Advanced Radar Imaging of Geophysical Flows

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Abstract: - The dynamics of geophysical flows such as snow avalanches and pyroclastic flows are of great interest, not least due to their potential for catastrophic consequences, and have received substantial attention over recent years. A variety of models have been formulated to predict the behaviour of such flows but there is currently a lack of suitable experimental data to validate these models and inform the choice of model or coefficients for a given situation. Radar measurements are useful in, for instance, observation of snow avalanches in order to provide velocity vector information of the movements of snow below the powder cloud, thus providing information that is not available using optical instruments. Simple radar observations, consisting of a one-dimension range profile of low resolution, have been made of snow avalanches. This work sets out to develop and utilize a more sophisticated radar instrument able to perform high resolution 3-D images of, in particular, snow avalanches but also pyroclastic flows, in order to provide a step improvement in the observational data with which to compare with a range of flow laws.

Key-Words: - Snow, Avalanche, Pyroclastic, Flow, Radar, Imaging, Velocity, Vectors.

1 Introduction
Catastrophic movements of granular and particle-laden fluids such as pyroclastic flows and snow avalanches are significant natural hazards. Gaining an improved insight into the dynamics of such flows is thus not merely of scientific interest, but of great practical importance. The dynamics of these flows has received a great deal of attention from scientists from a range of disciplines in recent years [1-3] coupled to a growth in interest in the dynamics of granular flows more generally [4, 5-7]. The usual approach to modelling dense flows (which also includes debris flows) is to use a shallow-water approximation to simplify the equations [13], and to then express the flow resistance through a variety of terms, including Coulomb bed friction [8-11], an active-passive pressure coefficient to distinguish between extensional and compressional regimes [8-10], terms to represent pressure effects due to the interstitial fluid [9], and a velocity-squared dependent drag [10, 12]. Although such models have been tested against laboratory flows [11] and applied to the run-out distance of natural events [13], there is a genuine lack of appropriate observational data to validate the velocity estimates obtained from the models. The suspended component of the flow is usually modelled as a plume or gravity current [14], or tackled numerically with turbulence closures [15], although these closures are applied outside their traditional domain of validity. The consequence of this is that we have very little knowledge of the appropriate flow law for such flows, or the appropriate values for coefficients within a particular flow law, limiting our ability to predict flow travel distance and impact pressures, information that is essential for formulating risk zones for settlements [16]. Thus, better data are required in order to gain an insight into the flow dynamics of these processes because at present, the appropriate constitutive relations are poorly constrained.

2 Objectives
This project aims to study the dynamics of environmental particle-laden flows with the aid of an advanced phased array radar that will provide high resolution 3-D animated imaging and velocity data. In addition we plan to utilise our expertise in micro-Doppler target recognition to enable the identification of specific details in these flows. These components are expected to have very
distinctive Doppler signatures which can be analysed to extract information such as relative velocities and sizes of particles. The instrument offers greatly enhanced imaging performance, well beyond that currently available, providing internationally-leading capabilities in this field. The research promises to generate new data from which we will gain new insights into the flow dynamics, eventually resulting in models for hazard and risk applications with an improved physical basis.

2.1 Radar imaging system
The instrument that we are deploying will offer a substantial number of technical and scientific advantages over previous instruments used to study geophysical flows:
(1) Existing instruments form only a one-dimensional image and average the signal over a range-gate with a 50 m length, as illustrated in Fig. 1. Our radar will use range-gates with a resolution of approximately 1 m. Hence, the velocities and velocity fluctuations will be reasonable approximations to those of the individual blocks in the upper part of the flow. Examination of these data will lead to genuine insights into the processes controlling the acceleration and deceleration of avalanche flows and the relevance of ideas from the granular flow literature for natural processes. Velocities obtained at this resolution can be related directly to those obtained with other sensors at Vallée de la Sionne (VDLS), permitting a physical interpretation of the data that was not possible when the range-gate was 50 m;
(2) The use of a phased array will enable us to achieve two-dimensional imaging and velocity vectors rather than the average one-dimensional magnitudes that are currently possible [17];
(3) With multi-waveform digital pulse generation and 100 frame per second imaging capability, the instrument allows a fully animated reconstruction of events. Merging data from a range of waveforms gives versatility and allows us to work with waveforms that are optimal for imaging particular flows;
(4) Use of micro-Doppler processing methods will enable us to resolve the flow in unparalleled detail.

