Next level for snow pack monitoring in real-time using Ground-Penetrating Radar (GPR) technology

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***Abstract*—Currently available snow pack monitoring methods are limited due to spatial resolution or to adequate weather and secure avalanche conditions. Snow pack monitoring is impossible if the method is destructive as snow probing and thereby the use for avalanche forecasts limited. Ultrasonic snow height sensors are not feasible for an application in snow deposition areas along ridges or in avalanche paths. For the validation and improvement of snow pack simulation models, it is of high importance to measure snow pack conditions with a high spatial resolution in real-time. We have developed a measuring concept for the application of Ground Penetrating Radar (GPR) -systems from below the snow pack. With a vertically moving GPR-antenna it is possible to record reflections, which can be related to snow height and internal layering with adequate density steps and layer thickness. Field data sets from three winters in the Austrian Alps resulted in an average value for the velocity of propagation of pulsed radar waves in dry snow with a coefficient of variation (CV) of about 6 %. Additionally we conducted some preliminary measurements in a wet spring snow pack to analyze the feasibility of the system. In contrast to Frequency Modulated Continuous Waves (FMCW) radar, the snow-air-interface was detectable and thereby the snow height could be estimated. The applied sensor system is able to determine snow height, snow accumulation and erosion rates in combination with a known electrical permittivity value of dry snow. In combination with nearby traditional snow height measurement systems, the snow water equivalent can be derived very accurately and with high temporal resolution.**
KEYWORDS: Ground-penetrating radar, snow stratigraphy, snow pack monitoring.

I. Introduction

The automatic measurement of snow depth is currently limited to flat areas which are not exposed to avalanches. Direct snow depth determinations in avalanche paths are impossible, or very expensive to instrument with radars [5] or with synthetic aperture radars [16]. The possibilities for field observations are limited due to manpower or avalanche danger. For the local or regional avalanche warning services, at areas critical to arrive, additional information would be an immense support for the evaluation of the current avalanche danger. Currently, in case of doubt, an usage of explosives is made to verify and reduce the avalanche danger. This technique requires helicopters or special on purpose fabricated railways to get to the points of interests and provides no internal information about the current snow conditions. Additionally, it is very expensive to determine the avalanche danger with explosives and helicopters. Otherwise, the regional avalanche danger level is estimated by manual snow pits which require a huge effort and result in rare point measurements. For short-term predictions and localized danger evaluations these field analysis are not adequate. Especially for the information about the formation of snow depositions along ridges or within avalanche paths an automated snow pack information system will be useful. A sensor system buried in the ground and operating independently of the current snow and weather conditions will transmit the recordable snow conditions to the responsible avalanche warning centers in real-time. Although spatial resolution will be coarse, the measurement can be taken at all critical locations. The previous research work on sensor systems for the non-destructive analysis of the snow stratigraphy [3, 4, 11, 20, 22, 6, 14] concluded that radar is the the most reliable technique to monitor snow pack properties. Marshall et al. [15] received convincing results with the application of FMCW radar in resolving snow pack stratigraphy from above the surface. The problem of FMCW radar is that up to now the systems are custom-made and single-unit productions. Additionally FMCW radar needs a calibration measurement to eliminate artifacts before the snow pack record [15]. This will be very difficult to realize from below the snow pack. In contrast to FMCW, GPR is produced by several manufacturers and has a wide field of application. The aims of the present study are: (i) to develop a measuring arrangement for the application of GPR beneath the snow pack, (ii) to analyze the possibilities of GPR systems to quantify snow stratigraphy and (iii) to determine the differences in the electromagnetic response for different snow pack properties. One aim of this research work is the determination of an approximate value for the velocity of propagation of pulsed radar waves in dry snow conditions. This approximate value will be a tremendous improvement for further field work thereby snow thickness and layer location could be calculated from the radar data without the need of a conventional snow profile.

