. The area is subdivided in three sectors, having common geo-morphological peculiarities:

- sector n. 1 bordered by Colle Superiore di Cime Bianche and the Goillet Lake (from 3.000 m to 2.700 m),
- sector n. 2 bordered by Tête Grise and Cime Bianche Lakes (from 3.450 m to 3.150 m),
- sector n. 3 bordered by Tête Grise of Théodule glacier and the Goillet Lake (from 3.470 m and 2.700 m).

Two campaigns were performed during April 2008 and April 2009. The goal of the first one was to test the reliability of new devices in evaluating rapidly the thickness and the density of snow cover and supporting the information given by classical technique. The second survey has been performed to maximise the number of measurements (in particular the average density of snow cover) already taken in the sectors n. 1 and 3 following and draft the SWE map of the

---

Corresponding author : Barbara Frigo.
Fondazione Montagna Sicura - Loc. Villair de la Palud, 1 – 11013 Courmayeur (AO), Italy
E-mail: bfrigo@fondms.org

basin in the future. This short note presents the first result of the project and describes each device, the methodology of the survey, the data acquisition and their processing.

2 TRADITIONAL TECHNIQUE

To validate the measurements performed by GPR, TDR and WCR techniques, the traditional survey has been done. The height of snow cover has been punctually measured by the vertical insertion of graduated metal probes with conic tip. The maximum length of probes was 3m. Higher covers are only characterised by “height > 3m”. To localise univocally the point of measure in the basin, its position has been labelled by a geo–referenced UTM ED 50 coordinates. Besides, for some points, the survey of the average density of the snowpack has been done by the excavation of snow trenches. The vertical density profiles is obtained by means of horizontal metal cylinder with 0,5 dm^3 of volume. From the top of the trenches to the soil, the density has been measured each 50 cm, without considering the stratification of the snow cover.

3 GEORADAR GPR

Radar techniques can be used to determine snow depth from the two-way travel time of an electromagnetic wave propagating through the snowpack. The georadar is able to give accurate estimates of mean snow depth with much less time spent in the field compared to conventional measurements (Harper and Bradford, 2003). The density of dry snow, also related to the liquid water content, if it is present, can be estimated by snow permittivity (Gerdel, 1954).

Sand and Bruland (1998) described georadar acquisition and data processing for applications on snow cover and demonstrated the utility and the convenience of the technique. Performance and accuracy of radar systems for snow depth analysis have been discussed by several authors (Koh et al. 1996); these properties are mainly affected by environmental conditions.

3.1 Data acquisition

The survey was conducted in April 2008 and April 2009. In the first survey (2008) more than 9 km of radar profile were acquired with high spatial density (trace distance along the profile of few centimetres) by tracking the transmitter and receiver antennas in continuous reflection mode. The radar traces was referenced by GPS real time acquisition, that guarantees a theoretical spatial accuracy in the order of few meters. Two IDS georadar systems were adopted, using antennas operating at the main frequency of 900 MHz. At this frequency, in a snow with wave velocity of 0.2 m/ns, the theoretical vertical resolution is about 0.06 m (wave length/4). Lateral resolution is on the order of the Fresnel radius, in this case is about 0.5 m for a snowpack thickness of 2 m. The survey was performed in all different sectors of the basin: sectors 1 and 3 are related to the survey of the snow depth directly deposed on the ground; while the sector 2 refers to the investigation of the snow depth on the glacier of Ventina.

3.2 Processing

Data processing involved standard analysis of georadar acquisitions. The main operations that we performed on raw data are: dewow, filtering to remove main bang effect, gain to recover geometrical spreading and trace stacking to improve signal to noise ratio. Finally we picked the two way traveltimes of the snow-bedrock interface on the processed radar sections. Radar traces with traveltimes were georeferenced in UTM ED 50 coordinates system.

3.3 Results

In figure 1, two radar sections are reported; the sections are processed as previously explained. The snow-bedrock interface reflection can be easily detected; the reflection demonstrates the great variability of the snow cover also for small distances.

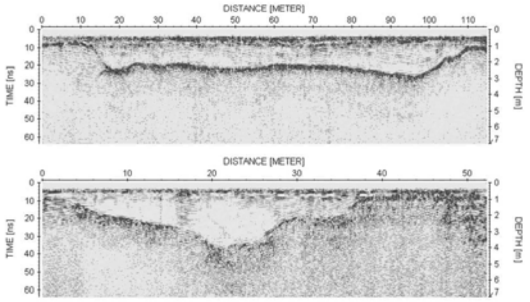


Figure 1: example of radar time-sections in sector 1 along two different transects. The snow-depth is computed considering an average wave velocity of 0.225 m/ns.

