A novel approach for calculating the internal layers of snowpacks using a S-band radar

P. F. Espín-López[#1] and M. Pasian[*2]

[#]Geomatics Research Unit, Centre Tecnològic de Telecomunicacions de Catalunya, Castelldefels, Spain

[*]Department of Electrical, Computer and Biomedical Engineering, Università di Pavia, Pavia, Italy

[1]pedro.espin@cttc.es, [2]marco.pasian@unipv.it

***Abstract* — In the last years, the development of new ground-based techniques for studying the snowpack has tried to fill the gap between satellite and manual techniques. In particular, ground-based radars are considered a very useful technology for their ability to sound relatively deep snowpacks in a non-destructive way. Obtaining the bulk physical parameters of the snowpack (density, liquid water content...) has been successfully done using ground-based radars by several research groups, however, estimating the internal structure of the snowpack remains as a challenge due, mainly, to technological limitations. This work presents a novel quasi-automatic approach to estimate the internal structure of the snowpack, in terms of density and liquid water content (LWC), based in a double receiver S-band radar. The approach is validated with numerical simulations and the very first field results.**

***Keywords* — radars, multi-layer, snowpack, snow water equivalent.**

I. Introduction

The development of satellite-based remote sensing techniques for monitoring the cryosphere, and in particular, the seasonal snowpack, has become a hot topic due to the possibility of observing wide areas automatically [1]. However, the trade-off between observable area and spatial/temporal resolution has not yet achieved satisfactory results, especially in mountainous regions. In addition, the accuracy of satellite-based remote sensing techniques compared with traditional ground observations is still far away from becoming a reliable alternative [2].

For these reasons, the development of new ground-based techniques for studying the snowpack can fill the gap between space-borne remote sensing and manual observations, improving the accuracy of satellite-based techniques and overcoming the spatial and temporal limitations of the traditional observation methods [3]. In particular ground-based radars are considered a very useful technology for its ability of sound relative deep snowpacks (when relative low frequencies are used) in a non-destructive way [4].

One of the main challenges of using ground-based radars is the estimation of the internal layers of the snowpack. The lack of range resolution when using low frequency radars makes impossible to detect thinner layers, while using higher frequency radars reduces drastically the penetration capability of the electromagnetic wave, especially in humid snows [5]. In addition, the proposed solutions are usually operator dependant and far away from being automatized[6].

This work uses a dual receiver S-band radar, which has been successfully validated in several field campaigns for obtaining the bulk parameters of the snowpack [7], and applies a novel quasi-automatic approach in order to estimate the internal structure of the snowpack.

II. S-Band Radar Description

The architecture of the radar system is depicted in Fig. 1 for the case of a downward-looking implementation, this is, with the radar looking at the surface of the snowpack, and assuming that the snow is composed by an unique layer. The architecture is composed by two pairs of transmitter-receiver (tx-rx1 and tx-rx2) working at a central frequency f and with a bandwidth B. For this work, the central frequency is 2.75 GHz with a bandwidth of 1.5 GHz (from 2 GHz to 3.5 GHz), corresponding approximatively with the operating fundamental mode (TE10) bandwidth of the WR340 standard waveguides. The central frequency and bandwidth have been chosen for satisfying the trade-off between the penetration depth and the radar range resolution.

In Fig. 2 it is described the hardware used for implementing the proposed architecture. It is composed of three WR340 open-ended waveguides acting as radiators, a VNA (Keysight Field-Fox N9916A) and a Raspberry Pi based computer for processing and visualizing the data.

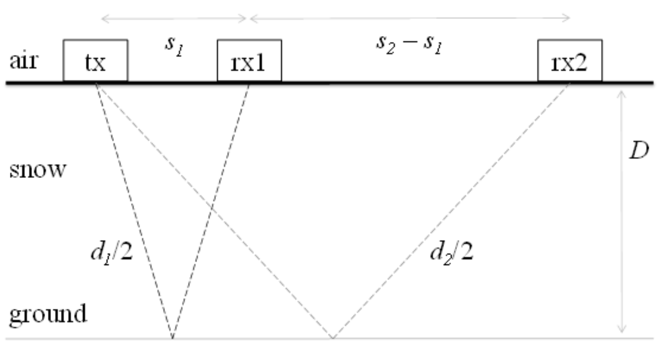

Figure 1 Horizontal distance and the propagation distance are s1 and d1, respectively, for the first receiver, and s2 and d2, respectively, for the second one. Drawing not to scale. [7]