The radar system is shown, in block diagram form, in Fig. 2. It consists of a 15 W transmitter unit, with digital waveform generation, capable of generating 10 consecutive waveforms per frame at 100 frames per second, and eight receiver modules, with FMCW operation, providing azimuth information. The radar uses a 150 MHz sweep bandwidth equating to a range resolution of around 1 m. Using a sparsely-sampled receive arrangement, an azimuth resolution of approximately 10 m at 1 km range is expected. Thus it will be possible to perform a reconstructed animation of events with high spatial and temporal resolution.

2.2 Specific aims
The specific scientific objectives of the work are as follows:
(1) To obtain data on the dynamics of snow avalanches and pyroclastic flows using our radar;
(2) To validate these data using measurements from other instruments at VDLS;
(3) To interpret our data with respect to the relevant physical processes to constrain the possible form of flow laws for such phenomena.
(4) To determine the optimal waveform(s) for measuring flow processes with a multi-waveform FMCW radar;
(5) To develop image processing algorithms and micro-Doppler methods to give best quality flow imaging and to resolve individual motions of blocks in the flow;

3. Planned trials
It is planned to trial the radar instrument in the Vallée de la Sionne avalanche test site, Switzerland. Fig. 3 shows a photo of the avalanche-proof bunker at this test site, in which our radar, along with other imaging systems, will be housed and Fig. 4 shows the view from the bunker during the course of an avalanche event.

![Fig. 3. The VDLS bunker.](image)

There are three other instruments in the avalanche track at VDLS that provide velocity measurements. These all work by measuring the correlation time between sensors located at different positions. They are a pair of Frequency-Modulated Continuous-Wave (FMCW) radars, which point vertically and reflect from different layers in the snowpack/flowing snow, opto-electronic sensors, which measure the reflectivity of the snow to infrared radiation and load cells that measure normal and shear stresses. These provide velocity information averaged over fixed regions of a few metres. The high resolution of our instrument means we will be able to derive velocity estimates at the same locations and averaged over similar regions, so we will be able to quantitatively validate its performance. It is this capability to validate our data at a point on the track but then to gain data throughout the avalanche over the entire track, coupled to the ease of artificial release and recovery of instrumentation that means snow avalanches are the best mass movement flow processes to study in this fashion.

![Fig. 4. Artificially-triggered avalanche at the Vallée de la Sionne test site, Switzerland.](image)

Our micro-Doppler analysis will enable relative velocities of individual flow components to be analysed, which will mean that the question of what the instrument is measuring can be resolved and the data can be interpreted for the first time in a physically meaningful way. By relating the flow data to the DEM of the area, we will study the relationship between avalanche velocity, velocity variance and terrain. Any differences in the dynamical behaviour of the head and body of the flowing snow will also be determined. All such data will increase our understanding of avalanche flow dynamics.

Additional scientific questions that then emerge are related to the most appropriate way to model the system based on the field data. It is often presumed in the physics literature that theoretical granular flow research [18] has the potential to explain the behaviour of rapid environmental flows, but this is by no means certain [19]. Velocity profiles for snow avalanches have been interpreted as showing the existence of a thin shear layer at the base of the flow [20] and models have been formulated on the premise that such a layer exhibits collisional behaviour similar to a granular flow [21]. The collection of high resolution flow data will enable us to discern the extent to which the flow behaves as a relatively coherent sliding mass [22], or the extent to which the variance in velocity is significant for the overall flow dynamics (from initiation to cessation). At the 1 m resolution, fluctuations in the velocity should approach those of the flow’s granular temperature and, given the importance of granular temperature in kinetic flow theory [18, 21], our data will be able to determine the validity of such theory for the behaviour of the upper part of the flow. For example, if it acts as a plug, with a low shear rate, then granular flow theory is likely to be less useful for describing the dynamics than if fluctuations in the velocity are large, implying that momentum...
transfer by collisions between blocks is of dynamical significance.

4 Conclusions
Geophysical flows have been of great interest to the scientific community for some time. A variety of flow models have been postulated, but there is currently a lack of high quality field data with which to validate such models. To date, only limited radar imaging has been applied to the field of snow avalanches, in the form of one-dimensional range radars with low range resolution (of the order of 50 m). This work sets out to develop and apply a far more sophisticated radar to this area, operating at 5.3 GHz with a 1 m range resolution, approximately 10 m azimuth resolution, multiple waveform capability and able to form 100 images per second. Such an instrument will provide high-resolution measurement of velocity vectors beneath the snow powder cloud and allow a complete reconstructed animation of events with high temporal resolution. Data merging from the disparate waveforms will also be valuable to resolve Doppler ambiguities and perform micro-Doppler analysis of the data. It is hoped that the instrument will provide a step-change in our observational data in this area of help validate and inform the various flow laws.

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