NEW INSIGHTS OF MECHANICAL SNOWPACK PROPERTIES MEASURED BY ACOUSTIC AND SEISMIC DISTRIBUTED FIBER OPTIC SENSING

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ABSTRACT: Since 2012 we successfully monitor avalanche activity using distributed seismic fiber optic sensing at our avalanche test area at Lech am Arlberg, Austria. We now focused on measuring mechanical snow pack properties utilizing a unique measurement set-up, where a fiber optic cable was inserted in a weak layer, near the snow surface and at the ground/snow interface. For the first time it was possible to measure and analyze the collapse of a weak layer in an avalanche release area. On February 14th we inserted the fiber optic cable within the snow pack and after a major snowfall a slab was formed and the weak layer collapsed on February 17th in the middle of the night with consecutive two small avalanche events happening. We could measure the collapse of the weak layer on a section of 250 m along the cable with a speed between 25 and 100 m/s corresponding to values found in literature. As the fiber optic cable was located close to the snow surface we were also able to measure strong winds affecting the snow surface and we see that early in the morning of February 17th strong gusts most likely triggered mechanically small avalanches. Furthermore we are able to locate strong wind patterns such as turbulence and linear wind flows along a length of 300 m along the cable and the data of the whole winter season correlated with wind speed and direction data that is available on site leads us to question current snow drift models and we indicate possible improvements that can be made using our data. Finally we are also able to see skiers moving along our cable and we are able to analyze their behavior in regard of avalanche safety measures. We can see at what time and how many and most importantly in what distance to each other those skiers crossed the avalanche prone slope. In a time of unstable snow pack stability conditions we conclude that not all skiers follow the recommended safety rules and our data is very useful for analyzing different mechanical snow pack properties and processes.

KEYWORDS: distributed seismic sensing, fiber optic, weak layer collapse, mechanical properties.

1. INTRODUCTION

In 2012 we started to develop a fully automated weather-independent, multi path avalanche monitoring and detection system using distributed fiber optic acoustic and seismic sensing (DAS) and presented our successful installation and warning tool at ISSW 2013 and 2014 (Prokop et al., 2013 and 2014). The method is based on an optical time (or Frequency) Domain Reflectometry (OTDR) (Nikles 2007), which dates back to the 1970‘s and detects seismic vibrations and acoustic signals on a fiber optic cable that can have a length of up to 30 km. Optical Time Domain Reflectometry first was used for fault detection in optical fibers and this technique was presented by Barnoski et al. (1976). The introduction of Distributed Fibre-Optic Sensing (DFOS) systems in geophysics represented a significant milestone in the development of geophysical measurement methods (Paitz et al., 2023). Compared with many conventional avalanche monitoring methods, which often have limitations in terms of spatial resolution, measurement coverage and line of sight, DAS offers numerous advantages. Detection and monitoring can be carried out regardless of weather conditions (Edme et al., 2023; Prokop et al., 2024). Furthermore, avalanche activity can be used as an indicator of snowpack stability (Prokop et al., 2024). Recent studies show that distributed acoustic sensing based on fibre-optic cables can be used to detect seismic and acoustic signals over long distances (Prokop et al., 2024; Prokop et al., 2013). In practical terms, this form of avalanche monitoring enables measures such as evacuations and the temporary closure of transport routes and infrastructure to be implemented. The high costs for a DAS interrogator device precluded a wider application of our system for avalanche detection in the past. Fortunately in recent years the costs decreased significantly and DAS is used as an avalanche monitoring and detection system operational e.g. along roads (Turquet et al, 2024).

Other than for avalanche monitoring purpose, where the fiber optic cable is deployed underground or between the ground and the snow pack, in this study we inserted a fiber optic cable into the snow pack in close vicinity of a weak layer

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https://doi.org/10.15788/1790098479

to be able to gain information about mechanical properties of the snowpack in a rather scientific approach. Recent studies tried to model the speed of the collapse of a weak layer in an indirect approach using e.g. image processing (Trottet et al., 2022; Bergfeld et al. 2021), we attempted here to directly measure the speed of crack propagation and other mechanical snow pack properties such as wind induced snow drift processes.

