INNOVATIVE HIGH-SPEED CAMERA ARRAY FOR UNPRECEDENTED INSIGHTS INTO POWDER SNOW AVALANCHES

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ABSTRACT: Powder snow avalanches (PSAs) pose significant threats to human lives and infrastructure in mountain regions. Measuring inside these natural flows is challenging because of their destructive power, which limits our understanding of these events. Previous research revealed a complex layering, characterized by a superposition of three distinct layers. The dense basal layer, where particle-particle interactions are dominant, is situated below two aerial layers: the suspension and transition layer, both of which are particle laden turbulent flows. In contrast to the suspension layer, the transition layer hosts a higher amount of suspended mass and intense clustering processes, resulting in high local density fluctuations. Up to now technological limitations have prevented measurements within the dilute flows, especially the inability to capture turbulence at large scales. This lack of direct observations of dilute layers complicates model development and inhibits accurate predictions of PSAs' destructive impacts.
To address this gap, we developed a non-invasive measurement technique consisting of a high-speed camera array. We installed this array on a vertical structure at the Vallée de la Sionne test site in Switzerland, probing the transition and suspension layers of fully developed PSAs. The new array consists of three high-speed cameras and captures images at mm resolution from 5 m up to 11 m above ground.
On December 2nd, 2023, we measured the first PSA using the new setup. The collected images show individual suspended snow particles inside the transition and suspension layers, revealing complex air-particle dynamics. With image processing algorithms, including particle image velocimetry, we extracted essential flow characteristics such as the vertical velocity profiles.
This research paves the way for understanding the destructive potential of PSAs, but also lays the basis for improving prediction models and mitigation strategies. Additionally, it offers intriguing images from the inside of a PSA.

Keywords: Powder Snow Avalanche, Experimental Avalanche Dynamics, High-Speed Cameras

1. INTRODUCTION

Powder snow avalanches (PSAs) pose a significant threat to populations and infrastructure in alpine environments. To understand the destructive power behind this natural flow, we must understand its inner structure. After many experimental studies on avalanches (McClung and Schaerer, 1985; Norem et al., 1985; Beghin and Olagne, 1991; Schaer and Issler, 2001; Turnbull and McElwaine, 2007; Sovilla et al., 2008), the current state of knowledge on their structure is that it consists of a superposition of three layers (Schaerer and Salway, 1980; Norem et al., 1985; Nishimura et al., 1993; Kawada et al., 1989; Sovilla et al., 2015; Issler et al., 2020), where two aerial components cover a dense layer moving underneath.
Unlike the well-studied dense basal layer (De), the two airborne components of an avalanche have received less attention. Over time, the definition and nomenclature for these two layers have evolved. Initial experiments conducted with load cells showed the existence of two aerial layers which were named the saltation and the suspension layers (Su) (Schaerer and Salway, 1980; Norem et al., 1985; Nishimura et al., 1993; Kawada et al., 1989; Schaer and Issler, 2001). Subsequent experimental measurements led Issler (2003) and Issler et al. (2020) to emphasise the importance of fluidization within the saltation layer, which they subsequently renamed the fluidized layer. Later, Sovilla et al. (2018) identified mesoscale coherent structures within this same layer. These structures were associated with significant fluctuations in pressure, velocity, and density, leading to intermittent processes. Consequently, this layer was renamed the intermittency layer. However, there is still no consensus on this terminology, largely due to a lack of understanding of the underlying physical processes at play. Therefore, in this study, we will use a neutral term and define the intermittency layer as the transition layer (Tr). The final terminology used in this paper is shown in Fig. 1, which includes the layers with their abbreviations.

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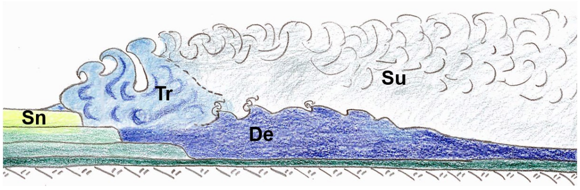

Figure 1: Sketch of a PSA from Sovilla et al. (2015), flowing from the right to the left and entraining material from the snow cover (Sn). The abbreviations correspond to: the transition layer (Tr), the basal dense layer (De), and the suspension layer (Su).

