# Acoustic Emission Analysis of Snow

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**Kurzfassung:** Kontinuierliches Überwachen von Bruchvorgängen innerhalb der Schneedecke mit Hilfe der Schallemissionasanalyse (SEA) liefert Einblicke in die mikroskopischen Vorgänge, die vor einem Lawinenabgang geschehen. Zu diesem Zweck wurden Experimente im Kältelabor mit einem SEA-System und einem Scherapparat durchgeführt. Es konnte gezeigt werden, dass die Signale typischerweise in einem Band um 30 kHz liegen. Weiters zeigten dreidimensionale Lokalisierungsexperimente, dass die Schwachschicht innerhalb geschichteter Schneeproben der bevorzugte Ursprung von SE-Events ist..

## 1. Introduction

Avalanches are a considerable natural hazard in mountain regions, and therefore an adequate avalanche warning service is of great importance to save lives and reduce economical losses. There are various classifications of avalanches [1], mainly depending on snow conditions and fracture mechanics. In this article, emphasis is placed on the fracture mechanical processes leading to natural dry-snow slab avalanches. These avalanches occur in dry snow (contrary to wet-snow) and involve the release of a cohesive slab (contrary to loose snow) by shear failure in a weak layer below. The term "natural" refers to the fact that no artificial triggering (e.g. skiers, explosives) is required prior to avalanche release. Hence, natural avalanches occur due to natural effects like gradual uniform loading (precipitation) or meteorological changes [2].

The initial process leading to natural avalanches, i.e. the crack initiation without any external triggering, is still not fully understood. It is believed that snow-failure processes at the micro scale ($10^{-4}$ m), also called "bond breaks" occur in extremely weak zones. If they reach a significant size, they may be able to be self propagating. Thus, it is of big interest to monitor the processes inside the snowpack which lead to natural dry-snow slab avalanches in order to monitor and distinguish precursor events prior to avalanche release in order to improves avalanche warning systems. For visible processes, this monitoring is possible by detection devices such as seismometers, radar, light beam and trip wires [3] which partly are in practical use. Obviously, only already released avalanches are reported and no further information about the avalanche is provided. On the other hand, snow mechanical tests like the classical Rutschblock test (RB) or more recent methods like for example the

Propagation Saw Test (PST) provide more informations about the snowpack before a possible avalanche release[1]. Unfortunately, great human dedication is needed, and the demand for continuous monitoring cannot be satisfied.

Acoustic emission testing (AET) might fulfill the requirements of continuous snowpack monitoring at every scale: Figure 1 depicts the acoustic emissions of snow and the required instrumentation depending on the size of the failure (adapted from [2]).). Small failures produce low amplitude emissions with high frequency. The larger the failure, the higher the amplitude and the lower the frequency. Any dry-snow slab avalanche release follows three main process steps: Starting with an initial failure (micro-scale) a crack inside the snowpack is introduced which, at favorable conditions, may propagate (meso-scale) and reach a size big enough to cause a snow slab to glide off (macro-scale).

