APPLICATION OF A K-BAND MICROWAVE SENSOR IN THE DETECTION OF WATER MELT-FREEZE STATES WITHIN A SNOWPACK

Santiago Rodriguez[1]*, Dr. Hans-Peter Marshall[1]

[1] *CryoGARS group, Geosciences Department - Boise State University, Boise, ID, USA*

ABSTRACT: Microwave radars in the X and K bands have been used to track spatial variability in in the snowpack depth in mountainous snowpack and ice-sheets. In other applications microwave radars in the X and K bands have been use to estimate equivalent snow water equivalent in the snowpack with respect to spatial or temporal dimensions. In other cases, microwave sensors are useful in tracking the snowpack development and its stratification due to their higher spatial resolution.

A new application of microwave radar is the tracking of the presence of a liquid in water at the snow surface or within the snowpack. The attenuation properties of the K-band microwave radiation under the presence of liquid water and its high spatial resolution is an attractive tool to identify the temporal progress of a wetting front as well as it movement within the snowpack.

In this study it was demonstrated the value of a Frequency Modulated Continuous Wave (FMCW) microwave sensor to detect melt-freeze phase changes of water in a mountainous. K-band FMCW radar returns were processed to detect phase shifts intrinsic of water phase changes. This technique is a robust technique that reliably identifies not only the presence of liquid water but its transitions from melt to state and vice versa.

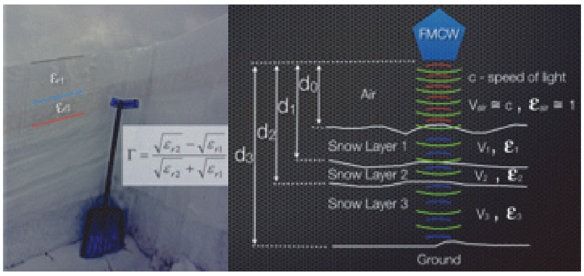
Tracking of the snowpack surface or its layering melt-freeze state with microwave sensors is a valuable new application that will allow to characterize events such as the onset of spring snowmelt processes, introduction of liquid water from rain, or the introduction of liquid water due to solar radiation on a snowpack with cold content (winter snowpack). In other applications it might provide insights of snowpack lateral flow for hydrological or avalanche stability assessments.

KEYWORDS: Microwave radar, microwave sensor, k-band, snowpack, water phase detection

1. INTRODUCTION

Snow stratification is the natural result of weather variation, where temperatures, precipitation rate, wind, humidity, and many others factors interact to generate snow layers with different densities, liquid water content, crystal size and type, impurities, and anisotropic or isotropic properties. These layers typically result in discrete interfaces with defined boundaries. The contrast between these layers produces reflections of electro-magnetic waves used in radars. Radar reflections are based in the contrast of snow permittivity at various layers, which is primarily affected by the available free water, and snow density (e.g., Marshall and Koh, 2008 (Figure 1).

* *Corresponding author address:*
Santiago Rodriguez, CryoGARS Group, Department of Geoscience, Boise, ID 83725-1535;
tel: +1 208-473-6532
email: chagorodriguez@u.boisestate.edu



Frequency Modulated Continuous Wave Radars (FMCW) radars have been used for snow science applications since the late 1970's [e.g. Ellerbruch and Boyne, 1980; Gubler and Hiller, 1984; see review by Marshall and Koh, 2008]. Upward pointing FMCW radars have been used to measure avalanche release and speed, and over the last decade we have been developing portable systems for large scale high resolution snow surveys (see earth.boisestate.edu/cryogars).

FMCW in the 6 to 18 GHz have are built and used by Boise State University Cryosphere Geophysics and Remote Sensing (CryoGARS) group for snow research during NASA/ESA snow stratigraphy in Alaska, Greenland, Europe, Canada, and most mountain ranges in the continental USA, as well as Colorado and Idaho.

Low cost and low power FMCW radar chipsets recently became available for application development. We are leveraging these technological advances in radar electronics to develop a new generation of low cost, low power, and ultra-compact X and K bands FMCW radars operating in the 10 GHz and 25 GHz frequencies. The low cost and low power requirements of these two radar systems open new opportunities for radar instrumentation at remote sites, such as snow survey locations, National Resource Conservation Service (NRCS) Snotel Stations, avalanche centers study plots, hydrological power utilities monitoring stations, among other snow based operations, to track snowpack depth, stratigraphy, and snow water equivalent.