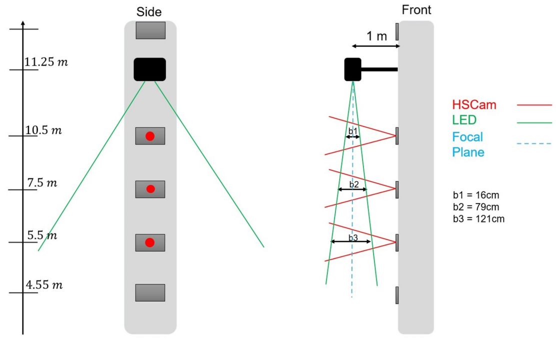

Figure 2: Sketch of the camera arrangement on the 20 m high pylon. Left: Lateral view, with the avalanche approaching from right to left. Red dots indicate the positions of the cameras. Right: Frontal view, looking downhill in the direction of avalanche flow. The red lines represent the cameras' view cones, while the green lines represent the light cone formed by the LED panel (black square).

Despite significant advancements in measurement techniques, only sparse measurements have been conducted within the transition (Tr) and suspension (Su) layers in PSAs. The limited data hinders both the confirmation and further characterization of these layers, as well as the understanding of the complex coupling processes between turbulence and particles. However, as more experimental data from the aerial layers becomes available, new insights are expected to emerge, particularly regarding the relationship between mesoscale coherent structures and turbulence within avalanche flows.

To obtain highly resolved experimental data from the aerial layers, we extended the existing experimental facility at the Vallée de la Sionne test site (VdlS), in Switzerland, by adding an array of high-speed cameras. This new setup allows us to investigate the Tr and Su layers at different elevations and reconstruct their dynamics. We present the first measurements conducted during the 2023-2024 winter season inside a PSA and provide an example of processes and information that can be extracted from them.

2. METHODS

2.1 Camera setup

To explore the transition and suspension layer, we extended the measurement setup at VdlS by installing a vertical array of three high-speed cameras and a LED (light emitting diode) panel as light source on a 20 m high pylon, located at the beginning of the runout zone of large PSAs. The pylon serves as a platform for measuring internal flow parameters, such as temperature, velocity, flow height, density, and impact pressure, with most measurements taken below 6 m in height. The camera array extends these measurements up to 11 m. To maximize vertical coverage and minimize information gaps between the cameras, they were positioned at 5.5 m, 7.5 m and 10.5 m above ground (Fig. 2). The focal plane of the cameras was set in the middle of the light cone to enhance the visibility of the snow particles in the images.

The cameras' resolution is adjustable from 800 x 600 px^2 (SVGA resolution) to 1920 x 1080 px^2 (HD resolution) with corresponding maximum frame rates ranging from 1800 to 1000 FPS (frames per second). To maintain both high resolution and frame rate, we set the camera to HD resolution with a frame rate of 1000 FPS. We used Zeiss Dimension lenses with a 12 mm focal length and an f/2 aperture.

To ensure the cameras withstand the harsh winter weather conditions and protect them from the destructive forces of avalanches, we installed the cameras inside the pylon. Holes were drilled into the hatches' lids and filled with reinforced glass to protect the lenses and cameras. To prevent damage from condensed water drops falling onto the cameras, we designed a 3D printed cover and mounted a small PC vent on its rear end. This vent blows excess heat from the back of the camera to the front, helping to keep the reinforced glass defrosted and preventing the lenses from fogging up. Figure 3 shows how the cameras are protected while the lenses peek out from the 3D printed cover.

A server located in a cavern next to the pylon handles camera settings, image acquisition, and data flow management. Each camera has its own dedicated network card to ensure smooth data transfer onto the servers' storage. Acquiring images at 1000 FPS, HD resolution and over a period of 240 s leads to almost 2 TB of image data for each avalanche. After an avalanche event, the images are transferred via fiber optic cable to a NAS device (Network Attached Storage) located in a reinforced building at the bottom of the slope.

2.2 Data processing: Particle Image Velocimetry (PIV)

A major objective of our measurements is to extract the velocity within the aerial layer of the PSA. The images we collect allow us to distinguish individual snow particles as well as particle clusters as shown in Fig. 4.