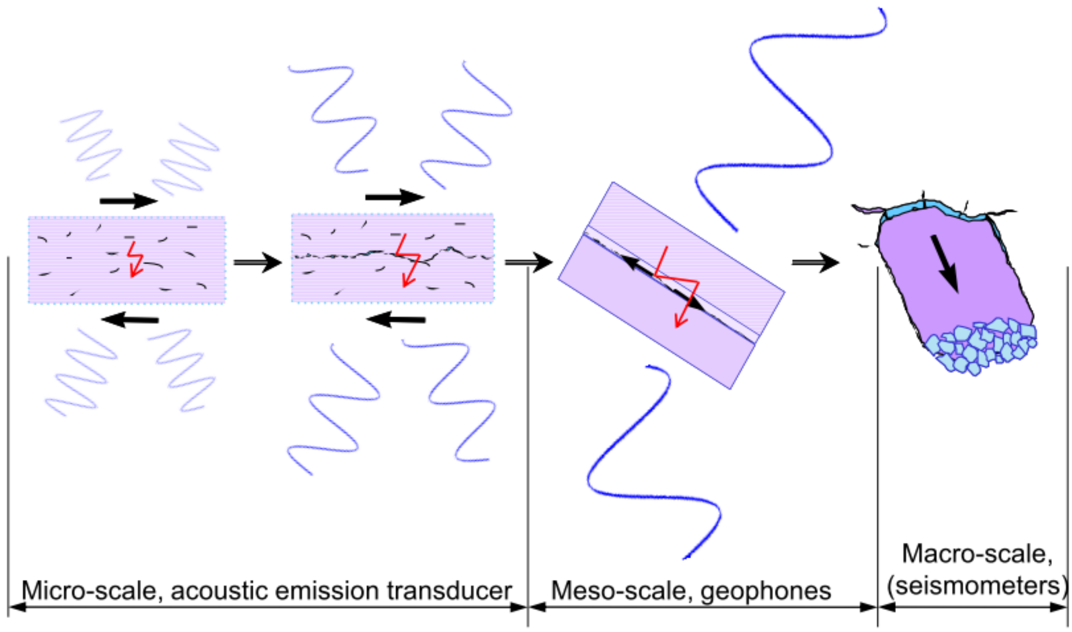


Figure 1: Acoustic emission signals caused by of propagating snow cracks, in the micro-, meso- and macro-scale (adapted from [2]).

## 2. Material Characteristics of Snow

### *2.1 Mechanical Properties*

Obviously, snow is not a persistent material. Once fallen on the ground, it starts a metamorphosis all the way until its melting. Even in well controlled environments in terms of temperature and humidity, like a cold laboratory, metamorphosis takes place. Investigating the snow as a material thus requires knowledge of at least the most important mechanical properties of snow. Parameters like grain shape, grain size, density, hardness, and snow temperature can be used to characterize snow samples. As widely agreed, the release of dry snow slab avalanches requires the existence of a snow slab which is located above a weak snow layer. Most slabs consist of cohesive wind-deposited or well-bounded old snow and have hardnesses in the range of very low to high [1]. Dry-snow slab release starts with a fracture in the weak layer, which propagates in basal direction inside the weak layer and causes a whole block to be cut out of the snow. The hardness of the weak layer is nearly always very low.

Snow is a viscoelastic material. Whether snow shows ductile or brittle behavior depends on the load. Many laboratory experiments have shown that this load-rate determines the mechanical behaviour [3]. Loading snow at a small rate results in a nonlinear viscous behavior. At high rates brittle failure occurs, i.e. the elastic properties dominate.

Well consolidated snow shows so-called strain softening, which means that the stress level decreases after a certain amount of displacement, either until fracture occurs, or the stress level reaches a residual stress [3]. For viscoelastic materials, the fraction behavior can be related to the type of strain. Volumetric strain causes brittle failure, distortion strain causes ductile failure.

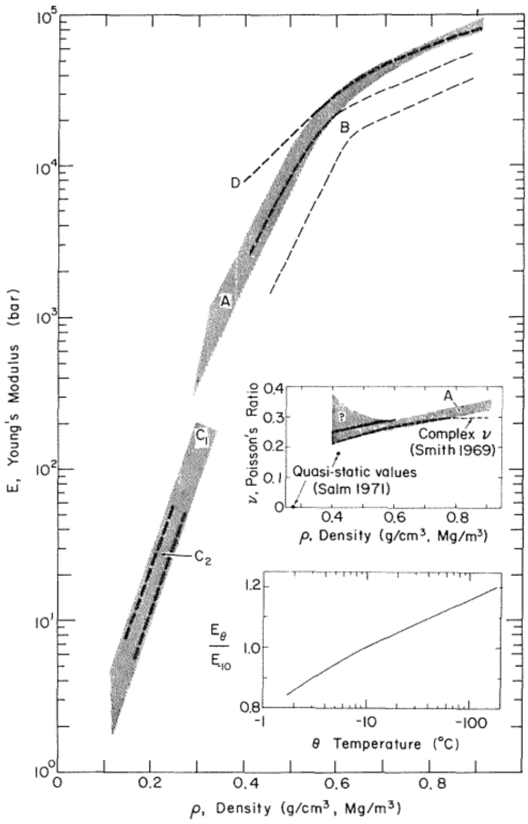


Figure 2: Young's modulus for dry coherent snow [4]. Great spreading can be examined depending on different measurement techniques and parameters

