Two-Dimensional FMCW Radar Imaging of Entire Avalanche Events

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Abstract: Avalanches pose a significant threat to human life and settlements, hence their study is key in formulating settlement risk zones. Validating models of avalanches, developed to predict their behaviour, are limited by the quality of current field data. Radar measurements of avalanches have been made, however these measurements suffer from coarse 50 m, single dimensional localisation. This work describes the design and installation of a sophisticated FMCW phased array radar with sub-metre range resolution for imaging avalanches. With this radar, we aim to provide a high quality, 2-D, animated reconstruction of avalanche events. The radar is currently installed in a bunker at a well-equipped avalanche test site; Vallée de la Sionne, Switzerland. It will operate throughout the 2010/11 winter, automatically recording data when a natural avalanche event occurs. Indeed, a wet snow avalanche has already been recorded on the 7^{th} December 2010. A sample output from the data recorded during this event is shown in this paper in the form of a range-time image. The data gathered during this event will be further exploited using sophisticated radar signal processing algorithms. We hope also to analyse micro-Doppler signatures of the component blocks of snow in the avalanche.

Key–Words: FMCW, Radar, Avalanche, Phased array, Imaging

1 Introduction

Avalanches pose a significant threat to human life and settlements. Hazard mapping of avalanches has historically relied on observations of avalanche occurrence and run-out distances. This means that large, and possibly extreme, avalanches are missed [1]. A need to model avalanche behaviour has been born out of this weakness. However, we currently struggle to validate models of avalanche behaviour due to insufficient field data. Consequently our ability to predict avalanche run-out distances and impact pressures, parameters that are extremely important in formulating risk zones for settlements [2], is limited. The gathering of high quality, quantitative field data to gain greater insight into avalanche dynamics is crucial for progress in this area [3].

There are many different types of remote sensor used for gathering avalanche data. Radar instrumentation is currently used in avalanche research to measure the spread of velocities within the avalanche, from which retarding forces are also inferred. There are three kinds of radar in general use: continuous wave (CW), pulsed Doppler (PD), and buried FMCW radar [4], [5], [6], [7]. CW and PD radar provide similar information with PD radar providing better localisation of its velocity measurements. However, in their current form they only provide single dimension range measurements, and their available transmit power limits them to a range resolution of the order of 50 m, too coarse to provide a true representation of the avalanche dynamics. Buried FMCW radar are limited to making point measurements of the avalanche and so to gain a reasonable measure of the avalanche's progress, several of these are deployed at different points along the avalanche track and the average velocity between them is calculated.

This paper describes the full design and installation of a newly developed, sophisticated FMCW radar at a well equipped avalanche test site, Vallée de la Sionne (VDLS), in Switzerland. A prototype version has been used in the past for smaller scale snow movement measurements [8]. Since those measurements, the radar has been upgraded and installed in a reinforced-concrete bunker at the VDLS, on the opposing slope of the avalanche track. The bunker is equipped with other radar systems [9] and a trigger mechanism for gathering data from naturally occurring avalanches. The fully developed radar has been operating throughout the 2010/11 winter and successfully gathered measurements of a large scale avalanche in the early hours of the 7^{th} December 2010.

2 Radar Design

The aim of this project is to study the underlying dynamics of avalanche flows with the aid of an advanced FMCW phased array radar [10]. The radar system in a simplified form is shown as a block diagram in Fig. 1. The majority of the radar components were commercially sourced to aid system flexibility and reliability. Our radar performs deramping in hardware by mixing the local FMCW radar signal with the return FMCW radar signal. The output of this process is a baseband signal whose frequency spectrum can related to target range using Eq. (1).

$$R = \frac{f_d c T}{2B} \tag{1}$$

where f_d is baseband frequency, c is propagation speed, T is chirp duration, and B is chirp bandwidth.

