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Two-dimensional radar imaging of flowing avalanches

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ABSTRACT

Radar has emerged as an important tool in avalanche research. However, existing radar sensors suffer from coarse range resolution capabilities. This limits the usefulness of the data they collect in validating models of avalanche dynamics. This paper details the development of a frequency modulated continuous wave, phased array radar, and its associated signal processing, for non-invasive measurements of entire avalanche events. The radar outperforms existing avalanche radar sensors in terms of range resolution, and it provides cross-range resolution using a phased array receiver. The radar has been operating at the Vallée de la Sionne avalanche test site in Switzerland since the 2010 winter season. It has successfully gathered measurements of entire natural avalanche events. In this paper we show two-dimensional radar images of a naturally occurring avalanche, the first of their kind, which reveal movements of layers or particles of the flowing avalanche in unparalleled detail. Furthermore, the potential of the measured data is shown with tracking of avalanche fronts in two spatial dimensions. This marks an important step towards providing a library of high-quality avalanche measurements to improve our knowledge of avalanche dynamics.

1. Introduction

Avalanches pose a significant threat to human life and settlements. Hazard and risk assessments of avalanche prone regions are typically based on the statistical analysis of observed avalanche run-out distances (Keylock et al., 1999), or more commonly, combine knowledge of extreme snow depths (Blanchet et al., 2009) with a dynamics model to assess run-out properties (Eckert et al., 2010) or potential damage and vulnerability (Bertrand et al., 2010; Keylock and Barbolini, 2001). Given the importance of these numerical models for accurate risk assessments, it is not surprising that there have been concerted efforts to develop physically meaningful flow laws for inclusion in numerical codes (Bouchet et al., 2003; Dent et al., 1998; Eglit, 1974; Gray and Tai, 1998; Kern et al., 2004; Nishimura and Maeno, 1988; Norem et al., 1986; Salm, 1993). Such research has also examined the role of entrainment processes in the dynamic behaviour (Gauer and Issler, 2004; Naaim et al., 2004) and there have also been attempts to benchmark models against one another for recorded events (Barbolini et al., 2000; Issler et al., 2005). However, the lack of high-quality data still means that there is still significant uncertainty in the relevant physics for flowing snow, making model validation problematic.

Radar has emerged as an important tool in avalanche research for obtaining avalanche measurements. It has been employed for gathering velocity measurements of entire avalanche flows (Gubler et al., 1986; Rammer et al., 2007; Schreiber, 2001), and localised erosion and deposition measurements (Gubler and Hiller, 1984). The use of these measurement instruments has led to great improvements in our knowledge of avalanche behaviour over the last couple of decades, with attempts made to determine rheological parameters from such data (Ancey and Meunier, 2004). However, these measurements suffer from weaknesses in certain respects, in particular regarding range resolution. Consequently, the drive for developing a better understanding of avalanche dynamics is hindered somewhat by a lack of high-quality data.

Localised radar measurements clearly do not provide an accurate picture of the entire avalanche. Non-invasive measurements of entire avalanche flows have been taken with pulse-Doppler radar to produce localised velocity maps of the avalanche using range gating. Indeed, the usefulness of these measurements has been demonstrated with the recording of the spread of velocities along an avalanche, showing that velocities decrease rapidly behind the avalanche front, which has the maximum speed (Gauer et al., 2007). However, the finest range gates before the development of the instrument discussed in this paper were 25 m. This limited range resolution means that localisation of sub-components of the avalanche is not possible. Furthermore, these radar systems are single channel systems, limiting measurements

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to a single (range) dimension, hence missing the lateral dynamics of the avalanche.

In this paper we describe a novel frequency modulated continuous wave (FMCW) phased array radar capable of taking non-invasive measurements of entire avalanche events with a range resolution that greatly improves upon existing radar instruments and provides cross-range resolution for the first time. We will provide an in-depth description of the radar and antenna array design, and an analysis of the system performance. We also detail the signal processing steps required to produce avalanche images from the radar measurement data. Finally, we will report some measurements of avalanches as recorded during a winter season, including two-dimensional radar images of a flowing avalanche for the first time.

2. Radar system design

2.1. Microwave characteristics of snow

The radar system operates in the microwave electromagnetic spectrum and its design started with a brief analysis of the microwave characteristics of snow so that a radar link budget could be formulated. An avalanche, and the regions comprising an avalanche, can be characterised by their snow/ice density, water density and air density. In the interest of formulating a link budget, it is good practice to design for the worst-case scenario. In this case, that scenario is the one which provides the lowest backscatter coefficient, $\sigma°$, a dimensionless quantity that describes the average effectiveness of a surface to scatter radiation upon it. In this paper, we are interested in measuring the underlying dynamics of the dense core region of an avalanche. This region tends to have the highest snow and water density within the avalanche. The density of the water content defines whether the avalanche is *dry* or *wet*. In this application, the radar is designed to measure the dynamics of dry snow avalanches in the first instance. For a dry snow medium, the contribution of the imaginary part to the complex dielectric constant is negligible. It is generally agreed that the real part of the dielectric constant of dry snow is a function of snow density. The suggested practical model for the real part of the relative dielectric constant of dry snow is (Hallikainen et al., 1986; Tiuri et al., 1984):