2. METHODOLOGY

2.1 Installation

During the 2026 winter season, a DAS system has been installed for measuring snow-avalanches and other related phenomena occurring at our snow and avalanche research test site in Lech am Arlberg (Austria). The associated Fiber Optic (FO) cable has been deployed for 600 meters from the DAS interrogator, a model Febus A1-R (Figure 1). The FO cable was trenched 20 cm underground in the first 300 meters and, then, inserted in the shallow snowpack in the vicinity to a weak layer. The FO cable was running mostly at the same altitude, to make an iso-topography-cal installation and maximize the gain in physical/geometrical information about avalanches (e.g. frontal dimension, duration).

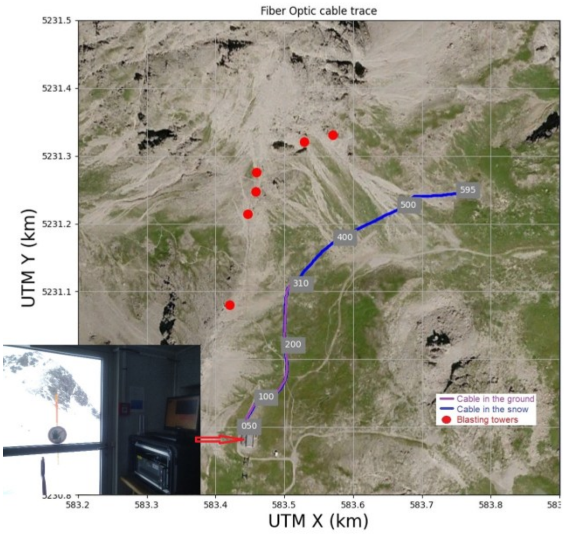

Figure 1: Geometry of the Fiber optic (FO) cable used in the experiment. Purple line: deployment of the FO cable in the ground, blue line deployment of the FO cable in snow (as seen in Fig.2). Numbers indicate the distance (m) along the FO cable. Red dots show the position of the bombing turret for triggering snow-avalanches. Small picture of the instrumentation inside the top lift station.

Figure 2: Geometry of the Fiber optic (FO) cable in the field: Right: deployment of the FO cable in the ground; Left: deployment of the FO cable in snow.

During winter 2026 snow pack conditions remained unstable, remote triggering was possible for a long time, so perfect conditions for an attempt to measure the collapse of a weak layer. As a major snow fall with wind was forecasted that most likely will form a slab, we inserted the fiber optic cable within the snow pack on February 14th, 2026 (Fig.2. left image).

2.2 Data processing

DAS acquisition parameters included 8 meters of Gauge Length, re-sampled 8 times (i.e. DAS channel spacing is 1 meter). Strain-rate data are acquired with 500 samples per seconds. Pulse Width was set as large as 2 meters (about 10 nanoseconds). Data was visualized in a waterfall diagram every minute and the image created is send to the end-user via WLAN connection.

3. RESULTS

3.1 Weak layer collapse and consecutive avalanche events

During the night of February 17th, 2026, we observed a natural collapse of the weak layer in the fresh snowpack (Figure 3) directly on-top of the FO cable. The collapse (called Event A in Figure 3) was associated to a number of related phenomena: few precursory seismic events occurred in the snow pack exactly where the collapse started (Event B), two small snow-avalanches following the collapse (Snow avalanches 1 and 2) and few seismic events in the snow avalanche coda (Event C). Looking to the spectral content of each event, we recognized that each class of events has its own frequency characterization: very low- frequency for the weak layer collapse:

1-5 Hz (Figure 4), high frequency content for the seismic events in the snow pack: 10-200 Hz (Figures 5 and 6), and intermediate frequency band for the snow-avalanches: 10-40 Hz (Figure 7). Those frequency bands have been used to filter out the raw signals and to retain the general features of the class of events. After filtering, signals have been visually inspected and their on-set times have been defined, channel by channel, using the Obspy picker which implements Baer's approach (Baer and Kradolfer, 1987; Krischer et al., 2015). Assuming a quasi-linear geometry of the FO cable, the on-set time data have been linear interpolated to estimate the approximate speed of propagation of the collapse in the snow pack (Event A) and the seismic velocity of the propagation of seismic waves in the snowpack for the seismic events (Events B and C). Filtered signals have also been used to define the duration and frontal extension of the two snow-avalanches from visual inspection.