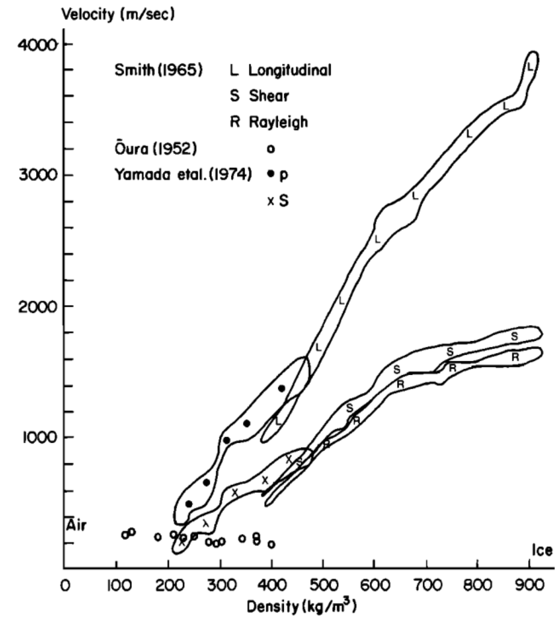


Figure 3: Sound velocity depending on the snow density [6].

*2.2 Wave propagation in snow*

The speed of sound waves in snow can be calculated analytically. Unfortunately, snow shows a variance in Young's modulus depending on the measurement method and the snow's properties (density, texture, etc.) of five orders of magnitude [4]. This fact is illustrated in Figure 2. Additionally, there are actually two media responsible for wave propagation in snow, the ice structure and the air between [Sommerfeld1982]. Especially for low snow densities, analytical and experimental determination of wave speeds becomes quite complex. There is also a lack of data on low-density snow in literature.

Concerning wave propagation in snow, snow microstructure has significant influence [5].

The microstructure of snow refers to the configuration of the ice and the air spaces and cannot be reduced to a single parameter. It is given by a set of parameters, including for example density, porosity, or specific area. Thus, microstructure together with grain shape and size describes the so-called micro scale.

One way of determining the wave speed is direct measurement by recording the arrival time of a known input signal. In fact, acoustic emission techniques have been used successfully use to determine Young's modulus and Poisson's ratio. In [6], the summary of three sound velocity measurements depending on the snow density form different authors is presented (compare Figure 3).

For the measurement of sound speed in snow, snow can be either treated as porous media consisting of a rigid ice skeleton or as a continuous elastic or inelastic medium. Both of these approaches do not adequately explain observed wave propagation phenomena in snow [7]. Treating snow as a poroelastic material (porous media, consisting of an elastic, fluid saturated skeleton) seems to be the best way to model wave propagation in snow.

The theory on wave propagation in poroelastic materials (e.g. water or oil saturated rocks, soil, tissues, foams), is known as Biot's theory. This model predicts a fast (first kind) and a slow (second kind) dilatational wave as well as a shear wave. The first dilatational wave and the shear wave both correspond to measured values in the experiments where the motions of the ice framework were measured. It seems that these two waves travel through the ice skeleton. Interestingly, the slow dilatational wave of the second kind seems to travel through the air pores. Predicted speed of the slow wave and measured speed in experiments where air borne sound is sent through snow samples [8],[9] correspond well. Obviously, an elastic wave caused by an acoustic emission event always excites the ice framework and is detected on the ice framework as well. Therefore, the presence of dilatational waves of the second kind is assumed to be negligible in this present research on acoustic emissions. Recent experiments on acoustic emissions of snow [10] prove this assumption.

## 3. Acoustic emission in snow

Figure 1 depicts the phenomenon of acoustic emissions in snow. Every failure event inside a snowpack produces elastic waves. Their frequency and amplitude characteristics depend strongly on the size of failure. While small events produce high-frequency waves (small wavelength) with low amplitudes, amplitude and wavelength increase with increasing failure size [11]. This fact is important for choosing the right instrumentation. The idea of using acoustic emission techniques in snow to assess snowpack stability actually had its pioneers in the 1970s. In laboratory experiments, [12] reported acoustic emissions recorded with geophones in the audio spectrum (20-7000 Hz) originating from snow samples under uniaxial compression. Acoustic emissions were associated with rates of deformation corresponding to brittle fracture of the snow sample. The existence of the Kaiser effect in snow, which means that in loading cycles there is no AE activity before reaching the previous loading level, was reported from [13]. Emphasis was placed on the frequency region between 50 and 100 kHz. An acoustic emission response model as function of stress and strain was developed by [12].