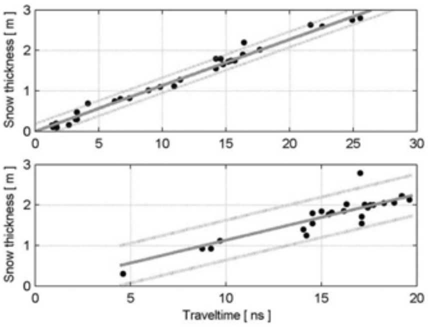
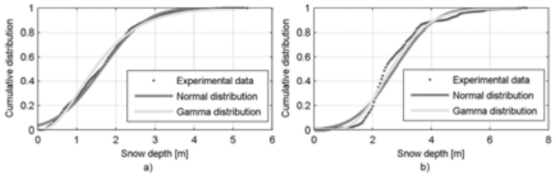


Figure 2: wave velocity calibration along two different GPR transects: top) transect 1 - velocity=0.227 m/ns; r_2=0.99; bottom) velocity=0.226 m/ns, r_2=0.79.

The statistical analysis for each sector computed the probability distribution function and the cumulative one of the snow depth The experimental data are fitted with normal and gamma distributions, the fitting are in good agreement with data (figure 3).



a)

b)

Figure 3: cumulative distribution of snow depth as estimated by georadar observations: a) data acquired below 3000 m; b) data acquired above 3000 m.

Distribution curves computed with GPR data are more consistent than the ones obtained with hand probing measurements only. These results are therefore useful for developing an hydrological model of the area.

4 TIME DOMAIN REFLECTOMETRY (TDR)

In snow, the electrical permittivity can be also measured by Time Domain Reflectometry method (Stein and Kane, 1983). The TDR cable tester produces a step voltage pulse which contains a bandwidth in the range 20 kHz to 1.5 GHz (Heimovaara, 1994), guided trough the porous media by two or three parallel metal rods inserted in the snowpack. The e.m. signal propagation velocity is mainly a function of the electrical permittivity of the material, through which it travels with potential modifications by conductive losses. However, the dry snow can be considered as a non-conducting medium; the electromagnetic wave does not suffer from the intrinsic attenuation as it propagates through a snowpack as a lossless medium. In fact, the snow is considered as a mixture of ice crystals, liquid water and air, at very low temperatures the presence of unfrozen water molecules can be excluded. In this condition the real part of dielectric permittivity is mainly related to the snow density.

The relationship between wave velocity and dry snow density can be written as (Looyenga, 1965):

$$\varepsilon_{r,snow}^{1/3} - 1 = x \cdot \left(\varepsilon_{r,ice}^{1/3} - 1\right) \qquad [\ 1\ ]$$

where x is the ratio between the snow mixture density and that of ice (920 kg/m^3); the relative values of electrical permittivity are: ε_{ice}=3.2, $\varepsilon_{\text{water}}$=78 (at 0° Celsius) and ε_{air}=1 (e.g. Matzler, 1996).

4.1 Data acquisition

TDR measurements have been carried out by means of Tektronix 1502C, with spacing of 2 m and using a set of two rods probes (0.15, 0.30, 0.50, 0.60, 1.00, 1.20 1.50 m lengths) inserted vertically into the snow cover. The surveys have been carried out along the same transects acquired by the GPR system.

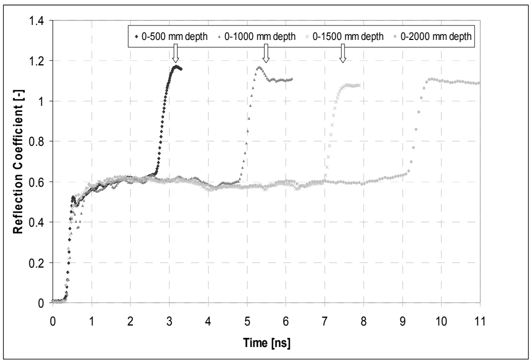


Figure 4: TDR waveforms related to different vertical probe lengths in the same measurement point.

The probes were made of two INOX stainless steel rods (diameter = 5 mm), spaced by a Nylon spacer at a distance of 50 mm (Knight, 1992). Each probe was connected to the cable tester by a RG58 coaxial cable with 50 Ω characteristic impedance. Nickel-plated brass BNC connectors were employed to connect each cable to the Tektronix 1502C.

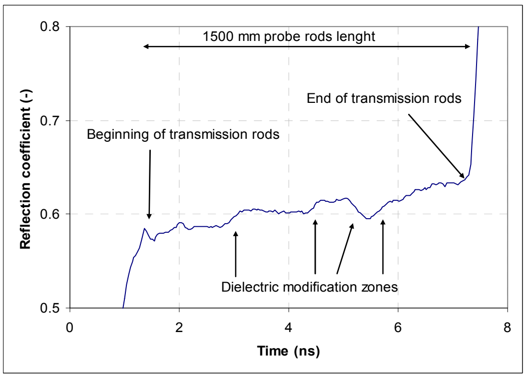


Figure 5: dielectric spatial variability in an acquired waveform (probe length: 150 mm)

The TDR waveforms (e.g. that highlighted in figure 5 and detected by a 150 mm length probe) are characterized by an evident local minimum, associated to the interface between air and snow. Some micro reflections are connected to the dielectric modifications and the snow density. The main reflection at the probe end is also well depicted.