Figure 3: Picture of the camera in its position inside the pylon during assembly. The camera shown is protected by a 3D-printed cover.

To achieve this, we performed Particle Image Velocimetry (PIV). Images with a resolution of 1920 x 1080 px^2 are divided into interrogation windows of 32 x 32 px^2, resulting in a grid of 120 x 66 windows per image. Subsequently, we analyze the displacement of particles between consecutive images using cross-correlation. Knowing the frame rate of the image series, the displacement vectors are then converted into velocity vectors. This process is repeated for each time step, allowing us to generate a complete set of velocity fields for the entire sequence of images.

3. AVALANCHE DESCRIPTION AND RAW DATA

Avalanche # 20243024 naturally released on December 2nd, 2023, at 5:20 AM. This avalanche displayed the characteristics of a fully developed PSA in the upper part of the track but transitioned into a wet flow at lower altitudes due to rising snow cover temperatures along the slope. It began its deceleration phase 200 meters above the pylon, and by the time it reached the pylon, the aerial components were already in a decaying phase. The dense, wet flow eventually reached the bottom of the valley. This was the first avalanche captured by the new camera array. Figure 4 provides an example of the images we were able to capture. Additionally, in Fig. 5, we stitched together several images to create a panoramic view of the snow-ice particles in motion over a time window of 230 ms.

Figures 4 and 5 are unprocessed images, made possible by the camera positioned closest to the light source, located at the top. For the other two cameras, the image data must be preprocessed to enhance contrast.

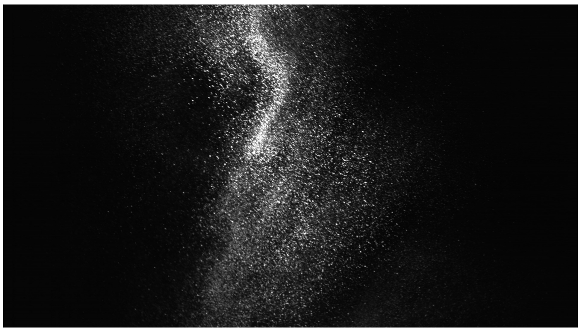

Figure 4: Raw image sample from avalanche #20243024, captured on December 2nd, 2023. The image was taken within the Tr layer, highlighting both individual particles and a larger particle cluster spanning the full vertical dimension of 1 meter.

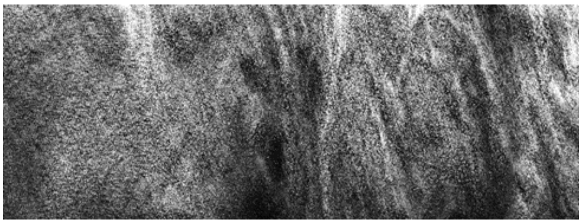

Figure 5: Stitched image of central strips from 230 individual images, covering a time window of 230 ms. The spatial dimensions are approximately 3m x 1m.

4. RESULTS & DISCUSSION

4.1 Particle distribution and clustering

Figure 4 shows both individual snow particles and their agglomeration or clustering. Here, the material is concentrated in the centre of the images due to the positioning of the light source, directly above the camera. The light beam's intensity peaks at the centre of the light cone, which is why the analysis will focus on this central region of the images.

To better visualize clustering processes, we stitched together the central strips of 230 consecutive images into a panoramic view, as shown in Fig. 5, covering a surface of approximately 3m x 1m. Moving from left to right across the image, which follows the chronological sequence, we initially observe a homogeneously distributed particle field. Following this, areas with higher particle concentration become evident in the upper section of the image. As we progress, local voids precede vertical clusters and the panoramic picture ends with denser structures.

Although this panoramic view captures only a quarter of a second within the Tr layer, it reveals the intermittent behavior in particle concentration and, consequently, in density. It also gives a sense of how dynamic the processes within this layer are.

4.2 Velocity profile

Starting with the PIV's velocity field, we focused on the central region, as previously discussed. This central velocity field consists of 20 x 66 (horizontal x vertical) velocity vectors, covering 320 x 1080 px^2 or 0.25 x 0.9 m^2. First, we binned the central velocity field into 20 vertical bins and spatially averaged the corresponding velocity vectors within each bin into a single velocity vector. This resulted in a vertical velocity profile containing 20 velocity points. In the second step, we calculated the spatially averaged velocity profiles over two 30 ms time windows at different positions within the avalanche. For each window, roughly 30 velocity profiles from all three cameras were calculated and then temporally averaged into the profiles shown in Fig. 6.