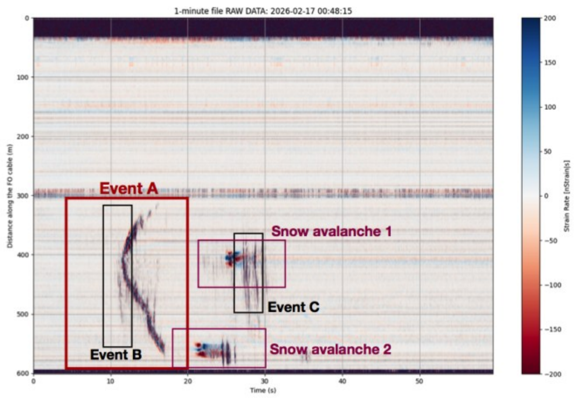

Figure 3: Waterfall view of the raw Strain-rate data from the DAS system. Data batches are 1-minute long. Starting time is written on top of the graph. Colors indicate Strain-rate value. Distance along the cable is represented in the y-axis, while time form the beginning of the file is represented on the x-axis. The colored boxes show the main signals (all occurred in the 300-to-600 meters section of the cable that was inserted into the snowpack, lower portion of the waterfall view). Event A is the targeted "Weak layer collapse". Event B is a precursory seismic event occurred in the snow pack few seconds ahead of the collapse. Event C are seismic events occurring in the coda of the Snow Avalanches. The two small snow-avalanches occurred at the end of the collapse are marked.

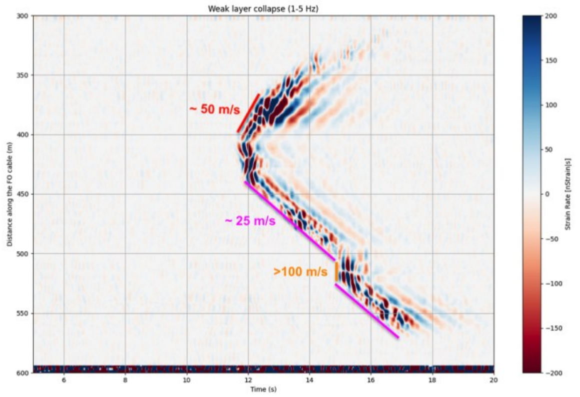

Figure 4: Weak layer collapse as measured in the low-frequency portion of the signal spectra. Raw data are filtered between 1 and 5 Hz, to remove all high frequency details and to measure the speed of propagation of the collapse, indicated in the figure with different colored lines. Collapse propagation occurs at variable speed between 25 and 50 m/s, with few spot where propagation is sub-sonic (higher than 100 m/s).

The propagation of the weak layer along the FO cable presents a complex time history. We observe that the collapse, started around X=400 m along the FO cable and propagated in both direction with different speed, and changing the propagation speed during the collapse. Based on our observations, we can approximately identify three main classes for the speed of propagation of the collapse: around 25 m/s (violet lines in Figure 4), around 50 m/s (red line in figure 4) and more than 100 m/s (dark yellow lines in Figure 4). Starting from X=400 m along the FO cable, and going backward toward the DAS interrogator, the weak layer collapse propagated for about 30 meters at about 50 m/s, before slowing to about 25 for the next 50 meters, and then stopping. Conversely, in the opposite direction, the weak layer collapse propagated at more than 100 m/s for the first 40 meters, before slowing down to 25 m/s till reaching X=510 m along the FO cable. At that point, the speed of the collapse increased dramatically to more than 100 m/s for the next 20 meters, before going back to the previous speed of about 25 m/s till reaching X=560 m along the FO cable.