2. THEORY OF OPERATION OF FMCW FOR SNOW STRATIFICATION APPLICATION

The physical principle used to compute radar signals is based on the time it takes for a signal to travel to an object, to be reflected and travel back along the same path to the emitter. The relationship is summarized in the following equation (1), where τ is the total two-way travel time:

$$\tau = 2 * d / V \qquad (1)$$

The miniFMCW radar has a bandwidth of 1.5 GHz with a sweep time of 125 ms. Various wave patterns are used, but the sawtooth sweep wave pattern is the most commonly used for snow stratigraphy.

Figure 2 illustrates the operating principle of a FMCW radar, where Ts denotes 'sweep time', which is the length of time for each radar pulse. During the sweep time the frequency of the wave is linearly increased. The linear increase occurs over the frequency band denoted as 'band width' or Bw. The following function (2) describes the frequency modulation of the radar:

$$F(t) = Flow + Bw/T_s*t \qquad (2)$$

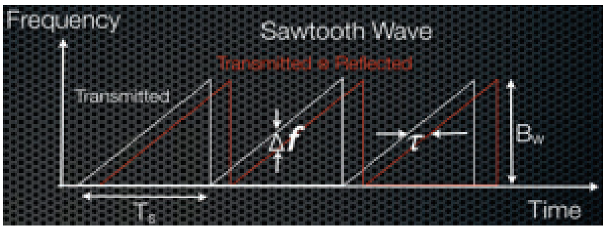


Figure 2: FMCW Principles - Sawtooth Wave Sweep.

Transmitted and reflected signals are mixed together in the FMCW hardware, which results in a signal containing terms with the frequency difference and frequency sum. Low pass filtering leaves only difference term. The mixed signal has a "two-way travel time" delay represented by τ, which is a linear function of the frequency difference Δf.

The theory of operation for the FMCW can be generalized for multiple reflections as illustrated below. For example, for three layers of reflectors, the superposition principle is applied, where each of the the reflected signals are mixed with the transmitted signal. Since there are three reflections, three distinctive 'beat' frequencies are generated; Δf1, Δf2, Δf3. (Figure 3).

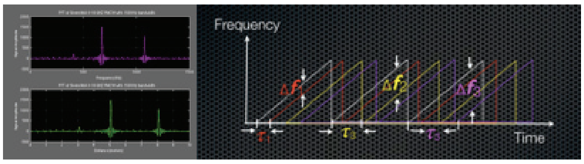


Figure 3: FMCW Principles - Superposition of reflected signals.

3. FMCW RADAR SCAN DATA ANALYSIS

Radar scans in the time domain are signal conditioned prior to frequency domain conversion. Frequency response of the radar scans are further processed using FFT padding and Kaiser-Bessel windowing. Post processing of the FFT results include making corrections for offset due to internal radar delays, finding frequency peaks, and computation of signal to noise ratios. Details of algorithms is beyond the scope of this extended abstract

4. DESCRIPTION OF FMCW RADAR HARDWARE

The system consists of a FMCW radar chip, chip controller, micro-computer, 5-volt voltage regulator, and high gain microwave antenna. Figure 4 summarizes cost, power and volume of the radar system.

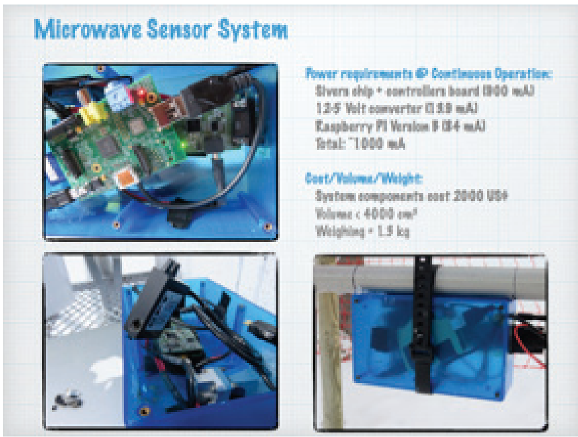


Figure 4: Cost, power, volume, weight of FMCW radar system.

The 25 GHz FMCW radar chipset selected use a single horn antenna design for transmit and receive. The high gain horn selected measures at angle of 15 degrees.

To minimize internal microwave reflections and cable attenuation the system was designed to directly connect the radar chipset to the antenna.

A proprietary controller board is used to acquire the radar data, perform the analog to digital (ADC) conversion, signal processing, and generate radar scan files. The controller board and Raspberry pi micro-computer are connected via serial USB. The raspberry pi is responsible for submitting radar control parameters to controller board, triggering radar, and storing scan data.

The system is powered by a 12.6 volt 6600 mAh li-ion battery. A compact usb based voltage regulator provides via micro USB the 5 volts required by the Raspberry pi.