II. Methods

A. Instrumentation

GPR-system

We used a commercially available RIS One GPR instrument (IDS, Ingegneria dei Sistemi, Pisa, Italy) with a 900 MHz antenna for the ground based application beneath the snow pack. In order to generate a modulated signal in pulsed radar the antenna must be moved. A modulation is needed to distinguish reflections caused by the snow stratigraphy from internal antenna reflections. Otherwise the system has to be operated throughout the whole winter to record a modulated snow pack. The energy consumption and the huge amount of data argue against an all-time usage of the system. A short time data request at specific times during the day would minimize this problem. By this, the practical implementation then needs an antenna moving horizontally or vertically in place.

Snow-data

A conventional snow profile (e.g. [1]) with density determination was made to compare to the radar measurements. Additional snow profiles were recorded with a high resolution penetrometer SnowMicroPen (SMP) [21]. The SMP is a unique instrument to gather highly resolved depth profiles of penetration resistance (250 measurement values per millimeter). Density was estimated from penetration resistance according to [10] as described in [7].

B. Theory

[12] and [17] state that in dry snow electrical permittivity is solely a function of density. Kovacs slightly improved the fit of [19] to

$$\varepsilon_r^{'} = (1 + 0.845\rho)^2 \tag{1}$$

with ρ the density or "specific gravity" of firn or ice. Mätzler, however, applied several fitting formulas on known ice volume fractions in various snow packs and compared the results to the effective medium formula of Polder and van Santen [18]. He concludes that an influence of a liquid layer is not detectable in dry snow conditions. In his opinion the Looyenga formula [13] with the empirical fitting parameters of $\varepsilon_h = 0.9974$ and $\varepsilon_s = 3.215$ with b = $\frac{1}{3}$ provided good results and the parameter are very close to the actual values

$$\varepsilon_r^b = (1 - \upsilon) \cdot \varepsilon_h^b + \upsilon \cdot \varepsilon_s^b \tag{2}$$

υ describes the ice volume fraction, the quotient of snow-density through ice-density.

Both equations differ less than 2 % (Table I) in resulting electrical permittivity applying the density records measured at the test site in the Austrian Alps (Figure 2) of the last three winters.

As the stratigraphic resolution and therefore the influence of the snow on the radargram depends on the electrical permittivity, we analyzed various data sets on changes in the calculated electrical permittivity. The permittivity was derived from manual density measurements and density estimations from the SMP data using both equations (Eq 1,2)

To calculate the velocity of propagation of electromagnetic waves in snow, we applied the following equation [9, 2]

$$\vartheta_s = \vartheta_a \cdot (\varepsilon_r)^{-\frac{1}{2}} \tag{3}$$

Table I

COMPARISON OF THE TWO DIFFERENT ELECTRICAL PERMITTIVITY DETERMINATIONS OF DENSITY BY [12, 17]. THE CALCULATED PERMITTIVITY VALUES BASING ON EQUATION (1) AND EQUATION (2) WERE DIVIDED AND THE AVERAGE AND MEDIAN VALUES OF THE MANUAL DENSITY RECORDS OF THE REFERRING WINTER SEASON WERE DISPLAYED IN PERCENT VALUES. THE SAMPLE SIZE (N) OF THE RESPECTIVE WINTER IS DISPLAYED AS WELL IN THE TABLE.

	N	mean $\varepsilon_{Kov}/\varepsilon_{Maet}$ [%]	median $\varepsilon_{Kov}/\varepsilon_{Maet}$ [%]
06	50	1.8	1.9
07	57	1.9	1.9
08	14	1.9	2.0

with ϑ_s the velocity in snow and ϑ_a the velocity in air.

C. Test arrangement

Since the frequency of a GPR-antenna is not modulated the interpretability of short term radar records is distinct improved by moving the antenna. Measuring from below the snow pack requires either horizontal or vertical movement. The horizontally moved antenna did not provide evaluable results for a movement distance of about 1 m length. Therefore we arranged an experiment set-up with a vertically moved antenna (Figure 1). We tried different test arrangements and varied the movement distance as well as the speed and manner. We used a lever and alternatively a pneumatic system. The variation of the movement ranged between 0.1 m to 0.3 m. The lever system resulted in a fast and continuous movement while the pneumatic system resulted in a very slow and jerky uplift.

