

ON TRIGGERING AVALANCHES, WHAT HAPPENS BETWEEN EXPLOSION AND RELEASE

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ABSTRACT: Triggering avalanches with explosives has been a well-established method for a long time, earliest records date back to the 1920ies. At least since [Gubler \(1976\)](#) we also know that it is most effectively done with explosives detonated at least 1 meter above the snow surface.

Previous research was unclear about what types of explosives or gas explosions work best. Also, we were lacking a clear model of how the explosive transfers its energy through the air into the snowpack.

Our new empirical model gives us a clear picture of what happens when the pressure wave travels across the snow surface and through the snowpack. It tells us what parts of the wavefront interact with which parts of the snowpack. After modelling the initial pulse of the explosion, we use a combination of Fourier-transform and non-linear attenuations to get a prediction of the pressure-waveform at any distance from ground-zero.

We have developed and verified this model with our own experiments. Now we can not only use this model to compare measurements taken at various distances on different ground conditions with a variety of explosive types and sizes and therefore verify our model with existing published data (e.g. [Seitz](#)). We could also leverage the model to predict the effects of a remote avalanche control system (RACS) in a location by combining it with terrain data.

The model is a combination of a very simple geometric scaling law for explosives, first introduced by [Hopkinson \(1915\)](#), an empirical model to predict blast pressures for explosives in free air [Kinney \(1985\)](#) and a frequency-based model accounting for the interaction of the pressure wave with the snow-pack as it travels along its surface and through its pores.

Our model confirms the work of [Gubler \(1976\)](#). More importantly, the model gives us insight into how the pressure wave induces an additional load and therefore breaks the weak layers and releases avalanches.

Keywords: Explosives, Avalanches, Pressure, Shockwave, Experiments

1. INTRODUCTION

When using explosives to release avalanches it is preferred to detonate the explosive some distance above the snow surface. According to [Gubler \(1976\)](#) this greatly increases effectiveness, as the shockwave is attenuated less in air than it is attenuated in snow. Therefore an above snow explosion creates higher stress in larger distances than the on snow or even in snow explosion.

It is known that the over-pressure at any given point on the snow surface correlates to the stress-wave introduced into the snow-pack below. It is however unclear what part of the wave affects the snow in which way.

In our previous work (see [Meier \(2023\)](#)) we presented a model that tries to fit historic measurements of (peak-) overpressures from different studies. The model splits the process of releasing avalanches with explosives into four different parts: **Explosion**, **Propagation**, **Interaction** and **Crack**. We will refer to this model as the EPIC model. It was

thought to be four processes that can be looked at individually. Also the data from other research ([Gubler \(1976\)](#), [Seitz \(2021\)](#)) did not suggest otherwise.

Nevertheless, the available data was of low resolution and bandwidth. Therefore we started our own experiments using high-end equipment, with the goal to further verify the model introduced in [Meier \(2023\)](#).

1.1 Shockwave theory

A shockwave from an explosion in free air will have a steep increase in pressure starting the overpressure phase, followed by an underpressure phase before returning to equilibrium (ambient pressure). Explosive shock waves are often characterized using peak-overpressure and duration of the overpressure phase, as was done by [Frielander \(1946\)](#). The Frielander function indeed only uses two parameters, peak overpressure $p = P_0$ at $t = t_0$ and duration of the positive phase t^* . In figure 1 we can see the Frielander function with its parameters. The paper of [Dewey \(2010\)](#) goes into detail about fitting the Frielander function.

The Frielander function is a good approximation of detonations in free air and a fairly good approximation of detonations above hard ground. In [Kinney](#)

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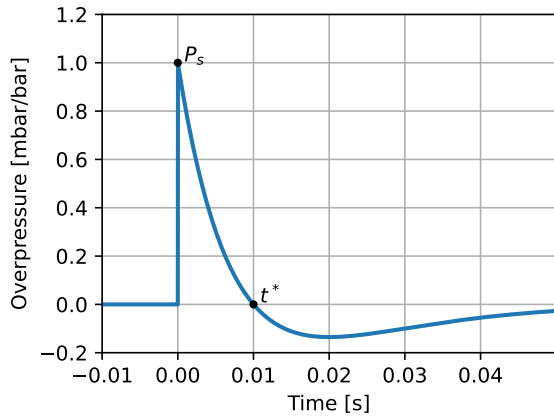


Figure 1: Frielander function describing the overpressure generated by an air blast.