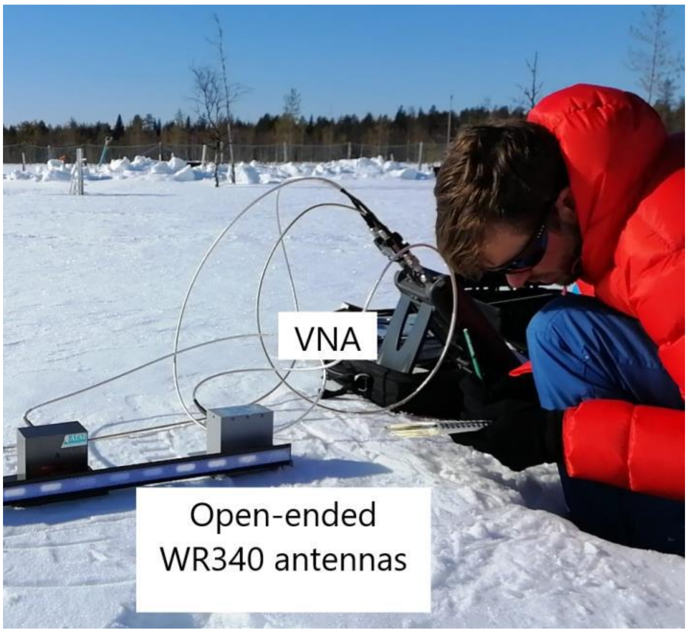

Figure 2 Radar Prototype used in a field campaign in Sodankylä, Finland.

III. MULTI-LAYER QUASI-AUTOMATIC APPROACH

The same architecture, processing, etc... explained in Section II and in [7] can be applied not only for obtaining the bulk parameters of the snowpack, but also for providing a estimation of the internal layers in terms of density or LWC contrast between layers.

Identifying all the peaks of the radar trace until reaching the ground-snow interface from both receivers can be done automatically (establishing a threshold of the 10% of the maximum peak and a maximum of 5 peaks). Then applying the SNOWAVE equations explained in [7] for estimating simultaneously snow depth, density and LWC for all the possible combinations of the time-of-flight between both receivers can be also automatically solved. Finally, non-physical results ($\varepsilon'<1$ and $\varepsilon'>4.3$) produced by wrong combinations can be automatically discarded. However, sometimes at this point human interaction is needed for discarding some *physical* results which make no sense with the actual snowpack condition (for example, high density layers where it is supposed to be fresh snow). These latter wrong results can be produced by wrong combination of maximums which unfortunately produce feasible results. An example of a radar result trace is shown in Fig. 3.

IV. NUMERICAL VALIDATION

In order to demonstrate the feasibility of the layer detection, two different scenarios have been validated numerically with a full-wave solver. The simulated model is composed by three open-ended WR340 radiators. The whole propagation medium from the transmitting antenna to the snow/air interface and back to the receiving antenna is simulated using the commercial full-wave solver Ansys HFSS, which considers non-ideal aspects, such as the antenna radiation diagram and mutual coupling.

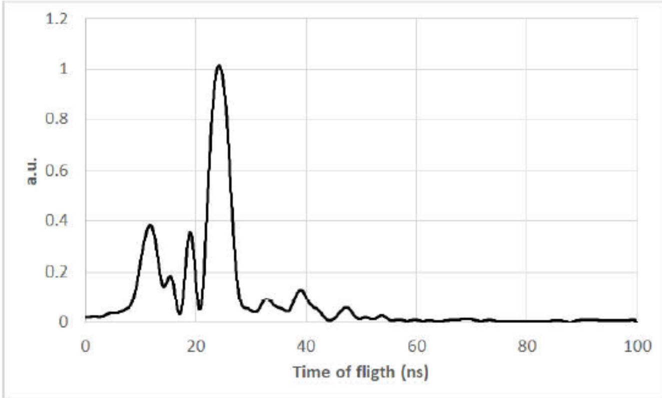

Figure 3 Example of a radar trace from the second receiver.

The entire signal processing chain is implemented using Mathworks MATLAB routines. The S parameters are obtained from the full-wave solver for the working frequencies (2-3.5 GHz), then in Matlab, an Inverse Fast Fourier Transform is applied to the S21 parameter of each receiver in order to obtain the time-domain radar trace. A Nuttall window is also applied to the trace for reducing side lobes. Finally, a study of the maximum values of the time-domain radar trace gives as result the time-of-flight values for each echo. For both receivers, the reflections given by the snow/ground interface and between the snow layers are detected.

In order to demonstrate the feasibility of the layer detection, two different scenarios have been used. The first case comprises two different dry snow layers, with dielectric constant values $\varepsilon'_1=1.7$ and $\varepsilon'_2=1.2$, for the lower and upper layer, with a thickness $D_1=0.5$ m and $D_2=0.8$ m, respectively (for a total thickness of 1.3 m). The distance between the transmitter and the first receiver was set, for practical reasons, to $s_1=0.4$ m, while the distance between the transmitter and the second receiver was $s_2=1.1$ m.