Since the Raspberry Pi storage and operating system reside on solid state SD cards as opposed to HDDs, it meets and surpasses the demands of operating under low temperature and ability to absorb shock during transport in the field. The choice of a computer with Linux as an OS was also not a coincidence: Linux has well proven reliability and fault tolerance.

5. RESEARCH SITE

This research was conducted at Arcalis Ski Resort. The ski resort is located in the Pyrenees Mountains near the town of Ordino in the Principate of Andorra, a small country in the Iberic peninsula between France and Spain.

Figure 5: Radar research site in the Pyrenees Mountains.

A 25 GHz FMCW radar system was installed at Arcalis main weather station located at 2050 meters in elevation (ASL) during the 2016 Winter. The system trigger the radar and recorded data every 5 minutes between the period of December 2015 through February 2016. The weather station has a NNW aspect but it is in a flat open area with sparse trees nearby. Ski runs surround the weather station.

Figure 6: Radar Systems at Arcalis Ski resort in Andorra.

6. RESULTS

For several seasons we have conducted research where we temporally track the snowpack stratigraphy with a K-band FMCW radar (Rodriguez, et all, 2014). During the 2016 Winter in the Pyrenees there were two events that sparked our interest due to the presence of liquid water in the snowpack. The first event was the burial and refreeze of a wet crust, and the second a rain event.

The radar system tracks the distance between the radar and the snow surface. When liquid water is present the radar is “blind” to the snowpack below the liquid water boundary due to significant attenuation of microwave radiation.

The phase angle of the signal provides higher resolution data at the sub-centimeter for the 25 GHz radar. This data is generally not necessary because the distance obtained through FFT is “good enough” for snow stratigraphy applications. Because of the nature of the snowpack development, the increase or decrease in phase angle is monotonic, and driven by snowpack settlement or new snow addition. However, when liquid water is present lack of phase “coherence” is observed and there is marked deviation from a monotonic trend.

During the period between January 19th and January 21 a wet surface crust developed due to solar radiation. A cold front rapidly moved and precipitated 10 cm of new snow above a wet crust. The new snow was had low density, below the 10% density. Figure 7 illustrates phase angle through the event. During the wet event, it can be observe what we describe as “lack” of phase coherence. Lack of phase angle coherence persist until the liquid water re-freezes past the 300th radar sweep.

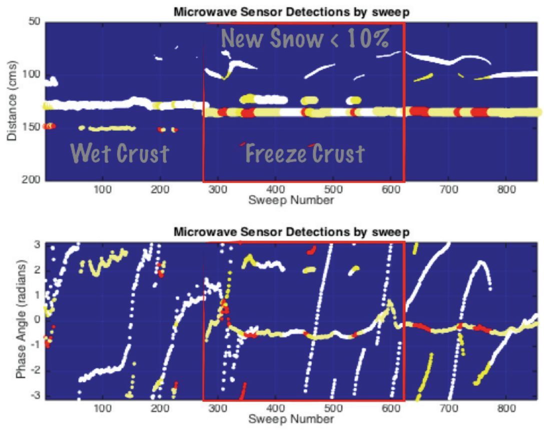


Figure 7: Processed radar data for Solar Radiation Wet crust and subsequent burial with new snow.

A rain event occurred between January 22 and January 24th. This liquid water event was more noticeable than the solar radiation wet crust event.

Figure 8 shows a clear separation in phase coherence between the dry and wet snowpack surface (sweeps range from 300th through 650th) that corresponds to the presence of liquid water in the snowpack.

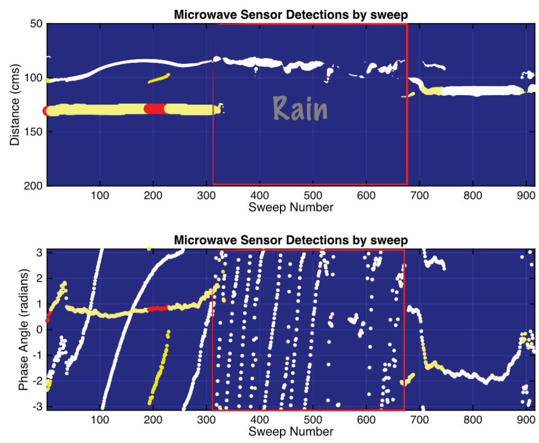


Figure 8: Processed radar data for rain event.

It is obvious that at the onset of the rain event, the radar system is unable to continue detecting the 130 cm layer below the 100 cm snowpack surface layer.

From the physics of liquid water and ice we recognized that there is a significant contrast in signal attenuation for the K-band radar utilized in this research. At 25 GHz the signal is minimally impacted when propagating in an ice or snow (top chart – Figure 9). The attenuation at 25 GHz happens to be near its minima for microwave radiation in ice/snow. In direct contrast, the attenuation or “dielectric loss” for a signal propagating in liquid water peaks near the 25 GHz. (bottom chart - Figure 9).