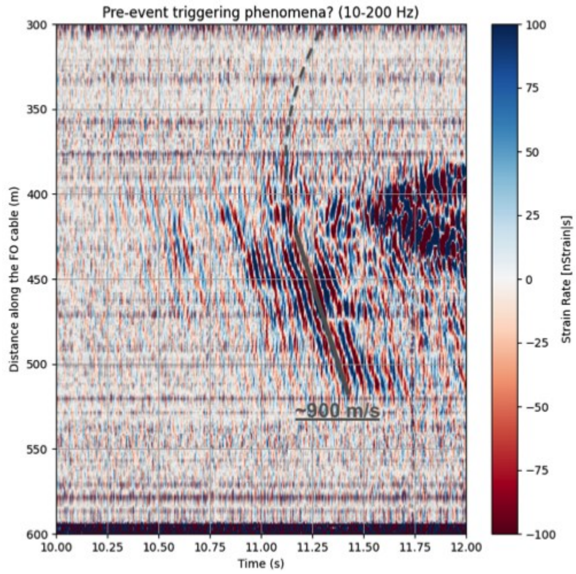

Figure 5: Pre-signal seismic event measured in the snowpack few instants before the start of the collapse. Seismic waves are clearly visible on one side of the propagation parabola (grey line). Seismic velocity is around 500 m/s. On the opposite side of the parabola, the seismic signal is not clearly visible (dashed line).

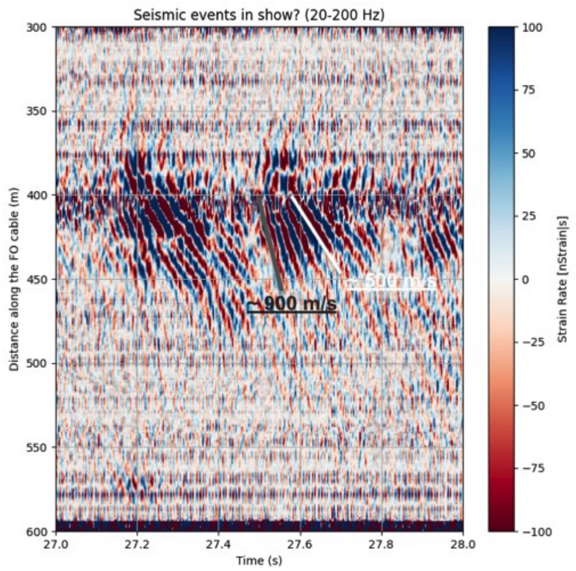

Figure 6: Example of seismic events occurring in the coda of the snow-avalanche. Pressure and shear waves propagate in the snow-pack during the "snow avalanche 1". Measured velocity are comparable with P- and S- wave velocity in fresh snowpack.

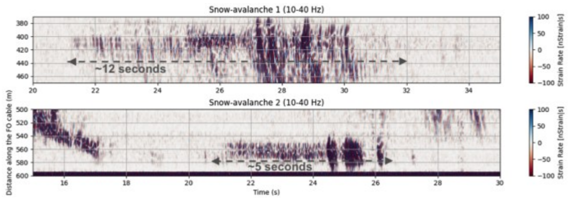

Figure 7: Snow avalanches occurring after the weak layer collapse. From DAS data, we can measure the duration of the snow-avalanche and its frontal width (because the cable is isotopographically installed). Assuming 10-20 m/s of velocity of the snow avalanche, Snow avalanche 1, with a duration of about 12 seconds, should have moved 100-200 meters from the cable. The Snow avalanche 2 should have been 50-60 meter long. The width is in both case limited to 20-40 meters.

The avalanche events have been validated by an alternative independent measurement method; an avalanche detection radar system (https://www.avalancheradar.com/, Koschuch et al., 2015) surveys the same avalanche prone slope (Fig. 8).

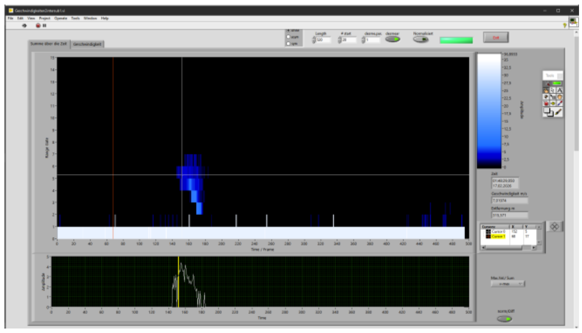

Figure 8: The avalanche radar detected the avalanche events at night February 17th, 2026 at the same time and similar in size, due to the large range gate of the radar, the 2 small avalanche events were recorded as a single avalanche.