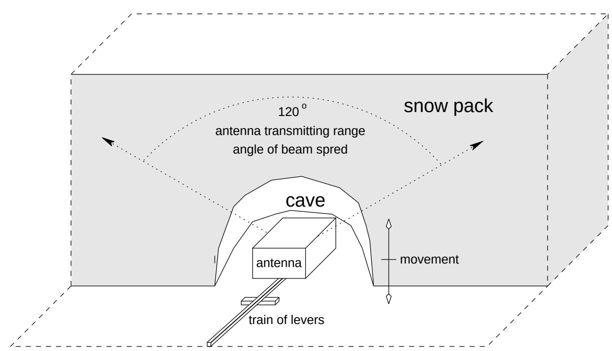

Figure 1. Sketch of the test arrangement for measurements with a vertically moved antenna with the use of a lever.

III. RESULTS

A. Radar records from below the snow pack

The results of the vertical measuring outfit were interpretable and different interfaces could be distinguished. The artifacts, resulting from internal antenna reflections of the GPR system, could be removed easily via this movement (Figures 3, 5). We applied various movement heights with the lever system. The longer the uplift the more of a circular movement the antenna will describe. With an uplift of d = 0.1 m the antenna will be turned by $\alpha_{0.1}$= 5.7°, with an uplift of d = 0.3 m, α will increase to $\alpha_{0.3}$ = 17.5. A 5° turn of the antenna is negligible in our opinion. In the following we describe measurements with the 0.1 m movement to keep the circular movement-error negligible. Another error occurs by the conversion of two-way travel time values in depth values. We used the velocity of propagation of radar waves in snow, but measured across two medias, air and snow.. Therefore the conversion of the transition air - snow above the snow cave is not correct. Nevertheless we disregarded this error as the focus lies on the correct reproduction of the snow depth and the snow stratigraphy above the cave, which will not be influenced by this error. In a future application the monitoring system will be installed in the ground probably in a plastics box with the top of the box at the ground surface. Therefore, the snow pack can be measured without the regard on the media transition.

B. Stratigraphic resolution with GPR systems

In January 2008 we performed field measurements on Stubai Glacier in the Austrian Alps on about 2850 m a.s.l. (Figure 2)

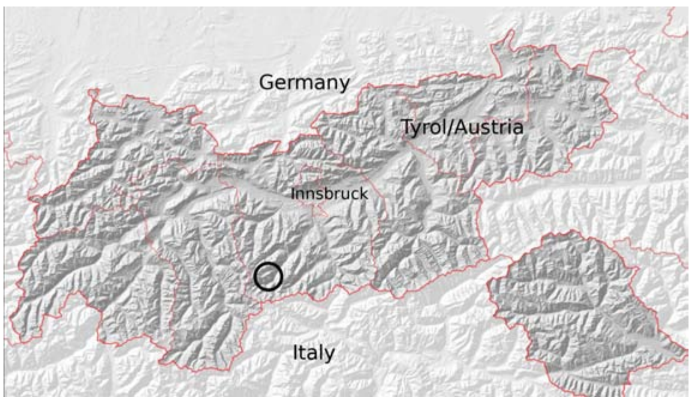

Figure 2. Map of the test site. The black circle marks the location of the field tests.

The results of a measurement with an uplift of 0.1 m is shown in Figure 3. At least four reflections are distinct developed. Named are the transitions from the snow cave to the snow pack (AIR - SNOW), at the snow surface (SNOW - AIR) and an artifact probably caused by the operator. The antenna movement is reproduced by a slight ascent of the reflections at the start of the uplift and correspondingly by a slight descent towards the end of the down lift. The depth conversion from the two way travel time is calculated for the velocity of propagation of the radar waves in snow. Therefore the reflection ascent and descent values at the border air - snow do not agree to the 0.1 m uplift. In contrast, the internal uplift reflections agree very well to the length of the vertical movement.