In dry snow, the high data quality allows a good accuracy in the waveform interpretation, even for signals acquired with shorter probes, because the absence of free water molecules induces relevant contact between rods and snow. Finally, together with the classical measurement of snow density, the TDR has also been tested to find the relationship between the snow density at different depths and the electromagnetic wave velocity. To do this, a TDR probe (30 cm) was horizontally inserted in the metal cylinder print to measure snow density and the electromagnetic signal has been recorded by a laptop.

4.2 Results

The potentiality of the TDR technique in snow surveying is demonstrated. However, it appears necessary to acquire high quality waveforms. In medium with very low dielectrics (such as snow), it is crucial to estimate, with high accuracy, the time when the signal propagates within the snow and when it is reflected to the cable tester. As a result, the use of a two-rod probe system inserted into the snow cover without modifying the compaction while preserving a large sampling volume, is preferable to a three rod system (Robinson et al., 2003). Taking into account the experimental uncertainties of the TDR measurements and the inaccuracy of the adopted model to convert the e.m. velocity to density values, the estimated accuracy in the density is about 10%. Obviously, length and geometry of probes influence the accuracy: using longer probes, the relative error in the travel time estimation becomes smaller.

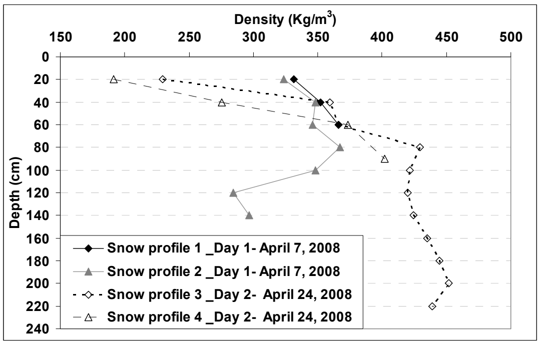


Figure 6: horizontal TDR measurements observed in a pit at two different dates during winter 2008 (zero refers to the ground surface).

By excluding the melting phase, information connected to the temporal variability of every layer could be obtained. In particular, the velocity profile obtained by TDR measurements provides a sort of snapshot of the snow cover conditions, and gives information about its physical and mechanical state. Two different situations are shown in figure 6: one meter of compact snow (with a wave velocity of about 0.22 m/ns) lying on a softer layer (with a wave velocity of 0.23 m/ns) was observed on April 7th, 2008. Vice versa, on April 24th, the snow cover was characterised by 40 cm of spring snow (wave propagation velocity close to 0.24 m/ns) that progressively evolved in higher density layers affected by constructive metamorphism, which justifies also a progressive increase of the velocity values (down to 0.21 m/ns).

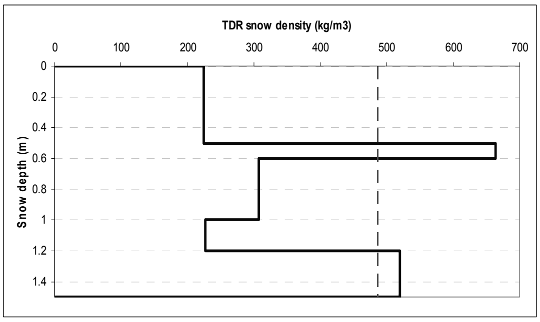


Figure 7: snowpack layering inferred by a TDR vertical measurement campaign conducted with five different length probes.

An interesting approach is the snowpack stratigraphic analysis provided by TDR waveforms by using vertical measurements with different probes length (figure 7). By applying the weighted average for every measurement length, it is possible to infer the different layering of the snowpack (continuous line). It's really interesting to highlight the potential information loss, if a single propagation velocity value is applied (dashed line).