$$\epsilon_r \approx 1 + 2\rho_{ds} \tag{1}$$

where ρ_{ds} is the bulk dry snow density relative to the density of water. This model is suitable for $\rho_{ds} \leq 0.5$, beyond which the error increases rapidly. The dielectric constant, ϵ_r, of a dry snow medium is therefore approximately 1.2 assuming that the dense core region of the dry snow avalanche has a density of 100 kg m^{-3} and that water has a density of 1000 kg m^{-3}. This approximation lies somewhere between the fluidized and dense region density (McClung and Schaerer, 2006; Schaer and Issler, 2001) and does not consider the variation in snow temperature and thus density along the avalanche path (Steinkogler et al., 2014). From this figure, we can calculate the backscatter coefficient using an equation derived from the reflection coefficient of a transmission line (Pozar, 2012):

$$\Gamma = \frac{Z_1 - Z_2}{Z_1 + Z_2} = \frac{\sqrt{\epsilon_r} - 1}{\sqrt{\epsilon_r} + 1} \tag{2}$$

$$\sigma^{\circ} = |\Gamma|^2 \tag{3}$$

where Z_1 is the wave impedance of free space and Z_2 is the wave impedance of the target snowcover. This gives an approximate backscatter coefficient of 0.002 at a grazing angle (the angle between the target surface and the incident ray) of 90°. For a particular radar system, the backscatter coefficient is a function of snowcover characteristics, grazing angle and surface roughness. Predicting and modelling some of these parameters are not trivial tasks so for the link budget calculations in this paper we have assumed a grazing angle of 7°, based on the worst-case geometry in this scenario, and a rough surface (the standard deviation of the surface height during a flowing avalanche is likely to violate the Fraunhofer criterion (Ulaby et al., 1982)). For a rough surface the variation in backscatter coefficient with grazing angle is less pronounced relative to a smooth surface (Ulaby et al., 1982), hence the link budget calculations in this paper we have not considered the angular dependence of the backscatter coefficient.

This system is primarily designed to provide measurements of snow movement and so the absolute value of the reflected signal is not of great importance. However, clearly it is necessary to have an understanding of the composition of these movements. The penetration depth of the radar signal is also dependent on the snow density and its water content (Ulaby et al., 1986). Our radar operates at C-band, at which the radar signal penetration depth for dry snow has been shown to be up to 10 m (Rignot et al., 2001). Hence, the backscattered radar signal is a superposition of reflections from the snow–air interface, the below-surface snow volume (which is comprised of multiple ice layers), and potentially the snow–ground interface. The results in the latter sections of this paper will show the ability to see these avalanche movements following processing of the recorded radar data.

2.2. Radar considerations

The new radar, Geodar, operates at 5.3 GHz (C-band), 5.7 cm free-space wavelength, in order to illuminate the blocks of snow comprising the dense core region of an avalanche, which are assumed to be in the order of centimetres to metres in size. The radar is of frequency modulated continuous wave type, meaning it continuously transmits a radar signal that is frequency modulated. In this case, the radar employs a linear frequency ramp (chirp) as the radar signal, which is described by:

$$y_t = a_t cos\left(2\pi f_o t + \pi\alpha t^2\right) \tag{4}$$

where a_t is the signal amplitude, f_o is the radar operating frequency, and α is the chirp rate (ratio of chirp sweep bandwidth B and chirp period T). The range resolution of such a radar signal is given by the well-known expression (Skolnik, 2001),

$$\Delta R = \frac{c}{2B} \tag{5}$$

where c is the signal propagation speed (assumed in calculations to be the approximate speed of light in a vacuum of $3 \cdot 10^8$ m/s). On reception, following two-way propagation, the radar signal is mixed with a portion of the transmitted signal in a process known as deramping. This generates a beat signal whose frequency can be described by (Stove, 1992),

$$f_d = \frac{2\alpha R}{c} \pm \frac{2 f_o v}{c} \tag{6}$$

where v is the velocity of the target at range R and assuming that the radar signal propagates through free space. The ± sign is included to indicate the use of triangular modulation in the transmitted radar signal; this will be explained later in this text. It is this beat signal that is recorded by the radar analogue-to-digital converter. Spectral analysis of the recorded signal is used to relate the signal to target range.

The maximum frequency sweep bandwidth of the radar is 200 MHz which gives a minimum theoretical range resolution of 0.75 m, a great improvement over existing avalanche radar instruments. The linear chirp period can be varied between 1 ms and 5 ms. This gives a deramp frequency of between 1333 Hz/m and 267 Hz/m. These parameters demonstrate some of the advantages of using an FMCW radar; namely that one can achieve high range resolution with a modest receiver sampling rate. In this case, the system employs a sampling rate of 2 MSa/s for each radar channel. This provides a maximum range of