The internal reflection in Figure 3 corresponds to a pronounced density and hardness step in the snow profile (Figure 4). We marked the internal layer and the media transitions by black lines and turned the radargram by 180° to assimilate it to the profile. The radargram was scaled to fit the layering, but obviously the relative differences between the both transitions and the internal reflection match perfect with the profile. By using $\upsilon = 0.237$ m·ns^{-1} the calculated snow depth in Figure 3 corresponds very well to the 0.9 m from the cave until the snow surface in the snow profile (Figure 4), according to the accuracy of the reflection to depth relation.

The density measurements of the conventional snow profile fit very exactly to the radar records (Figure 4) . The snow profile was dug to the glacier ice, while the radar records started at about 60 cm in the profile. Distinctive layers were recognizable in the snow pack with several various pronounced density steps. According to [17], [6] and others, in dry snow conditions contrasts in electrical permittivity are the only snow parameter causing reflections in a radargram. The electrical permittivity however is weakly sensitive to small changes in density [7], therefore an adequate density difference is needed to produce reflections in the radargram. Additionally the vertical resolution of GPR depends on the wavelength and the velocity of propagation in the medium (snow) [9], [2]. With an applied system frequency of 900 MHz and a mean velocity of propagation in dry snow of 0.237 m·ns^{-1} (Table II), the radar theoretically resolves vertical stratigraphy down to about 12 cm layer thickness. This is based on the assumption of [2] that the vertical resolution is approximately $\frac{1}{2}$ of the wavelength for small divergence angles (angle here is approx. 0°). The reflections in Figure 3, 4 and 5 confirm these theoretical approximations. The density step at 107 cm (Figure 5) with a layer thickness of 12 cm in the snow profile is clearly represented in the radar record at the corresponding depth including a 0.3 m delay. However, other density steps are not represented in the radargram. The delay value occur as the velocity calculation was only determined for snow and thereby the air gap above the antenna miscalculated.

In Figure 5 it is possible to allocate the density step at 107 cm to an internal reflection in the radargram. This density step is the only internal layer which has a sufficient thickness and contrast larger than the resolution limit. The other sharp density change with a sufficient layer thickness is too close to the snow surface and shadowed by the transition from snow to air and thereby not distinguishable as a single reflection.

C. Differences in electromagnetic responses for different antenna positions

Different test arrangements were used to measure the interactions between snow and electromagnetic waves between winter 2006-2008. The data of these three winters were analyzed for differences in electromagnetic response for different antenna positions. A GPR antenna was used from above the snow surface up to 12 m high as well as from beneath the snow surface. We calculated snow depths via the mean velocity of propagation for each radar scan and compared these depths with the results of snow probings. The agreement of both methods was very high using the resulting mean value in Table II. The velocity of propagation was calculated from directly measured density and density estimated from penetration resistance (Table II).

The average value of the different velocity determinations is $\mu = 0.237$ m·ns^{-1}, the standard deviation of these 121 measurements is σ= 0.015 and the resulting coefficient of variation with c$_V = \frac{\sigma}{\mu}$ is c$_V = 6$ %. The accuracy of the snow height determination by using the mean value was adequate in every radargram (see also Figure 3, 4, 5). Furthermore, preliminary test measurements from above the snow surface in May 2006