(1985) we can find formulas and diagrams which give the parameters of the Frielander function for any size of explosive charge at any distance. The equations make use of a geometric scaling law to scale the non-linear pressure-distance relation to different charge sizes. The scaling law was first introduced by Hopkinson (1915) and independently described by Cranz (1926), it is therefore called the Hopkinson-Cranz scaling law.

The EPIC model uses the formulae by Kinney (1985) to predict the Explosion and Propagation part of the model, only modified to account for some factor of reflection.

2. EXPERIMENTS

In order to verify the EPIC model we designed a few different experiments. Some data was gathered while testing other, unrelated things, such as moisture sensitivity of an explosive.

We bought a high quality setup built by Kistler with four pencil probes and a data-aquisition unit to measure side-on-pressure with high resolution.

Additionally we used geophones to measure the stress wave in snow, similar to the sensors used by Gubler (1976) and Simioni (2016) in some experiments. The geophones were embedded in a casing that gives an overall density similar to the snow density.

Here follows a description of the three main experiments conducted, and the findings from the corresponding analysis.

2.1 Sundlauenen

MAYBE ADD ABOVE HARD GROUND EXPERIMENT?

2.2 First

The first experiment was done in Grindelwald-First, Switzerland, March 25th, 2024. While testing sensitivity of an explosive with respect to water-content,

we were able to measure pressure in four different locations on a high-winter snowpack, using the Kistler setup.

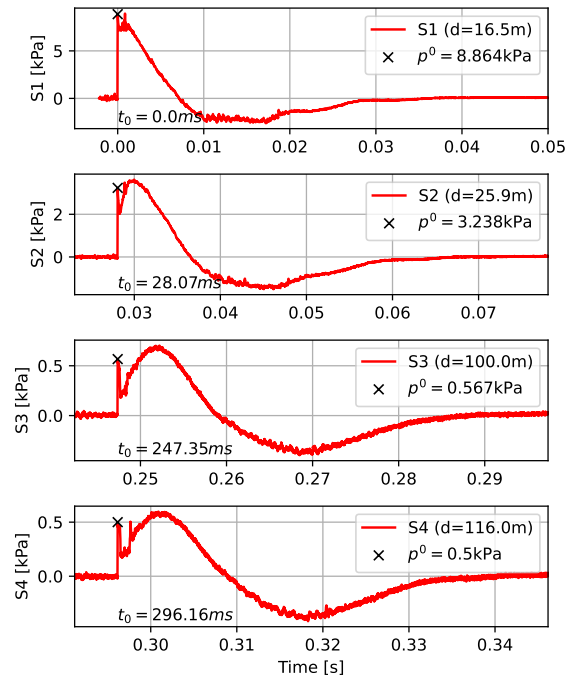


Figure 2: Pressure recordings of a Wyssen 2K explosive on snow at four distances shows different wave-form with increasing distance.

In figure 2 recorded pressures are shown at 16.5m (54ft), 50m, 100m and 116m from ground zero for one single detonation. While the waveform at S1 (16.5m) is in good agreement with the Frielander function in 1, the waveform is significantly different at larger distances (≥ 50 m). The wave has some short pulse at the beginning, then dips immediately and is followed by a slower increase to the actual highest pressure.

Since this changed waveform was never found in measurements above hard ground, it was assumed that this deformation comes from some sort of interaction with the underlying snow-pack, as the wave travels above. However the amount of data points and also time did not yet allow for the development of a model.

Also we should note that our measurements on hard ground were limited to smaller distances.

2.3 Alta

More data was collected during three days of experiments in Alta UT, mid of April 2024.

In these experiments we were able to measure different types of explosives as well as two gas-based remote avalanche control systems (RACS). We primarily measured overpressure using our equipment at distances from 16m to 100m.

2.3.1 Seitz vs. Kistler

At the same time we were able to record the overpressure using the equipment used by Seitz (2021), operated by Ryan Zarter from the CAIC, which will be referred to as the "Seitz equipment".

We could see that while the Seitz equipment recorded the same amplitudes and waveform, due to its poor resolution (both time and pressure wise) many details of the wave cannot be seen in the recordings. In figure 3 we can see the same signal recorded by the Kistler equipment and the Seitz-Equipment.