Problems in determining fracture properties arise from their strong dependence on the type of snow and strain or stress history [14],[4]. This history defines the current condition of the snowpack. Besides the current condition, the actual rate of loading and deformation is a highly crucial factor determining the possibility of catastrophic failure [1], [15]. Loading at small rates gives the snow time to heal itself, i.e. bond breaks are compensated by resintering processes at the same time, which results in plastic behaviour. [14] also attribute lack of acoustic emission activity to this phenomenon. At a certain loading rate, the number of damage processes exceed the number of healing processes and a residual stress arises and stays in the snowpack [16],[2]. Its exact location, magnitude and persistence cannot be reconstructed exactly, which in fact closes the circle to the unknown snowpack history.

Detecting and recording ultrasonic acoustic emissions in snow is more challenging compared to seismic signals mainly because of their low amplitudes. With its wide range of characteristics, snow is not an easy material to treat in terms of wave propagation. Snow shows high and frequency-depended damping, and how elastic waves (structure born sound) exactly travel inside a snowpack is difficult to determine [6]. In addition, as far as a natural snowpack is concerned, it always consists of various layers with different properties, i.e. snow is not a homogeneous medium [2],[19]. For the high-frequency elastic waves this means that there are boundaries all over the place which cause reflection, diffraction and artefacts in the signals. In order to work around these problems, the present work is based on research regarding ultrasonic emissions from snow in the cold laboratory at the Institute of Snow and Avalanche Research SLF. Laboratory work ensures constant conditions, both as far as the environment as well as the snow samples are concerned.

In terms of failure mechanisms, it seems quite certain that a major failure leading to avalanche release is associated with brittle failure. Recent laboratory measurements by [20] also indicate this relationship. It is reported that brittle failure is characterized by low-frequency acoustic emissions, produced by large crack formation originating in material flaws. Spectral analysis of acoustic emission waves with various sensors showed that AE signals show energy in a wide frequency range, depending on the type of failure. Peak frequencies of 500 kHz were observed during ductile deformation and can thus be associated with bond breaks. During brittle failure, peak frequencies were spread over a range of 30 to 100 kHz.

In order to find out if monitoring of slopes by means of acoustic emission testing equipment, it was investigated if AE parameters are capable of describing and distinguishing different breaking processes inside a snowpack. Furthermore, laboratory experiments have been designed and conducted in order to find out if different signals can be distinguished which belong to assigned failure mechanisms. Also, location of failure events inside a snow sample would be of great interest.

## 4. Experimental Setup

The experimental setup is depicted in Figure 4. Six AE sensors are connected each to a 60dB preamplifier, a 20 kHz-2MHz band pass filter, digitized at a resolution of 18 bit with a sample rate of 5 MS/s. The signals are fed into an FPGA DSP for feature extraction, waveform collection and further data processing (Physical Acoustics Corporation, PCI-2). Besides the AE signals, a set of process parameters is recorded simultaneously, which consists of the loading force and the resulting displacement vector. Another important factor is the tilt angle φ, which determines the amount of shear stress inside the snow sample. The experiments took place in a cold laboratory at a constant temperature of -5°C.

The specimens were snow samples made of natural snow. To ensure homogeneous behaviour, the samples were produced by sieving snow into special boxes and applying uniformly distributed pressure in order to produce various snow densities. Snow density, among others, is the main parameter determining the samples mechanical properties. Further variation in snow properties were achieved by producing artificial weak layers inside the sample. Such layers almost always form in a natural snow packs and are mainly responsible for dry-snow slab avalanche release [1].