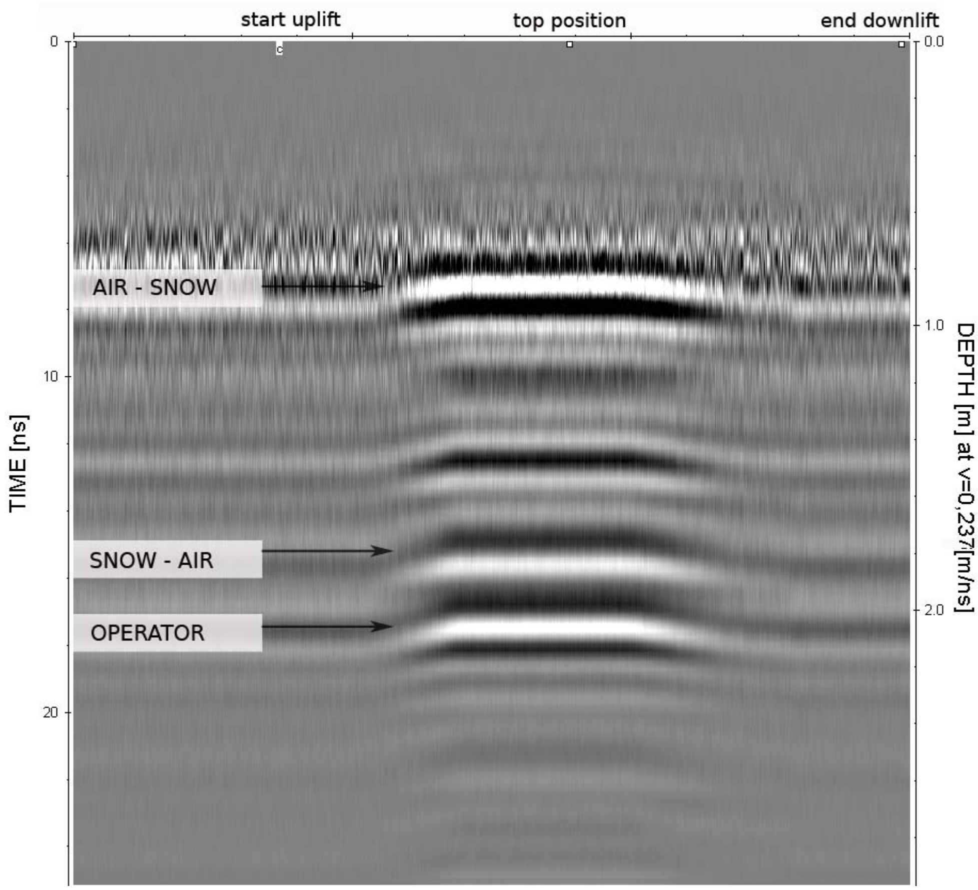

Figure 3. Radargram of measurements with a 0.1 m vertically moved antenna by a lever. The reflections at transitions are labeled. The operator reflection can be avoided by remote control.

Table II
CONVERTED ELECTRICAL PERMITTIVITY VALUES (ε) FOR DENSITY MEASUREMENTS CONDUCTED BETWEEN 2006 AND 2008 FOR DRY SNOW CONDITIONS. THE PERMITTIVITY HAS BEEN CALCULATED WITH EQUATION (1) AFTER [12] AND THE VELOCITY OF PROPAGATION VALUES (υ) WERE CALCULATED WITH (EQ 3). N IS THE SAMPLE SIZE.

year	ε mean	ε stdv	CV	υ mean [m·ns^{-1}]	υ stdv	CV	N
06	1.6552	0.2298	14 %	0.235	0.017	7 %	50
07	1.5889	0.1674	10.5 %	0.239	0.013	5.5 %	57
08	1.5839	0.5839	8.5 %	0.239	0.011	5 %	14
mean	1.6162	0.1946	12 %	0.237	0.015	6 %	121

with moisture in the snow pack penetrated a more than 2 m thick snow pack. It is not possible to apply a calculated average velocity of propagation value for moist snow packs. If layers with different water contents exist, a specific velocity value has to be calculated for each layer individually. Due to the lack of adequate wetness determination for each single layer and to the fact that the permittivity is no longer a sole function of density, it is more complex to calculate an average value for wet snow conditions. Nevertheless, it is still possible to monitor the interfaces with the applied GPR system.