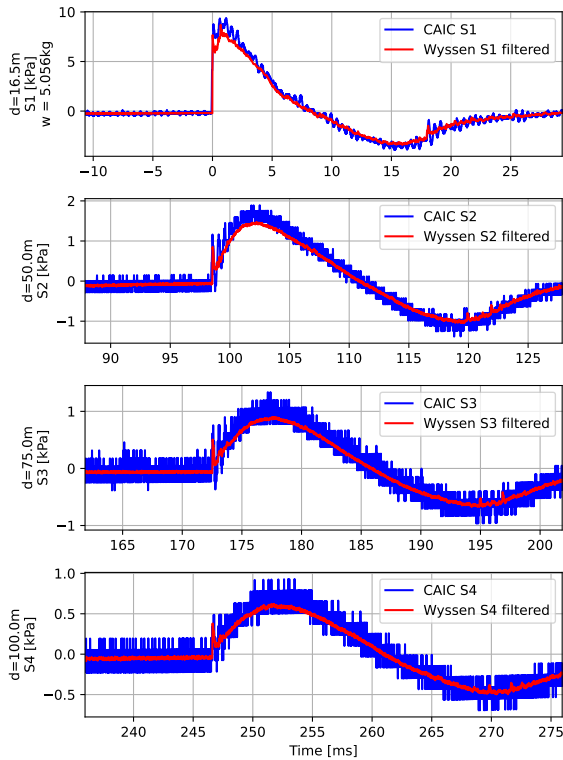


Figure 3: Recording of a TNT charge detonating above snow, simultaneous recording by the Wyssen/Kistler equipment in red and the Seitz/CAIC equipment in blue.

The Seitz equipment has quite high electrical noise. To overcome this noise, Seitz (2021) used a frequency domain filtering, omitting all frequencies above 1.5kHz. Therefore they were unable to see the effects as we discovered them.

2.3.2 Directionality by Seitz

However when deliberately only looking at the low frequencies the dataset by Seitz (2021) is extremely useful and is the only dataset of its size. We can use it to get a good understanding of the directionality of the different systems recorded.

2.3.3 Stress wave in snow

Gubler (1976) correlated overpressure above snow with measurements of the stresswave in snow.

For some detonations during our experiments in Alta we were also able to measure movement within the snow-pack using geophones. Unfortunately these measurements could not be fully synchronized to the pressure-measurements, which made the analysis really difficult.

However we were able to see that the stress-wave in snow does not have the same waveform as the recorded pressure pulse. It seemed that the snow is only coupling certain frequencies of the pressure-wave.

But since we were lacking the exact timing between pressure and stress-wave we were unable to exactly tell which part of the pressure wave is causing the stress wave. Further experiments had to be done.

2.4 Jungfraujoch

To get a better idea of what is happening at the air-snow interface, we repeated parts of the experiments at Jungfraujoch, Switzerland on June 6th, 2024. We used the data acquisition system of the Kistler-Equipment to record pressure with only two pencil-probes and use the other two channels of the data acquisition unit to record the signals from the geophones.

This allowed for fully synchronized sampling of pressure and the shock-wave in snow with 24-bit resolution at 200kHz. figure 4 shows recording of pressure and velocity at a distance of 50m from a Wyssen 2K charge (4.25kg). The geophone was placed 20cm below the snow surface.

As was later noticed, the geophones used at Jungfraujoch and in Alta were assembled upside down and could therefore not accurately measure the stress wave. As the geophones were only able to measure in one direction (downwards movement), this created sudden interruption of the signal and high-frequency content in a signal that would typically consist of very limited bandwidth.

In figure 4 we can see that behaviour and for further analysis we only use the first part of the signal. The amplitude of the recorded signal is certainly smaller than the real amplitude, but the general waveform should not be too far off.

There are plans to repeat this experiment with the correct orientation of the geophones in the upcoming winter. But for now we will use an estimation of the rest of the signal, approximated by a damped sine wave according to equation (1). The time t in this equation is the time from the zero crossing after the first negative peak. The parameters f_r (natural frequency) and τ (dampening constant) are selected as $f_r = 230$ Hz and $\tau = 5.1$ ms to roughly match the measurement.

$$v = \sin(2 \cdot \pi \cdot f_r \cdot t) \cdot e^{-t/\tau} \quad (1)$$

This approximation is very close to what Verplanck and Adams (2024) was using and was able to confirm using experiments.