3.2 Wind influence and snow drift

When strong wind gusts influenced the snow pack and the FO cable was buried close to the snow surface, not deeper than 0.5 meters we were able to track the mechanical influence of wind onto the snow pack and consecutive avalanche events. Along the cable length of 300 m we could measure the spatial distribution of wind affecting the snow surface. In early morning of February 17th, 2026 several small avalanche events happened most likely induced by strong wind gusts (Fig. 9,10, and 11)

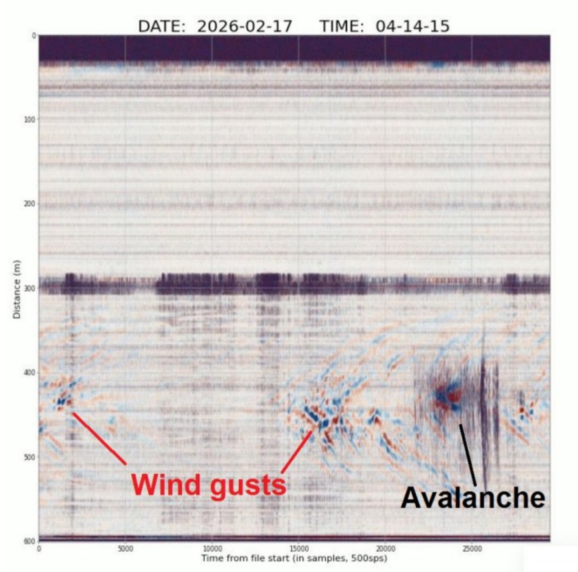

Figure 9: Waterfall diagram showing strong wind gusts affecting the snow pack right before an avalanche event occurred. Wind gusts are confirmed by a wind anemometer installed at 300 m cable length, avalanche event by radar detection.

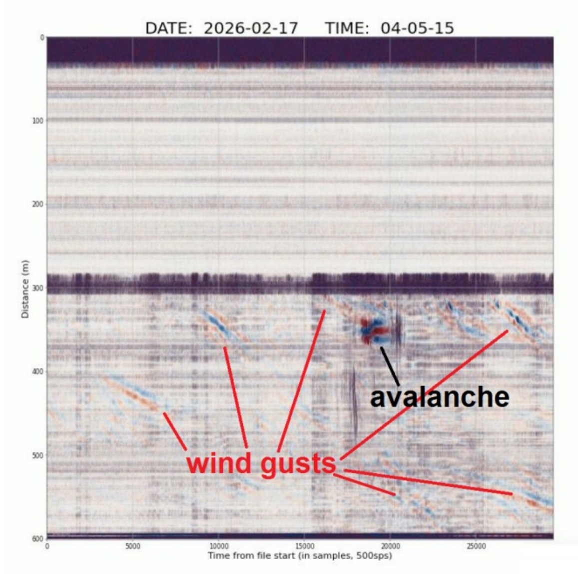

Figure 10: Waterfall diagram showing wind gusts most likely releasing a cornice fall avalanche. The DAS signature of the avalanche is related to a cornice fall.

It is important to note, that in figure 10,11, and 12 wind gusts occur dominantly in the area where the avalanche was released, the avalanche events occur within 10 minutes and happen in close vicinity to each other. All having strong gusts right before and exactly at the same location where the avalanches released.

