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# APPLICATIONS OF LOW COST AND LOW POWER FMCW RADAR IN THE CHARACTERIZATION OF DRY SNOW

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ABSTRACT: We developed a low cost and low power 10GHz and 25 GHz Microwave Frequency Modulated Continuous Wave radars performed tests in the Andean snowpack during the Austral winters of 2013 and 2014, and in the mountains of Idaho and Colorado during the Northern Hemisphere Winter of 2013-2014. A new generation of compact and low cost radars will make it easier for researchers to study snow at remote locations and to deploy remote instrumentation in the field due to their low power requirements. System components cost in the range of 2000 US$, have a volume of less than 4000 cubic cm and weight as little as 1 kg, which opens the door for new applications in avalanche safety and hydrological applications. Examples of applications tested are measurements of snow depth, stratigraphy, and SWE at remote mountain locations, snow depth and snow- water-equivalent at hydrological stations.

KEYWORDS: Radar, stratigraphy, instrumentation

## 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).

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).

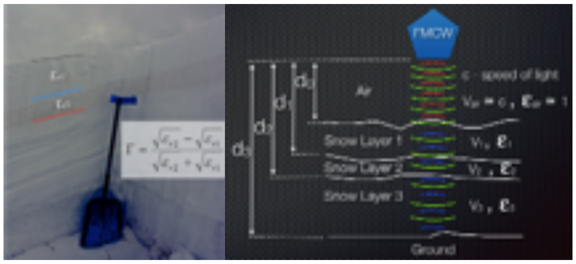

Figure 1: Microwave radar reflections occur where snow properties change..

FMCW in the 0.5 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

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track snowpack depth, stratigraphy, and snow water equivalent.

In association with a computer science student from UC-Berkeley, the Raspberry PI Linux based micro-computer (http://www.raspberrypi.org/ ) was adopted to control the system, generate calibration files, and store radar scan files. The extremely low cost and reliability of the Raspberry Pi made it a logical choice to further advance the low cost and low power attributes of the developed radar system , which we call miniFMCW Snow Radar. The solid state nature of the Raspberry Pi also addressed environmental demands of work in the field; which requires performance at low temperature and hardware that can endure the rigor of on the snow transportation.

## 2. FMCW FUNDAMENTALS

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 $\tau$ 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:

$$F(t) = F_{low} + B_w/T_s*t \qquad (2)$$

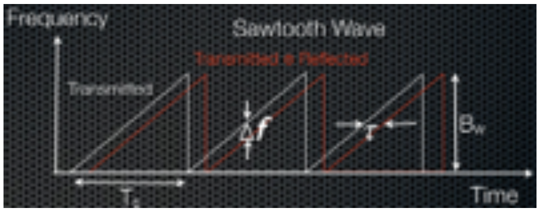

Figure 2: FMCW Principles - Sawtooth Wave Sweep.

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 $\tau$, , which is a linear function of the frequency difference Δ***f***.

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).

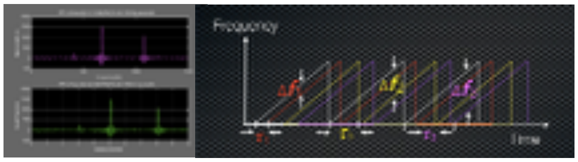

Figure 3: FMCW Principles - Superposition of reflected signals.

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 paper.

## 4. SNOW MINIFMCW RADAR

The 10 GHz and 25 GHz components are identical with the exception of the radar generation chipset and the antennas. Every radar frequency requires an antenna tuned specifically to the frequency range in used.

The first generation of the miniFMCW used a 10GHz radar chipset with customized split outputs for transmit and receive, requiring separate antennas (Figure 4-left). The second generation was lighter and with enhanced portability (Figure 4-right).

Figure 4: First and second generation of Snow MiniFMCW Radar systems.

This first generation system was tested with and without a 20dB signal amplifier in the transmit output. X and K bands radars are susceptible to liquid water in the snowpack, and the ability for the radar signal to penetrate the snowpack decreases dramatically with liquid water. The 10 GHz system was able penetrate close to 1 meter only with liquid water up to 1% during 2013 South America research campaign. This system operated well with dry snow, and penetrated up to 3 meters without the power amplifier.