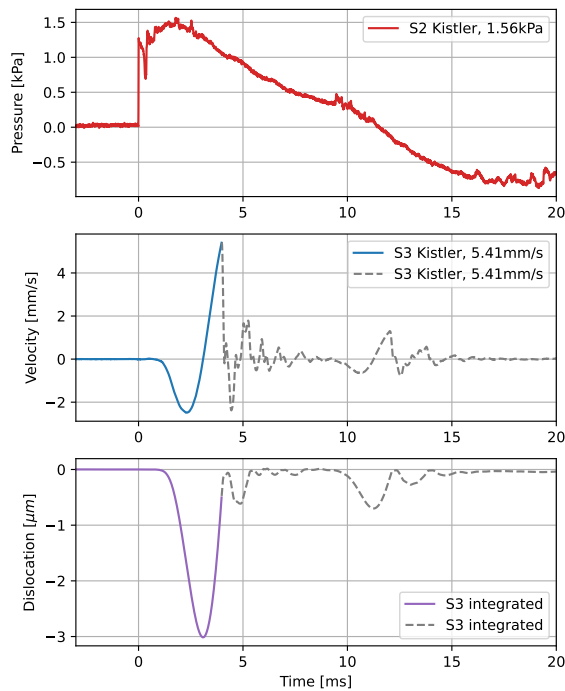


Figure 4: Recorded pressure above snow, velocity in snow and calculated dislocation, by integrating the velocity measurement from Test 1 at Junfraujoch. The geophone recording the velocity was mounted upside down and therefore has limited range and hits the limit, which creates the fast changes in velocity in the second half of the signal.

3. ANALYSIS

We can summarize the findings from the performed experiments as follows:

1. The Seitz equipment records the same peak pressures but is unable to capture details in the waveform
2. One such detail is that the waveform of the pressure wave is changed when travelling larger distances over snow
3. The geophones were incorrectly mounted we can only use a small part of those measurements and have to be aware that we might be missing larger parts of the signal
4. We have to re-measure geophone signals, in the mean time we approximate the signal according to [Verplanck and Adams \(2024\)](#)

The most surprising finding is clearly the waveform deformation over snow. In the original EPIC model, propagation and interaction were thought to be separated processes, but it seems as the wave interacts with the snowpack locally, it also influences the waveform for places where the wave will impact moments later.

This effect was observed in all of our experiments. The exact amount of "deformation" was different for each experiment, but so was the snowpack.

3.1 Frequency analysis

To investigate the cause of the waveform deformation we should have a closer look at the recorded waves. Using Fourier transform and some logarithmic spaced averaging to reduce noise in the frequency domain we can compare the spectra of the signals from a measurement in First. In figure 5 we can see the signal amplitude in the frequency domain for the four distances. For easier comparison the amplitude was normalized to 0dB at the frequency of 30Hz.

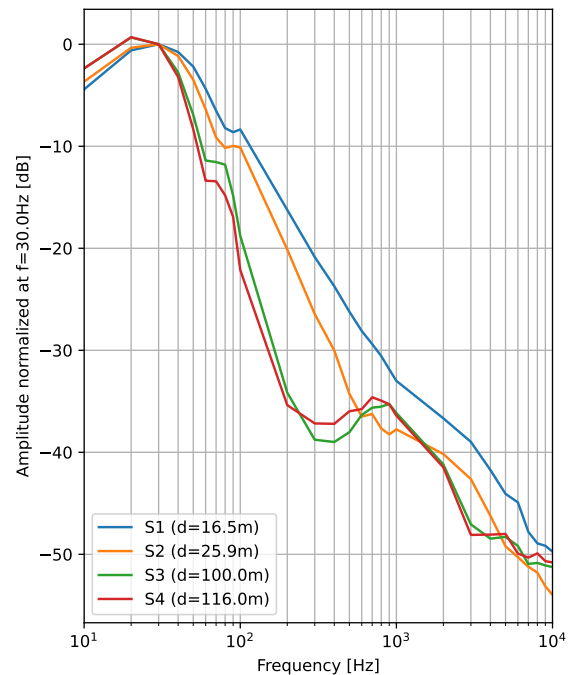


Figure 5: Spectral analysis of the signals in figure 2. Frequencies are smoothed and the amplitude averaged.

The frequency spectrum in figure 5 shows a similar overall form for all distances, higher amplitude around 30Hz decreasing with increasing frequencies. However we can see that some range of frequencies around 200Hz are attenuated significantly stronger over distance than lower and higher frequencies.