5 WATER CONTENT REFLECTOMETRY (WCR)

The WCR technique can provide snow density estimate following the same approach of the TDR technique. The WCR probes features electronics, embedded in the probe head, which generate and analyze the electromagnetic waves directly, eliminating the need of an external TDR instrument (Hansson and Lundin, 2006). The electronic circuit generates the electromagnetic wave that propagates along the rods and derives, from the travel time, a square wave that is the output signal of the WCR sensor. However, the electronics create a time delay, thus adding time to the travel time consumed along the rods themselves. Bilskie (1997) suggested the general relationship for the square wave period, P:

$$P = 2 \cdot t_{circuit} + {}^{2L\sqrt{K_a}}\!\Big/_{c} \qquad [\,2\,]$$

where $t_{circuit}$ represents the time delay. The square wave period P is scaled by the electronic circuit in the sensor head to make it compatible with conventional data acquisition devices. The probe output , P_{op}, is thus P_{op} = CP where C is a probe-model dependent constant. Hansson and Lundin (2006) explain how the WCR output

P can be used to obtain the apparent dielectric number using:

$$K_a = \left(\frac{(P - 2a_1)}{\left(2a_2 + {}^{4L}\!/_{c}\right)} \right)^2 \qquad [3]$$

where a_1 and a_2 are probe specific calibration coefficients. The WCR probes used in this study are the CS616 – Campbell Scientific.

5.1 Data acquisition

The aim of data acquisition was to find an empirical relationship between snow density and WCR output (*i.e.* square wave period P). Thus an extensive field campaign was conducted in the study area during 2009 winter period. For this campaign a portable WCR system consisting of CS616 probes and a datalogger was used. In each measurement point a value of CS616 period was collected together with the snow density of the corresponding snow layer. Measurements were done from early winter to late spring in order to cover a wide range of density values.

In the study area, a time series of continuous CS616 data was collected in a meteorological station. Probes were installed during summer at different height from soil (30, 60, 90 cm) so that they can be covered by snow during winter and connected to a datalogger. The aim is to apply the empirical relationship found between snow density and CS616 period in order to get a continuous monitoring of snow density.

5.2 Results

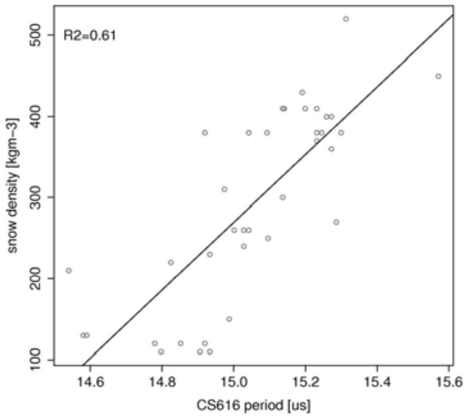


Figure 8: Scatter plot of CS616 period versus snow density data.

Results are still preliminary but the first analysis suggests that an acceptable relation between snow density and CS616 period can be found. This relationship is weaker for late spring snow when the amount of liquid water content increases. These results are quite promising and the future step will be the application of this empirical law on continuous CS616 data collected in the meteorological station in order to validate the model against independent snow density measures and eventually retrieve snow density evolution during winter.

6 CONCLUSIONS

The first conclusion of the project is that the application of e.m. devices (GPR, TDR and WCR) can correctly and rapidly measure snow properties (the height and thickness of the snow cover) and, consequently, ameliorate the estimation of the SWE at the wide basins.

7 REFERENCES

Gerdel, RW., 1954. The transmission of water through snow. Transactions, American Geophysical Union, 35(3), pp. 475-485.

Knight, J.H. 1992. Sensitivity of time domain reflectometry measurements to lateral variation in soil water content. Water Resour. Res., 28, pp. 2345-2352.

Koh G., Yankielun N.E., Baptista A.I. 1996. Snow cover characterization using multiband FMCW radars. Hydrol. Process. 10, pp. 1609–1617.

Hansson, K. and Lundin, L. 2006. Water Content Reflectometer Application to Construction Materials and its Relation to Time Domain Reflectometry. Vadose Zone J., Mar 2006; 5: 459 - 468.

Harper J. T., Bradford J. H. 2003. Snow stratigraphy over a uniform depositional surface: spatial variability and measurement tools. Cold Reg. Sci. Technol. 37, pp. 289– 298.

Heimovaara, T.J., W. Bouten, and J.M. Verstraten, 1994. Frequency domain analysis of time domain reflectometry waveforms. 2. A four component complex dielectric mixing model for soils. Water Resour. Res. 30, pp. 201–209.

Looyenga, H., 1965. Dielectric constant of heterogeneous mixtures: Physica, 31, pp. 401-406.

Mätzler, C., 1996. Microwave permittivity of dry snow. IEEE Transactions Geosc. and Rem. Sens., 34, pp. 573 – 581.

Robinson, D.A., S.B Jones, J.M. Wraith, D. Or, S.P. Friedman, 2003. A review of advances in dielectric and electrical conductivity measurement using time domain reflectometry: simultaneous measurement of water content and bulk electrical conductivity in soils and porous media. Vadose Zone J. 2, pp. 444–475.

Sand K, Bruland O. 1998. Application of georadar for snow cover surveying. Nordic Hydrology 29, pp. 361–370.

Stein, J. and D.L. Kane, 1983. Monitoring the unfrozen water content of soil and snow using time-domain reflectrometry. Water Resour. Res. 19, pp. 1573–1584.