After deramping we have also included an active baseband filter which compensates for two-way propagation losses by increasing the receiver gain in proportion to target range (i.e. increasing receiver gain with increasing baseband signal frequency). This design makes best use of the analog to digital converter dynamic range.

The operating frequency of the radar has been carefully selected to best match our aims. If we consider the occurrence of a dry snow avalanche, as the avalanche progresses the front and upper surface of the flow mix with the surrounding air forming a low density powder cloud [11]. Therefore, a simplified view of a dry snow avalanche is that it is composed of a dense core region and a powder cloud region. To measure the underlying dynamics of the avalanche we need to penetrate the powder cloud to reach the dense core region. Given that the size of the particles composing these two regions differs, we can select an operating frequency that will penetrate the powder cloud and illuminate the dense core. Our radar operates at 5.3 GHz ($\lambda = 5.7cm$) to penetrate the small powder particles and illuminate larger-than-centimetre size blocks in the dense core region. The radar design specification is summarised in Table 1.

The radar antennas are commercial antennas with a horizontal and vertical beamwidth of 29^o and 50^o respectively, sufficient to illuminate the entire avalanche track. An array of 8 receiver antennas is arranged over a 5.3 m linear aperture. Each of the 8 receiver channels produces an isolated measurement of the event. Cohering these measurements and combining them in post-processing provides cross-range information (i.e. a 2-D image of the avalanche). The 5.3 m aperture gives a narrow beamwidth (0.6^o) equating to a cross-range resolution of approximately 10 m at 1 km range.

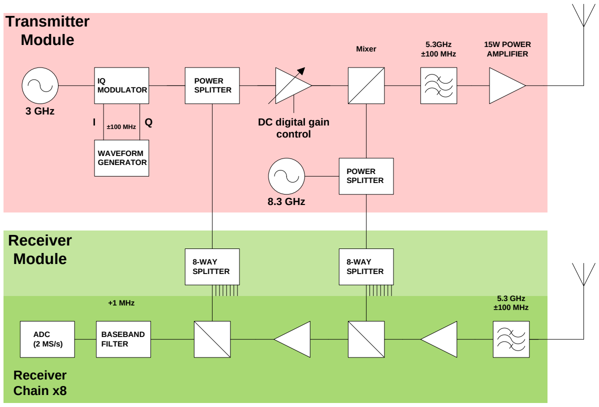

Figure 1: Simplified block diagram of the FMCW avalanche radar with 8 channel receiver array.

In addition, the radar signal is an important part of the design. The radar transmits 6 successive linear frequency modulated (chirp) waveforms with different chirp rates. A frame of waveforms (a full set of the 6 chirps) has a period of 20 ms. This means that the radar provides enough data to produce 50 images per second. It is assumed that a measurement stays reasonably constant over the course of a frame so splitting each frame into returns from each chirp provides redundancy to aid the process of extracting range and Doppler information from the deramped signals. The 200 MHz bandwidth of the chirps is constant throughout the frame equating to a c. 0.75 m range resolution. Hence, our radar waveforms and receiver array design mean that it is possible to reconstruct an animation of an entire avalanche event with high spatial and temporal resolution. In addition, given the high resolution of the radar, we will be able to derive velocity estimates at the same locations as the buried FMCW radar already present at the avalanche test site allowing us to validate the radar performance.

3 Radar Installation

The radar operates in a reinforced-concrete bunker positioned at the foot of the slope opposing the avalanche track at VDLS [12]. Fig. 2 shows the transmitter and receiver modules in the VDLS bunker.

To protect the equipment from the harsh temperatures and humidity in the bunker, the radar is covered with insulation and is actively heated with two 400 W fan heaters controlled by two series-connected

Table 1: Radar specification.

Operating Frequency	5.3 GHz
Waveform Bandwidth	200 MHz
Base-bandwidth	1 MHz
Transmit Power	15 W
Maximum Chirp Length	5 ms
Maximum Range	3750 m
Array Beamwidth	0.6^o

thermostats. The heating system keeps the ambient temperature within the insulation at a warm 10^oC.