Instead of looking at each frequency individually we decided to continue analysis in three frequency bands: A low frequency band (0..150Hz approximately), a middle frequency band (150-350Hz) and a high frequency band (above 350Hz).

Using digital filters the signals can be split in three different parts, depending on the exact filter implementation, the three different signals when added together give back the original (recorded) signal.

When we split each recording of the experiments in Alta into these three frequency bands and plot the peak pressure of the filtered signals against scaled distance in a double-logarithmic graph (figure 6), we

can see that the attenuation of the low frequency band follows more or less the original EPIC model, while the middle frequencies have a significantly higher attenuation.

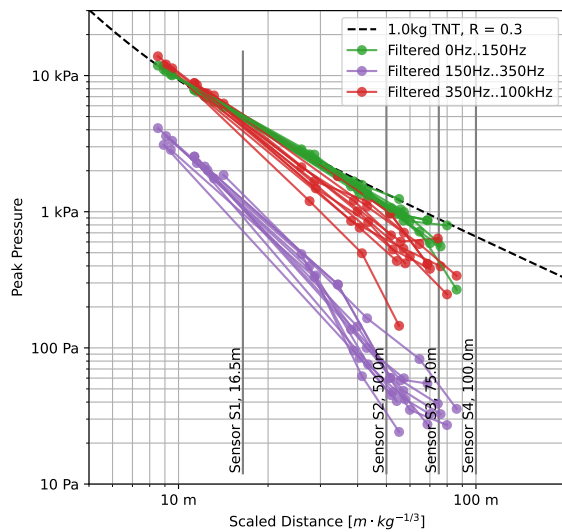


Figure 6: Each datapoint from Alta explosive testing, filtered in three frequency bands, evaluated the peak pressure of the filtered signal and plotted against the scaled distance.

This difference in attenuation over distance means that our initial EPIC model needs to be enhanced and at least give a propagation and interaction model for the three frequency parts separately.

3.2 Model

We then theorized the following mental model for the propagation & interaction part of the EPIC model:

- the low frequency part is passing through the snowpack, it does not interact with the snowpack in any way and has no relevance for avalanche release
- the high frequency part is fully reflected at the air-snow interface, the snow surface the frequencies are so high that the mass of the snow particles completely support the reflection, this part of the signal does not contribute to avalanche release
- middle frequencies induce movement in the snowpack, which in turn creates an opposing pressure resulting in a reduced pressure measured at those frequencies in air

In figure 7 there is a depiction of the mental model. Also some sensor locations are conceptualized in this figure. At such sensor locations certain parts of the wave should be present or absent. Since this models the behaviour in three frequency bands, we call this model the Trinity Model.

In the following sections we try to verify that mental model by measurements and observations.

3.3 Verification

3.3.1 Velocity waveform

Using equation (1) we can approximate the full measurement in figure 4. Compared to the pressure measurement from the same experiment, filtered in the middle frequency band we can see that the bandpass filtered signal quite closely matches the velocity signal and its estimated continuation. Both filtered signal as well as estimated velocity signal are shown in 8.

The geophone location corresponds to the Geophone marked in figure 7.

3.3.2 Pressure in snow

In Alta we placed the sensor at 50m in different positions. Measurement of the air pressure in a cavity ca. 50cm below the snow surface (see Pressure Sensor 2 in figure 9) shows no high frequencies or middle frequencies. Low frequencies, however, are fully present in the snowpack.

The sensor placed in an open pit, just below snow surface shown as "in pit" in figure 9 also shows significantly less high frequency content.

3.4 Plausibility

When looking at air overpressure measured above the snow (as it is usually measured) compared to in a snow pit or even inside the snowpack, in section 3.3.2 it is seen that the low frequency part is passing through the snowpack (see figure 9), while the middle and high frequency parts are not measured inside the snowpack. It seems the snow is transparent for these low frequencies. Interestingly, all previous studies concentrated only on these frequencies, which seem to not interact with the snowpack at all. This is visualized in figure 7 as the green signal path.

Frequencies below 20Hz are considered infrasound. Infrasound is known to pass through snow, sensors of infrasound-systems are usually placed intentionally in such a way that they get covered by snow as this reduces wind noise. This makes the previous conclusion even more plausible.