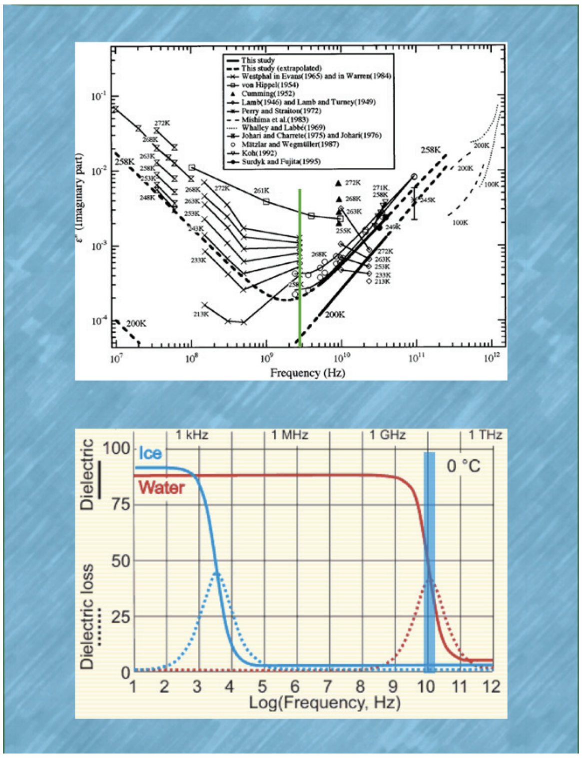


Figure 9: Frequency versus Signal Attenuation for Microwave radiation propagating in Ice and liquid water.

7. CONCLUSION

It is important to point out that the scope of the original research did not targeted studying wet snow surfaces. The research objective was to continue adding data sets during the application of 25 GHz FMCW radar for tracking dry snowpack. However, this preliminary work suggest that phase angle tracking can be a useful technique for detecting water phase changes between solid and liquid water in the snowpack.

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REFERENCES

Fine Resolution Radar for Near-Surface Layer Mapping, M.S Thesis, Rohit Parthasarathy, Electrical Engineering, University of Kansas, 2002.

Marshall, H. P., Koh, G. , FMCW radars for snow research ,Cold Regions Science and Technology 52 (2008) 118–131.

Ellerbruch, D. A., and H. S. Boyne (1980). Snow stratigraphy and water equivalence measured with an active microwave system. Journal of Glaciology, (94): 225-233.

Gubler, H., Hiller, M., 1984. The use of microwave FMCW radar in snow and avalanche research. Cold Reg. Sci. Technol. 9, 109–119.

Gubler, H., Weilenmann, P., 1986. Seasonal snow cover monitoring using FMCW radar. Proc. of the International Snow Science Workshop. Lake Tahoe, USA, pp. 87–97.

John H. Bradford, Joel T. Harper, and Joel Brown, Complex dielectric permittivity measurements from ground-penetrating radar data to estimate snow liquid water content in the pendular regime, WATER RESOURCES RESEARCH, VOL. 45, W08403, doi:10.1029/2008WR007341, 2009.241.

Heilig, A., C. Mitterer, C. Schmid, N. Wever, J. Schweizer, HPMarshall, O. Eisen, 2015: Seasonal and diurnal cycles of liquid water in snow – measurements and modeling. GeophysicalResearch Letters: Earth Surface, 120(10), 2139-2154.

Matzler, C, 1986, Microwave sensors for measuring avalanche-critical snow parameters. Proc of the Davos Symposium, IAHS Publ. no. 162, 1987.

Mitterer, C, Upward-Looking ground penetrating radar for measuring wet-snow properties. Cold Regions and Technology 69 (2011) 129-138.

Strobel, A., Comparison of Pulse and FMCW based Radio-location for indoor tracking system, Future Network & Mobile Summit Conference Proceedings, ISBN: 978-1-905824-18-2.

Modeling and Simulation Analysis of an FMCW Radar for Measuring Snow Thickness By Sudarsan Krishna B.E., Electronics and Communication Engineering,University of Madras, 2000.

Priandana, K., FMCW Phase-Processing for automotive applications, IPTEK, Journal of Proceeding Series, Vol I, 2014 (SSN: 2354-6026).

Rodriguez, S., Marshall, HP, Rodriguez, P., Applications of Low Cost and Low Power FMCW Radar in the Snow Characterization of Dry Snow. International Snow Science Workshop 2014 Proceedings, Banff, Canada.