The blue graph represents the spatio-temporally averaged velocity profile taken 3 seconds after the passage of the avalanche front, in an area characterized by large particle transport and clustering, similar to what is shown in Fig. 4 and the right half of Fig. 5. The red graph represents the spatio-temporally averaged velocity profile of a more homogeneous section, with less variation in concentration, at a later stage of the avalanche, similar to the very left part of Fig. 5, taken 30 seconds after the blue profile. Circles indicate the averaged velocities, while the error bars represent the standard deviation. Overall, velocities are low for a well developed PSA aerial layer in both profiles, reinforcing the observation that the avalanche is in its deceleration phase. The blue profile exhibits a higher mean velocity across the entire height compared to the red profile. Notably, the mean velocity is nearly three times greater in the two lower sections, while in the highest section it is only slightly higher. Additionally, the blue profile shows a larger standard deviation, indicating significant variability in the velocity measurements, whereas in the red profile, fluctuations in velocity are small.

The large standard deviations in the blue profile are caused by significant velocity fluctuations, likely associated with the presence of many particles moving at different velocities, which is a characteristic typically observed in the transition (Tr) layer as shown by (Sovilla et al., 2018). In contrast, the absence of large standard deviations in the red profile indicates a more homogeneous suspension, as expected in the Su layer. Based on this observation, we propose using the standard deviation of velocity as a criterion to define the boundary between the Tr and Su layers. According to this criterion, Fig. 6 suggests that the lower two sections of the blue velocity profile likely correspond to the passage of the Tr layer, while the upper section is part of the Su layer.

5. CONCLUSION

This study provided the first highly resolved experimental observations within the transition (Tr) and suspension (Su) layers of a powder snow avalanche

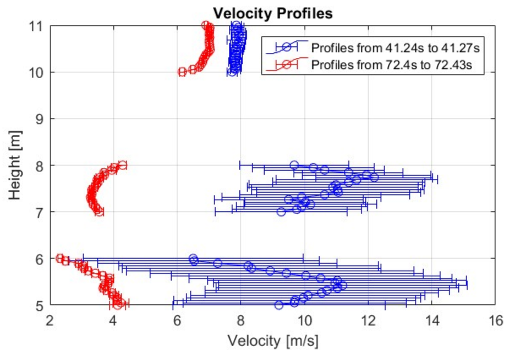

Figure 6: Velocity profiles at two different time windows, extracted from images captured by three high-speed cameras. The first time window, from 41.24 s to 41.27 s, is shown in blue; the second time window, from 72.4 s to 72.43 s, is shown in red. Circles denote the mean velocity, averaged over a 30 ms period, with error bars indicating the standard deviation within the same period. Since the measurements do not cover the entire avalanche depth, the velocity profiles are discontinuous.

using a high-speed camera array at the Vallée de la Sionne test site.

The spatio-temporally averaged velocity profiles revealed distinct differences between the Tr and Su layers. The Tr layer was characterized by significant particle transport and the presence of particle clusters, along with higher mean velocities compared to the suspension layer and notable velocity fluctuations throughout its height. In contrast, the Su layer displayed more homogeneous behavior with minimal fluctuations. These findings suggest that velocity fluctuations could serve as a criterion for distinguishing between the Tr and Su layers.

Although significant velocity fluctuations were observed in the Tr layer, likely due to particles and particle clusters moving at varying velocities, the underlying processes driving these movements remain unclear. However, the observed combination of high variability in particle concentration and higher velocity strongly suggests that these dynamics play a crucial role in the behavior of the Tr layer.

In conclusion, further research is needed to better understand the origin of these fluctuations and the interplay between turbulence and particle clustering. Future work will focus on refining camera settings and extending the analysis to additional avalanche events to enhance our understanding of these complex processes. This, in turn, will improve our ability to model and predict PSA behavior, contributing to better hazard assessment and mitigation strategies in avalanche-prone regions.

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