IV. DISCUSSION

The results of field measurements for the development of an automatic snow sensor based on GPR technology are motivating. First of all two different arrangements for the field tests showed that the only solution for a practical GPR sensor system is a vertically moving antenna. We could show that for dry snow conditions an average velocity of propagation can be calculated. Even if the density variation is underestimated the mean velocity over the whole snow pack in natural dry snow conditions varied only about 6 % as the analysis of density data for three winters showed. This fact displays that independently of a manual snow probe measurement the snow height determination with GPR instruments is adequately accurate for a remote snow pack monitoring. Especially if considering that exact reflection determination in depth values is quite improper in a radargram because of the difficult appointment of signals first arrival [2]. However, this is still an acceptable result for most practical applications, especially taking into account that the true values are very variable due to spatial variability. The presented average values were only determined for one region in the Austrian Alps (Figure 2).

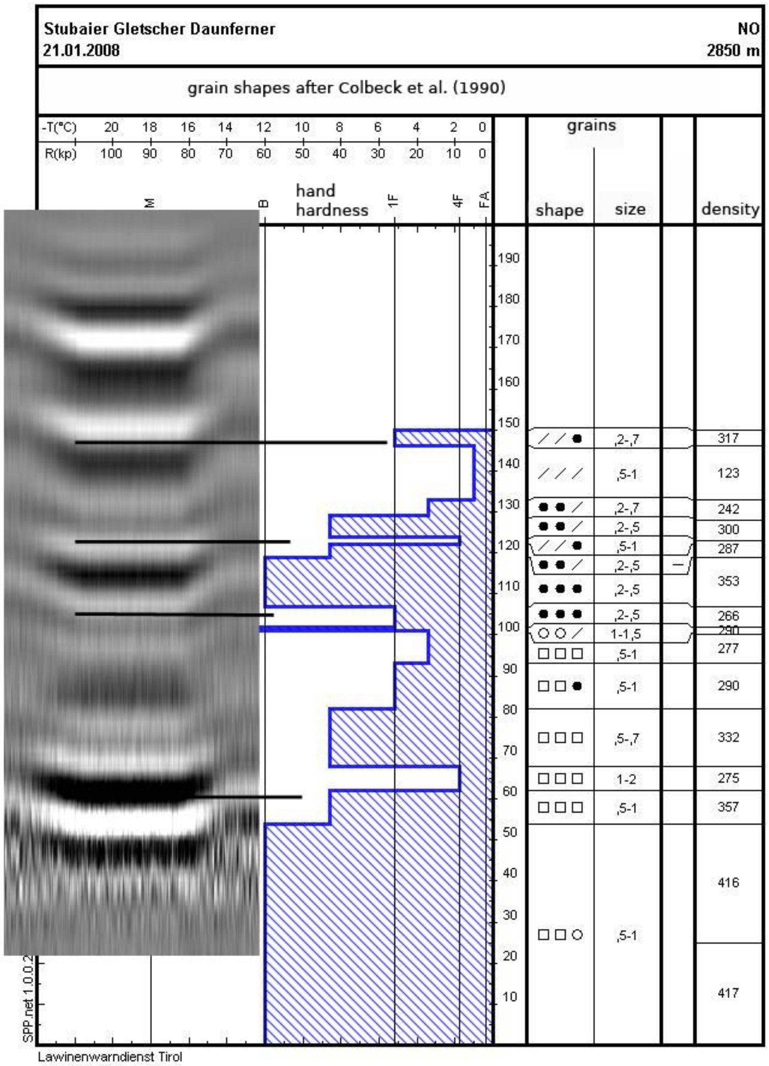

Figure 4. Direct comparison of the radar data and the conventional snow profile. The transition from air to snow in the cave was situated at about 0.6 m in the hand-profile. The reflections are linked to the corresponding layers or transitions by the black bars.

Geographical and meteorological conditions as the distance to the sea (salt or molecule concentration) and the average air humidity can influence the average velocity of propagation.