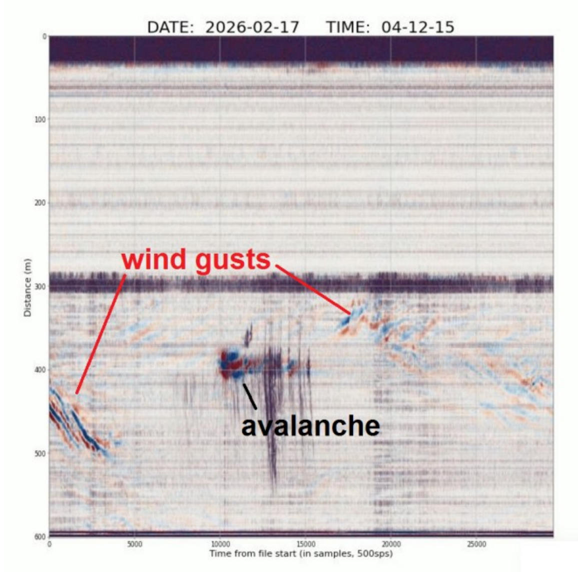

Figure 11: Waterfall diagram showing another avalanche event most likely induced by a very strong wind gust (left side). The intensity of this gust is the strongest of all 3 examples (Fig.9, 10, and 11).

Moreover we were able to locate strong wind patterns such as turbulence and linear wind flows along a length of 300 m along the cable (compare wind gusts fig. 11 on the left linear wind flow and on the right turbulent flow). The inhomogeneous character of the data within a scale of 300 m and in short time frequencies leads us to question current snow drift models, where rather continuous wind flow is assumed (Schneiderbauer and Prokop (2014), Aksamit et al. 2025) . Even though those are simplification of the models we think it's worth diving into the data presented and review such models.

3.3 *Skiers influence*

Additionally we like to stress here that of course the influence of skiers or snow boarders onto the snow pack can be measured as well. We analyzed this already in 2013 (Wirbel 2013), however with the installation in the winter season 2026 a larger data set was collected. This allows for analyzing interesting research questions regarding the mechanical influence of skiers penetrating the snow pack as well as their behavior in regard of avalanche safety.

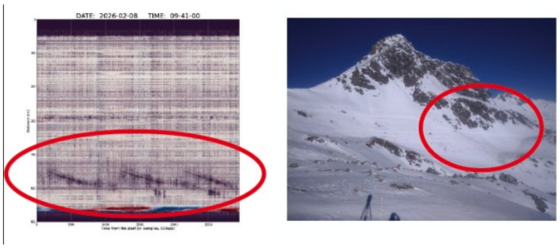

Figure 12: 4 skiers passing above and along the FO cable right image; left: signature of the skiers in the DAS data.

4. CONCLUSIONS

As far as we know, we presented here the first direct observation of the speed of a weak layer collapse at full slope-scale resulting in an avalanche event. Thanks to the dense spatial and temporal sampling of the DAS data, we were able to directly follow the weak layer collapse with unprecedented resolution. A unique installation of the fiber optic cable in the vicinity of a weak layer made the investigation possible. Previous measurements of crack and collapse speed have been obtained using indirect measurements from complex image processing and making specific assumptions (e.g. Trottet et al. 2022). Our measurements are direct measurements in the snowpack, which is less prone to bias given by the image processing and user-defined assumptions. As described in Trottet et al. (2022), the weak layer collapse can have both sub-Rayleigh and super-shear velocity, depending on the direction of propagation with respect to the topography. Our direct measurements confirm such behavior, showing that the weak layer collapse can reach super-shear velocity in some cases. In particular, it is interesting to notice that the super-shear velocity at X=510 m along the FO cable occurred where the cable is not deployed cross-slope, but has a small turn uphill, for 20 meters, exactly in agreement with the previous studies.

Moreover, for the first time we could measure the mechanical impact of wind gusts onto the snow pack which most likely triggered avalanches at the same location. We could follow wind gusts along the 300 m cable length and measured their geometry in time. The data leads to several research questions we like to address in the future; the data can improve existing physical snow drift models.

ACKNOWLEDGEMENTS

We thank Lech Bergbahnen AG for their logistical support and IPTP Koschuch e.U. for providing radar validation data. This research was partially supported by the TESI research line of the Earth Telescope Programme, under the ROSE infrastructural project of INGV (OB.FU.: 1215.010), funded by the Italian Ministry of University and Research. NPA thanks Gilberto Saccorotti and Giulio Selvaggi for their continuous and active support to his DAS studies.

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