Very high frequencies on the other hand should behave similar to ultrasound. Ultrasound (frequencies above 20kHz) is sometimes used to measure the snow-height from above by sending an ultrasound pulse and measuring the reflected signal. We can conclude that high frequencies should therefore be reflected at the very snow surface. This is visualized in figure 7 as the red signal path.

The data actually supports this hypothesis as the first high frequency pulse is not present in the air-pressure measurements in the snow-pit or below the snow (figure 9). As the high frequencies get reflected, they certainly interact with the snow surface in some way. But as no such high frequencies can be found in the stress-wave in snow, we conclude

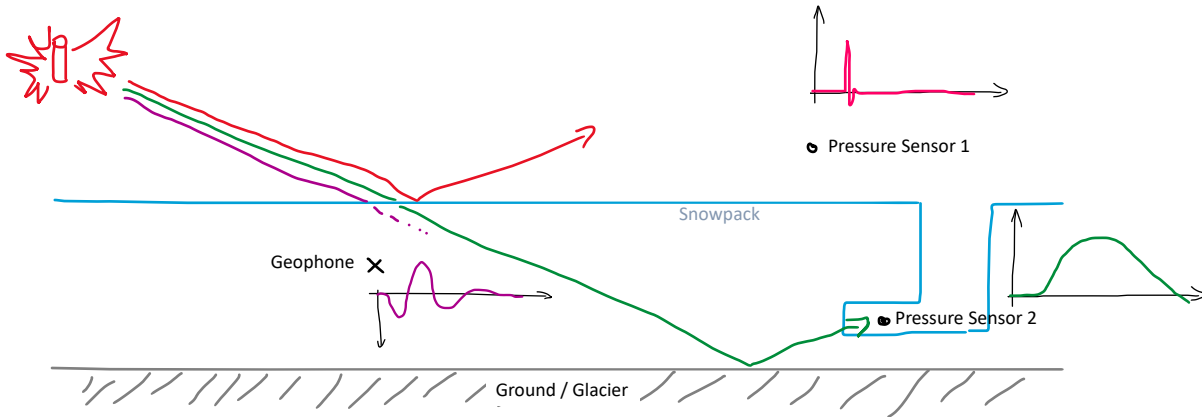


Figure 7: Depiction of the mental model for how the different parts of the signal interact differently with the snowpack, air and ground.

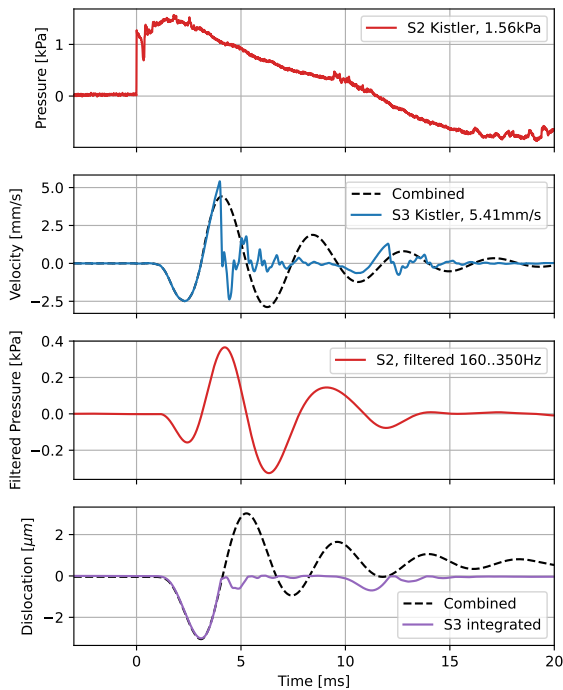


Figure 8: Signals recorded at 50m from ground zero. Pressure above snow (S2), filtered pressure using a 3rd order butterworth bandpass filter with corner frequencies of $f_1 = 160$ Hz and $f_2 = 350$ Hz, and the recorded and estimated velocity as well as the mathematical integration giving the dislocation.

that this process transfers only negligible amounts of energy into the snowpack.

It is expected that that a fresh snowcover would reflect only very high frequencies, while the lower end of our high-frequency range would probably be coupled into the snowpack. A warm, wet snowpack on the other hand, we would expect to reflect a much wider range of frequencies, and couple almost no amount of signal. Currently we do not have data to confirm or deny this hypothesis.