The second case comprises four different snow layers. The thicknesses are $D_1=0.75$ m, $D_2=0.45$ m, $D_3=0.36$ m and $D_4=0.44$ m (for a total thickness of 2 m). The distance between transmitter and receiver remains the same. The dielectric properties are $\varepsilon'_1=1.8$, $\varepsilon'_2=1.6$, $\varepsilon'_3=1.4$ and $\varepsilon'_4=1.2$.

The results are shown in Table 1. It can be observed that for both cases all four layers are detected.

V. EXPERIMENTAL VALIDATION

While moving from the simulation domain to the real field, the multilayer detection becomes more complicated. The variability of the internal structure within the snowpack and the smooth transitions of density between some layers increase the difficulty of the layer identification process.

A tentative of automatic retrieving the snowpack layers of a real snowpack (dry snow, for simplicity) is shown in Fig. 4. In this case, a density profile is retrieved automatically without human interaction. The measure was done the 20th March 2019 in Sodankylä, Finland, in a field campaign developed close to the facilities of the Finnish Meteorological Institute (FMI) at an altitude of 179 m.a.s.l (67°22'00" N, 26°39'05" E). The radar measurement was compared with manual measurements on the field performed each 10 cm in the vertical axis of the snowpit (density cutter of 198 cm^3).

It can be observed in Fig. 4 that three density layers are identified, following the trend of the ground truth. The results while not being very precise, are promising and keep the discrepancies with the ground truth always under the 50 Kg/m^3.

VI. Conclusion

This paper presents a novel approach for estimating the internal layers of the snowpack in a quasi-automatic way. The approach makes use of the radar architecture and implementation of a successfully tested S-band radar designed mainly for obtaining simultaneously the depth, density and LWC of the bulk snowpack. The approach uses the human interaction in some cases because some wrong peak combinations between receivers produce physically feasible results. The approach has been validated numerically providing encouraging results. At the same time, a first use of this technique in real snow has been presented. The results in the real case are still far away from a manual density profile done with traditional techniques, however, these rough results can provide, in a fast and non-destructive way, a first idea of how the snowpack is composed and take (or not) the decision of doing a deeper analysis based on manual techniques.

Acknowledgment

The authors would like to thank Regione Valle d'Aosta, Fondazione Montagna Sicura, Centro Addestramento Alpino of the Italian Army, the Finnish Meteorological Institute, and the project SnowAPP (funded by the Academy of Finland), for their support during the experimental campaigns.

Table 1 Multilayer Validation Results

Nominal	Calculated
Two layers case	
$D = 0.50$ m, $\epsilon' = 1.70$	$D = 0.51$ m, $\epsilon' = 1.68$
$D = 0.80$ m, $\epsilon' = 1.20$	$D = 0.80$ m, $\epsilon' = 1.15$
Four layers case	
$D = 0.75$ m, $\epsilon' = 1.80$	$D = 0.75$ m, $\epsilon' = 1.82$
$D = 0.45$ m, $\epsilon' = 1.60$	$D = 0.49$ m, $\epsilon' = 1.39$
$D = 0.36$ m, $\epsilon' = 1.40$	$D = 0.38$ m, $\epsilon' = 1.48$
$D = 0.44$ m, $\epsilon' = 1.20$	$D = 0.50$ m, $\epsilon' = 1.18$

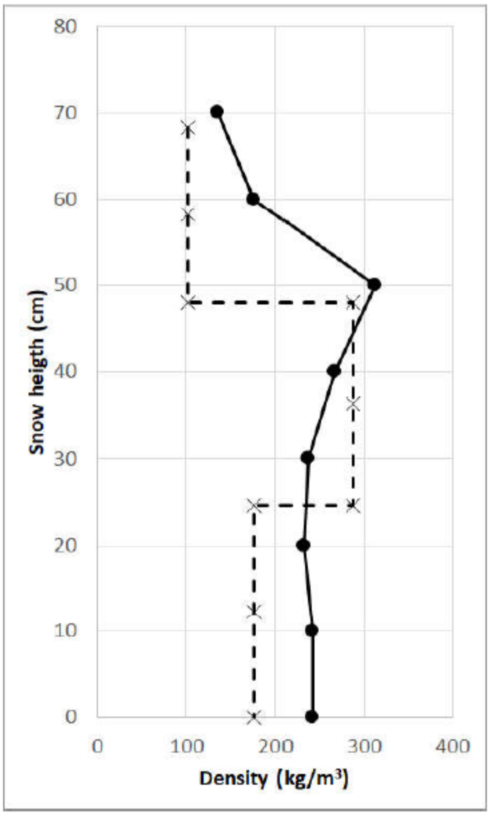

Figure 4 Automatic retrieving of the density profile of a real snowpack. Results obtained from a field campaign in Sodankylä, Finland. Ground truth is shown in solid line while dashed line indicates the radar results.

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