The second generation relied on a newer radar chipset that allowed to use a single  standard gain horn antenna for transmit and receive, thus enabling further cost reductions in the system. That decision resulted in a measurement angle of 15 degrees.

To minimize internal microwave reflections and cable attenuation the second generation system was designed to directly connect the radar chipset to the antenna. without the use of cabling, that will add noise to the signal.

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. Data is retrieved via high speed ethernet port to another computer.

The second generation miniFMCW system benefited from a compact LCD display with 5 buttons that resolved the sun and snow glare challenge when using other types of displays. The LCD control panel buttons were designed with ease-of-use in mind and to allow interacting with glove hands.

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. The combination of sound software engineering practices with reliable hardware has allowed us to focus on snow studies and applications of the radar.

For fixed remote radar installations a third generation was developed and tested in Argentina and Chile during the 2014 Austral Winter (Figure 5). A lower power Raspberry PI (Model B) without the LCD control impanel was implemented in the third generation.

Figure 5: Third generation MiniFMCW Snow Radar Systems. In the left (blue housing) the 25 GHz radar, in the center (white housing) the 10 GHz radar. Remote installation at Cerro Cautin, Malalcahuello, Chile.

The architecture and design of the Snow miniFMCW Radar has a patent pending.

## 5. RESULTS

After 12 months of development of a low cost and low power FMCW radars - the 10GHz and 25 GHz Snow miniFMCW Radar systems are ready to be installed at remote locations!

The first and second generation of the Snow miniFMCW Radar have demonstrated to be a reliable during field testing. The prototype miniFMCW systems were tested at many locations in Idaho and Colorado, with contrasting snowpacks that varied from deep dense dry snowpack to shallow and faceted snowpacks.

During the 2014 Northern Hemisphere winter, the 2nd generation Snow miniFMCW Radar performance was successfully demonstrated in dry snow. The miniFMCW system architecture decision to adopt a standard gain single antenna and low power system was able to detect reflections from the snow/ground interface up to 3.5 meters. This was critical for the development of the 25 GHz miniFMCW radar, since the higher frequency microwave radar has reduced penetration. The developers were uncertain about the ability to have a low power 25GHz penetrate deep dry snowpacks.

Field testing validated that the “10 GHz Snow miniFMCW Radar” is a best fit for SNOTEL and remote stations type applications tasked with tracking snow water equivalent in snow with up to 1% liquid water content.

Field testing also validated that the “25 GHz Snow miniFMCW Radar” is the best solution for “spatial high resolution’ tracking of the temporal development of dry snow snow stratigraphy.

The 10 and 25 GHz systems were installed at fixed remote locations at multiple mountain regions in the Andes during the 2014 Austral winter. These installations were allowed to capture the temporal development of the snowpack.

One example of a time series radar scan for a fixed 25 GHz FMCW radar installation is included in Figure 6. Surface is at 60-80 cm. Reflection at 110 cm corresponds to a dirty snow layer saturated with liquid water. The 90 cm layer reflection corresponds to a significant density change between new and old snow layers. The settlement documented by the radar scans occurred during a period diurnal air temperatures above zero degrees Celsius.

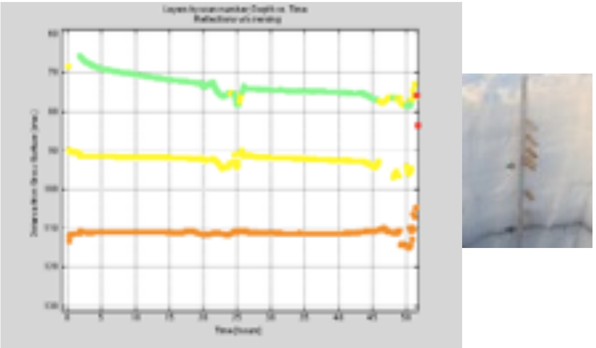

Figure 6: Radar scan time series for the 25 GHz FMCW radar at Cerro Cautin, Malalcahuello, Chile.