The derived stratigraphic resolution of the radar data corresponds to the theoretical values. An adequate step in the gradient of density as well as in layer thickness can be reproduced in the radargrams. The question arises if this vertical resolution is appropriate for the intended application. FMCW systems are probably more capable to resolve the stratigraphic layering in the snow pack and to determine their spatial variability but are not feasible in conditions with moisture in the snow pack [15]. However, the relatively cheap and established GPR technology will be more realizable and affordable for automatic snow pack monitoring. Additionally a higher layer resolution is possible by increasing the applied antenna frequency. The spatial resolution of snow monitoring via GPR is not comparable to repeated laser scanning but the capability is completely independent of the meteorological conditions, which is an immense advantage compared to laser systems. Additionally by increasing the number of sensors beneath the snow pack it is possible to improve the interpolation among the measured points. In contrast to ultrasonic systems these sensors can be installed at every slope aspect and angle. These circumstances allow placing the instrument at the most interesting and critical locations. If the average density of the snow pack can be estimated by nearby traditional measurements, snow water equivalent can be determined accurately and with high temporal resolution.

In wet snow conditions with a completely temperate snow pack the used GPR system was detecting the snow-air interface in a very attenuated way [8]. Internal reflections were caused by water layers and not by density or hardness steps. In all spring measurements performed from above the snow surface, the snow and ground-interfaces could be detected in the radargrams.

The development and deployment of such an automated snow pack monitoring system requires still a lot of work. Up to now the problems of power supply, remote operation, remote data transmission have not been fully discussed in a further application. Nevertheless, these problems occurred

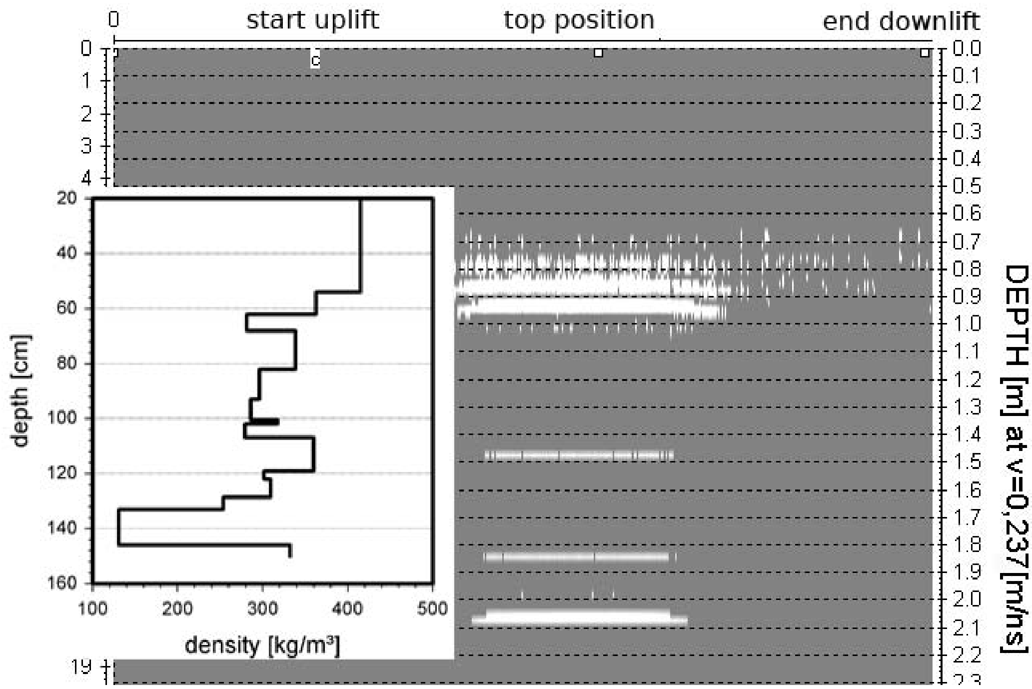

Figure 5. Density profile in comparison to the processed radargram. The cave position in the density profile is linked to the first radar reflection.

already in other implementations as automatic weather stations or satellite techniques and should not be the obstacle for further investigations in this research.

V. Conclusion

This feasibility study demonstrated that it is possible to derive snow depth and major snow stratigraphic features from beneath the snow pack with a GPR system. Furthermore an average value for the mean velocity of propagation of the whole snow cover could be determined to calculate snow depths in high winter conditions independently of a manual snow profile.

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