The transmitter antenna is positioned on the south wall of the bunker, separated from the receiver antennas to avoid direct coupling of the transmitted signal to the receivers (see Fig. 3). The receiver array consists of 8 elements spaced sparsely over a 5.3 m linear aperture. The average separation between each antenna is 15λ. However, the antenna separations are randomised to mitigate the effect of grating lobes [13]. The radar has two different antenna array options (of the same design) for different purposes; one spread over the inside of the bunker's 1.3 m windows, and the other mounted outside on the roof of the bunker.

The indoor array is used for artificial releases, i.e. people are present in the bunker and able to operate the window shutters. During these experiments, the shutters are open so that all of the sensors within the bunker can measure the avalanche. The shutters are manually closed when the avalanche reaches the foot of the avalanche track to protect the equipment.

During periods when the bunker cannot be accessed (the majority of the winter), the shutters are left closed to protect the sensors within the bunker from naturally occurring avalanches and the weather. Thus, a further outdoor array was installed for measurement of natural avalanches. The occurrence of such a natural avalanche, as measured by acoustic sensors in the avalanche track, triggers the radar to immediately begin recording data. The disadvantage of this array relative to the indoor array is that it introduces more attenuation due to longer cable lengths to connect with the receiver module.

The radar operates in a sleeping state throughout the winter awaiting an avalanche trigger (the transmitter power amplifier (PA) is switched off and data is not being acquired). When the trigger occurs, it activates the data acquisition software which in turn activates the transmitter PA by switching a relay. Data acquisition proceeds for 3 minutes to capture the entire avalanche event, storing the data on a fast but limited capacity solid state hard drive (SSD). Every night at 1 am, or if the SSD becomes full, the data is then transferred to a large-capacity external hard drive, which is not expected to fill up over the course of the winter season. Hence, an entire season of avalanches may be recorded automatically. The radar has been gathering data throughout the 2010/11 winter.

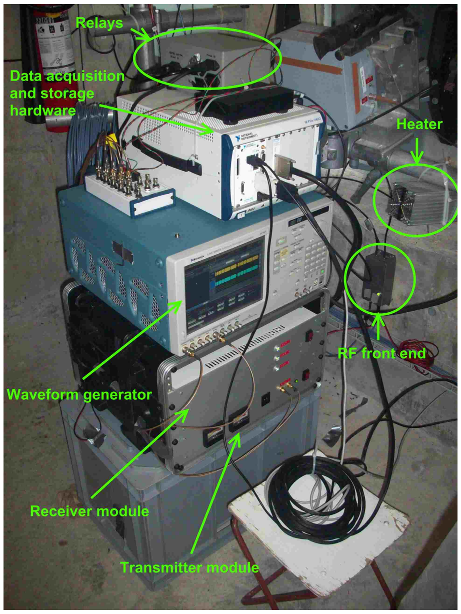

Figure 2: Radar in the VDLS bunker before application of insulation.

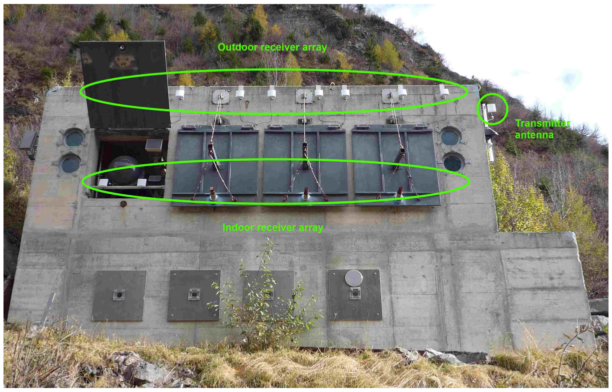

Figure 3: Transmitter antenna, and indoor and outdoor receiver antenna array at the VDLS bunker.