The (narrow) range of frequencies between the low-

frequencies and the high-frequencies we call the middle frequencies. When the pressure signal is filtered with the right parameters it matches the velocity in snow (stress-wave) very closely. The waveform of the velocity (and therefore also displacement) looks like a damped oscillation. A system with the tendency to oscillate at a natural frequency can reliably be excited by a sharp force input (step function) with a high enough bandwidth. The same effect is used when one plays the guitar, the string is loaded and then suddenly released (negative step). This step is the same for each string, but the string will quickly start to oscillate in its natural frequency. The impulse provided by an explosive is certainly steep enough to excite an oscillation, and in fact can for our purposes be considered infinitely steep. The impulse should therefore be able to excite whatever resonance frequency the snowpack may have. However, as the interaction of the pressure wave with the snowpack attenuates these middle frequencies stronger, less energy of that desired frequency will be available at larger distances.

4. RESULTS

So, let's try to answer the question from the title: What happens between explosion and avalanche release?

The pressure pulse initially is in the shape of the Frielander function figure 1 and has an amplitude (peak pressure) and time-constant that can be estimated using the Scaling Law by [Hopkinson \(1915\)](#) and the adapted pressure/distance curve from [Meier \(2023\)](#).

As the pressure-wave interacts with the snowpack as described above, it gets deformed. We can model that behaviour by filtering the signal in three bands, assigning a different additional attenuation over distance for each frequency-band.

In figure 7 we can see how the three different frequency bands interact with the snowpack differently.

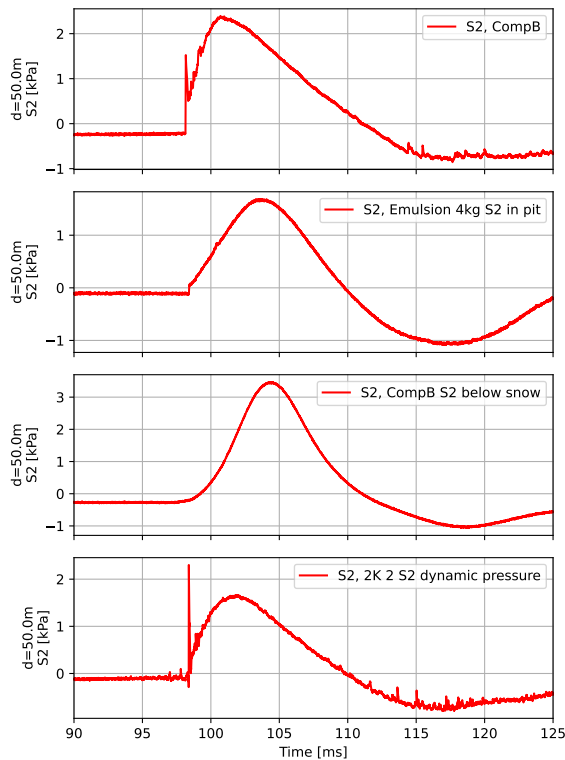


Figure 9: Different pressure waveform depending on sensor placement. Regular placement, slightly below snow surface, in cavity below snow, above snow facing the explosive for dynamic pressure.

The low frequencies pass through the snowpack as if it was air. More technically it probably travels through the air in the snowpack and experiences so little resistance that it is practically untouched. In turn the snowpack experiences no additional stress from these waves and that part of the signal does not contribute to releasing avalanches.

Conveniently the shock-wave in snow has the same waveform as the middle frequency band. From that we conclude that the middle frequencies are probably the only ones that induce stress into the snowpack. The snowpack is therefore starting to move in those frequencies which in turn reduced amplitude of said frequencies in the air. However, this data needs to be re-measured as the sensor was not placed correctly.

The stress wave then propagates downwards into the depth of the snow where the additional stress can break ice-bonds and therefore release avalanches.

When looking at data from experiments, one should be aware that frequencies below 150Hz tend to not interact with the snowpack at all. Therefore the amplitude of these low frequencies is not directly related to stress in snow and also not directly relevant for the capability to release avalanches.

Also, as the pressure-wave gets deformed by the

snowpack it seems wrong to draw conclusions about the explosive strength from measurements above snow without factoring in this effect. We therefore do not (yet) present any results with regards to explosive strength and effectiveness.

More experiments to further investigate this coupling between pressure wave and snow are planned. Especially the effect of different snow-conditions on the coupling should be studied.

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