Sensor coupling is an important part in acoustic emission testing. For snow, a special technique for the coupling of acoustic emission transducers was used successfully in previous research [17],[18]. This technique involves two steps. First the sensors are heated slightly above 0◦ C by means of an industrial hot air gun. After that, the sensors are pressed decently on the snow surface. A thin ice layer develops between sensor and snow surface, ensuring a mechanically rigid low impedance connection. In the metal plates, the sensor's wear plate surface was aligned with the plate's surface. Problems with this design arose when snow samples were not completely in touch with the sensor plate. Air between snow surface and sensor of less than 1 mm was enough to destroy proper coupling. Therefore, also another design involving plates made of foam with the sensors being placed inside the plates elastically was tested successfully. Since the characteristics of the snow's AE-signals could not be estimated in detail, wide band Sensors (Physical Acoustics Corporation WD transducer) with an operating frequency range of 100-900 kHz were used.

After placing the snow inside the plates and checking the sensor coupling, the test procedure was started by controlled increasing of the force on the upper plate, i.e. applying more and more stress on the snow sample. The test was finished by either reaching a maximum level of force or by rupture of the sample.

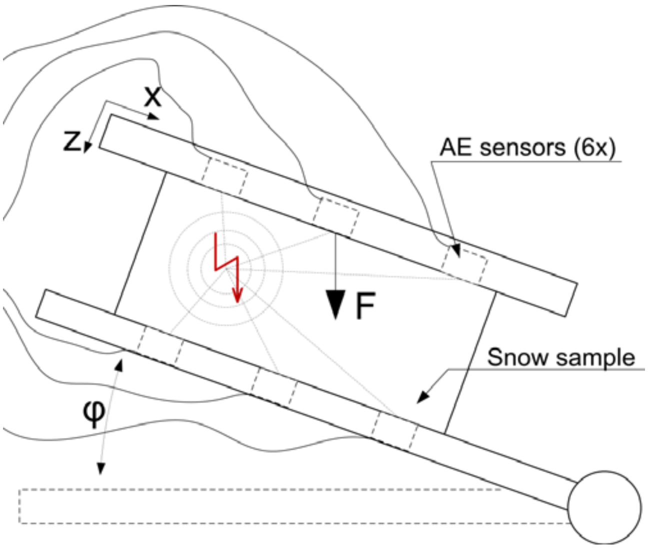


Figure 4: Measurement setup.

## 5. Experimental Results

In Figure 5, experiments of a snow sample loading test run are depicted. The top plot shows the process parameters load and resulting displacement. In the middle plot, the number of counts per hit is displayed for the same period as a scatter plot. The bottom plot shows the count rate as histogram along with the displacement velocity of the snow.

It can be seen that the displacement velocity corresponds quite well with the number of counts in the AE signals. The underlying hits have low-frequency characteristics (around 30 kHz). A second type of signals has a more spike-like character, with peak frequencies around 300 kHz. These hits are assumed to be related to microscopic bond breaks which occur prior to and duringe larger ruptures resulting in detectible displacement.