4 Natural Avalanche Event

A large natural wet snow avalanche occurred at VDLS at around 3am on the 7^{th} December 2010 and was successfully recorded by the radar. A sample of the data in its early stages of processing is shown as a range-time plot in Fig. 4. This image is from a single re-

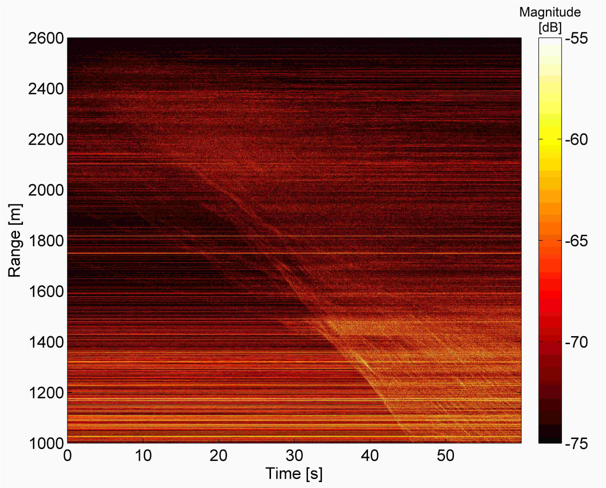

Figure 4: Range-time image of deramped signal from longest duration chirp at receiver channel 1.

ceiver channel only and each pixel along the x-axis (time axis) is from the longest period chirp in a single frame. The y (range) coordinate of each pixel has been calculated by simply performing a fast Fourier transform (FFT) on each frame and relating the frequency to range using Eq. (1). The range has also been calibrated using pre-determined measurements of transmission line length between the antennas and the back-end of the radar.

The image clearly shows the movement of the avalanche. By following the front of the avalanche, sudden changes in the flow velocity are visible from changes in the range-over-time profile. This is due to changes in the slope angle as the avalanche progresses along the avalanche track, but could also be a result of collisions between the snow and features of the mountain. In its current state, it is difficult to conclude much more from this image as each range measurement is an amalgamation of range and Doppler effects. However, to the author's knowledge, such fine resolution measurements of entire avalanche events have not been seen before.

5 Conclusions and Future Work

Understanding the behaviours of avalanches is of great importance in formulating risk zones for settlements. Our ability to validate our models of avalanche flows is limited due to a lack of high quality field data. Current radar for measuring avalanches suffer from coarse single dimension range resolution. We have described the design and installation of a newly developed, sophisticated, FMCW radar for measuring avalanches. The radar is capable of recording enough data to produce 2-D range images at a rate of 50 frames per second with sub-metre range resolution. It has been installed in a bunker positioned at the foot of the slope opposing the avalanche track of a well equipped avalanche test site; Vallée de la Sionne, Switzerland. The radar has been gathering data throughout the 2010/11 winter.

A large natural wet snow avalanche event was successfully measured by the radar in the early hours of the 7^{th} December 2010. Initial simple processing outputs have shown promising outputs from the radar. The next step for this project is to begin applying sophisticated processing techniques to the radar data. We intend to begin applying methods of cohering the data from each receiver channel and combining it so that 2-D images can be produced. Following this we can start to look at tracking the avalanche particles to resolve the range and Doppler information carried by the data. The geometry of the radar and topography of the avalanche track will be compensated for during this process. Our velocity estimates from the Doppler information will be validated against the data also collected by the buried FMCW radars. Also, with the Doppler information we plan to perform micro-Doppler analysis. By analysing the micro-Doppler signatures we hope to be able to evaluate individual blocks of snow within the avalanche and provide statistical data on velocity and flow vectors of underlying snow movements from natural avalanche events, for comparison with flow models.

Acknowledgements: The authors would like to thank the Swiss Federal Institute of Snow and Avalanche Research for their help throughout the duration of this work. The authors also thank the Natural Environment Research Council for their support, grant ref. NE/F004621/1.

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