Another example (Figure 7) is a time series for the 10 GHz fix installation at Chapelco Ski Resort in Argentina during the 2014 Austral Winter which it is illustrated in figure 6. The radar scans and the air temperature events track the radar recorded snow changes in height and stratigraphy. Detailed analysis of weather events and radar scan derived data (SWE and densities) will be shared during ISSW 2014 poster session by the authors.

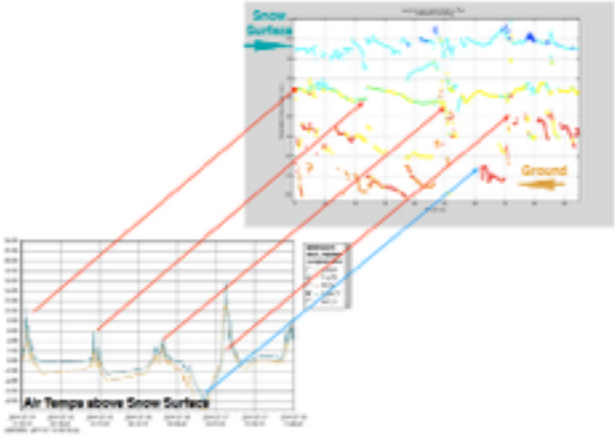

Figure 7: Radar scan time series for 10 GHz FMCW radar at Cerro Chapelco, San Martin de los Andes, Argentina. Snow surface air temperature as well as relative humidity also shown.

A seemingly trivial aspect, but essential to the success of remote MiniFMCW radar installations, was the evaluation of the design for the MiniFMCW radar support. The radar support allow us to easily change radar to snow heights as well as the radar to snow surface angles (Figure 8).

By mid August 2014, the radar support design evaluation was completed with overwhelming success after more than 6 weeks of use in the field.

It should be noted the Raspberry Pi micro-computer and software architecture demonstrated reliability in both hardware and software.

Figure 8: Radar support system first tested during Austral Winter 2014.

*Limitations identified:*

Due to high gain antenna, the Snow miniFMCW Radar is sensitive to angle deviations from the normal of the snow surface. When using the portable MiniFMCW Snow radar, great care in aligning radar horns normal to the snow surface is key to maximize signal strength of reflections. With the fixed radar installation this issue is addressed. On the other hand an alignment jig needs to be developed for the portable hand-operated scan system.

Both systems are sensitive to free liquid water, and the intrinsic signal absorption of 10 and 25 GHz signal by wet snow is further magnified by the nature of a low power system.

Systems need to have a solar system to reduce tedious battery changes.

## 6. FUTURE PLANS

The 2014 South American research campaign allowed further testing the second generation and field evaluate the third generation of 10 and 25 GHz microwave FMCW radar systems.

Hardware improvements as well as software improvements were identified for both MiniFMCW snow radars generations, such as the need to improve corrosion resistance of external power connectors, reduce field scan rates (from 1 hour to 15 minutes), better sealing of microwave antenas with non-reflective material that eliminates water condensation inside the horn antennas.

The necessary improvements identified will be leverage into three Snow miniFMCW Radars NEW installations planned at the Northern Hemisphere during the 2014-2015 northern hemisphere winter, including the NRCS Big Creek Summit Snotel station in Cascade-Idaho. This installation will use the 10 GHz system to track Snow Water Equivalent (SWE).

The second installation will be in the Payette National Forest, where a 25 GHZ Snow miniFMCW radar will attempt to track the formation of near surface facet layers and stratigraphy through the 2014-2014 avalanche forecast season. The installation is at a high elevation elevation NE aspect with 25-35 slope angle.

A third installation is scheduled at Swamp Angel Study Plot at the Center for Snow and Avalanche Studies (CSAS), Silverton-Colorado, with a 25GHz Snow miniFMCW Radar pointed into the sky to explore quantification of snow precipitation rates and snow/rain events.

The 25 GHz radar system is of most interest for snow research at this time, since very limited work has been conducted with snow at such frequency. New applications such as monitoring of avalanche starting zones, as well as detection of artificial avalanche triggering during low visibility periods will be investigated.

## 7. ADDITIONAL INFORMATION

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