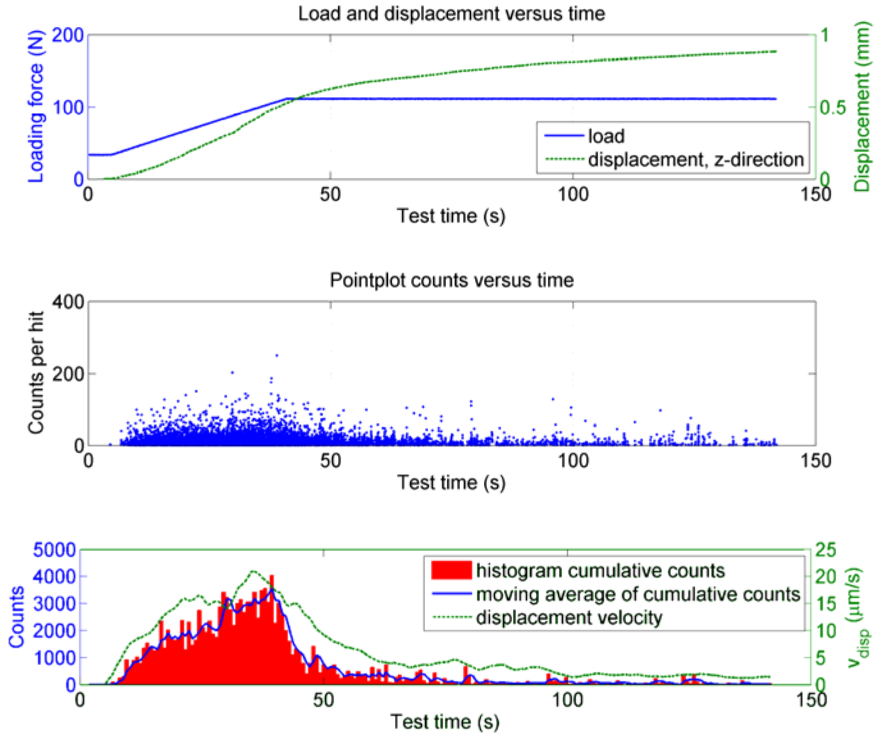


Figure 5: Forces, counts per hit and counts during a snow sample mechanical loading test run.

Figure 6 depicts analysis of a three dimensional localization experiment. Energy distribution versus sample height clearly shows AE activity in terms of energy release inside the weak layer. It can be seen that the main portion of AE energy can be located in the region of the weak layer, which supports the theory that in case of an avalanche release, the main rupture process occurs in the weak layers of the snow stack.

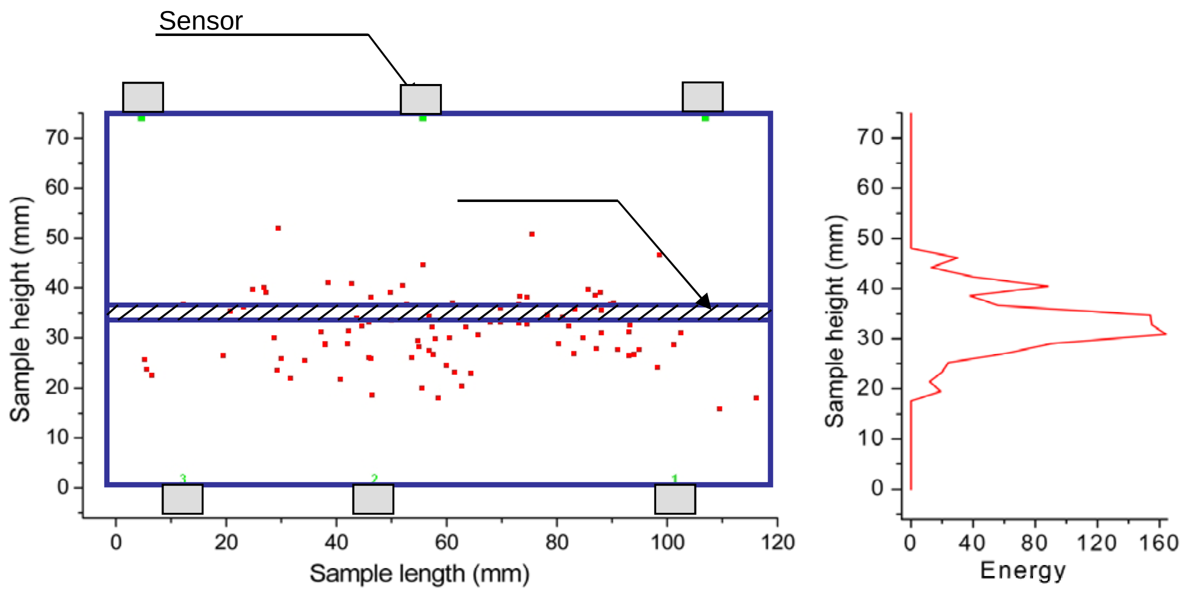


Figure 6: Example localization results for a layered snow sample using 6 AE sensors.

## 5. Conclusion

In this work, it could be shown that acoustic emission testing has potential in the assessment of layered snow structures. In a cold laboratory setup, mechanical loading tests with pre-fabricated snow samples have been conducted. It could be shown that snow under mechanical stress emits acoustic signals of two types, one in the 30 kHz range and one in the 300 kHz range. Furthermore, localization has shown to be possible in a laboratory setup. This setup has been deployed in a field test together with geophones for the winter season 2012/2011.

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