SNOW CHARACTERIZATION AND BLAST PROPAGATION MODELLING

A project carried out by the Otto Sverdrup Centennial Expedition (OSCE) during the wintering in Hourglass Bay (76 24 N, 87 48 W), Ellesmere Island, September 1999 – April 2000 on behalf of Norwegian Defence Construction Service (NDCS)

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PREFACE

This report is a presentation of results from a project carried out by the Otto Sverdrup Centennial Expedition (OSCE) on behalf of the Norwegian Defence Construction Service (NDCS). The field work was carried out during the wintering at Ellesmere Island, Canada from October 1999 to April 2000. The project was funded by NDCS who also provided most of the equipment required for the measurements. The method used for theoretical analysis was developed by Dr. Donald G. Albert, USACRREL, who also provided additional equipment and valuable advice during the fieldwork and the subsequent analysis. Dr. Albert also had the initiative to undertake ambient noise measurements during the wintering. The experiments could not have taken place without help from field assistants. Guldborg Søvik has assisted with most of the measurements. Greg Landreth and Graeme Magor also provided valuable help.

SNOW CHARACTERIZATION

1. Introduction

For accurate prediction of sound propagation outdoors, many factors have to be known. These include A) atmospheric effects, B) topographical effects and C) air-ground interactions. Much research remains before the combined influence of these factors on sound propagation is understood and can be predicted accurately. So far, numerical acoustic models include at most two of effects A, B and C, and the models are mostly one- or two-dimensional.

In this investigation, we try to look at the isolated effect of air-ground interaction on propagation of blast pulses along a snow cover. This means that we study propagation along a flat ground and that we try to select situations when atmospheric refraction can be ignored. The study has two purposes. First, we want to compare our measurements with predictions based on realistic ground parameterisation for a type of snow that has not been studied extensively before. The snow cover studied was exposed to strong winds (up to 25 m/s) and low temperatures (down to –43 ^{o}C) over a period of more than half a year. Previous investigations[1] on snow acoustics have concentrated mostly on fresh snow covers that have not been much influenced of wind. Second, once a method is established, we want to use it to indirectly estimate average acoustical properties of the snow layer. The most important factors are depth and flow resistivity[2-4]. Once this inversion method has been thoroughly tested out and validated on different snow types, it can be used in practical applications such as estimation of average snow depth over larger areas.

Propagation of an airborne pulse along a snow surface underlain by a frozen ground is a difficult theoretical case, since the three media have very different acoustic properties. It has been shown[2,5] that Attenborough's four parameter ground model[6] can be used to accurately predict the snow effect for propagation along a fresh snow cover with low flow resistivities and low densities. It has also been shown[1] that the inversion technique can accurately predict snow depths for this type of snow covers. Here, we study propagation above a high-Arctic snow cover that can be expected to have higher densities and flow resitivities mostly because of wind effects. In this report, an overview of the methodology is presented together with examples of measured and calculated results. We also present a few snow vibration measurements associated with the acoustic pulses, even if these are not essential for the snow characterization. However, they give information about air-ground interaction which can be useful in a deeper analysis.

Hourglass Bay (76 24 N, 87 48 W) is situated in the Canadian high arctic (Fig. 1). Figure 2 shows the terrain where the experiments were carried out.

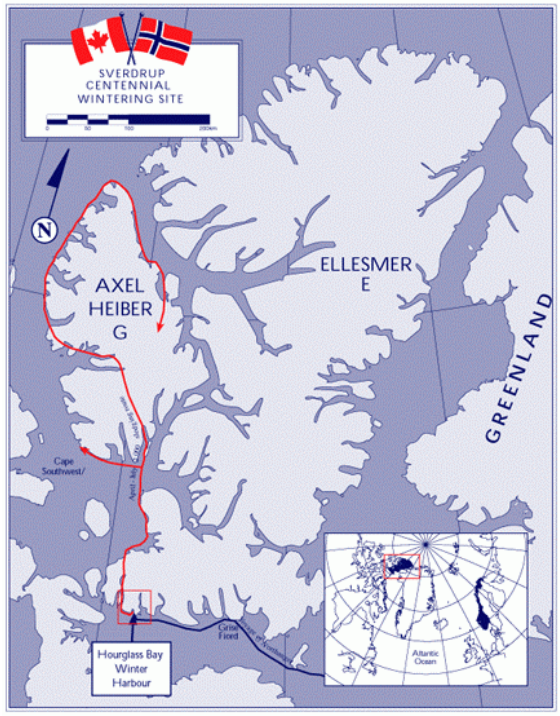


Figure 1: Map of Ellesmere Island showing Hourglass Bay (76° 24’ N, 87° 48’ W) where experiments were carried out.

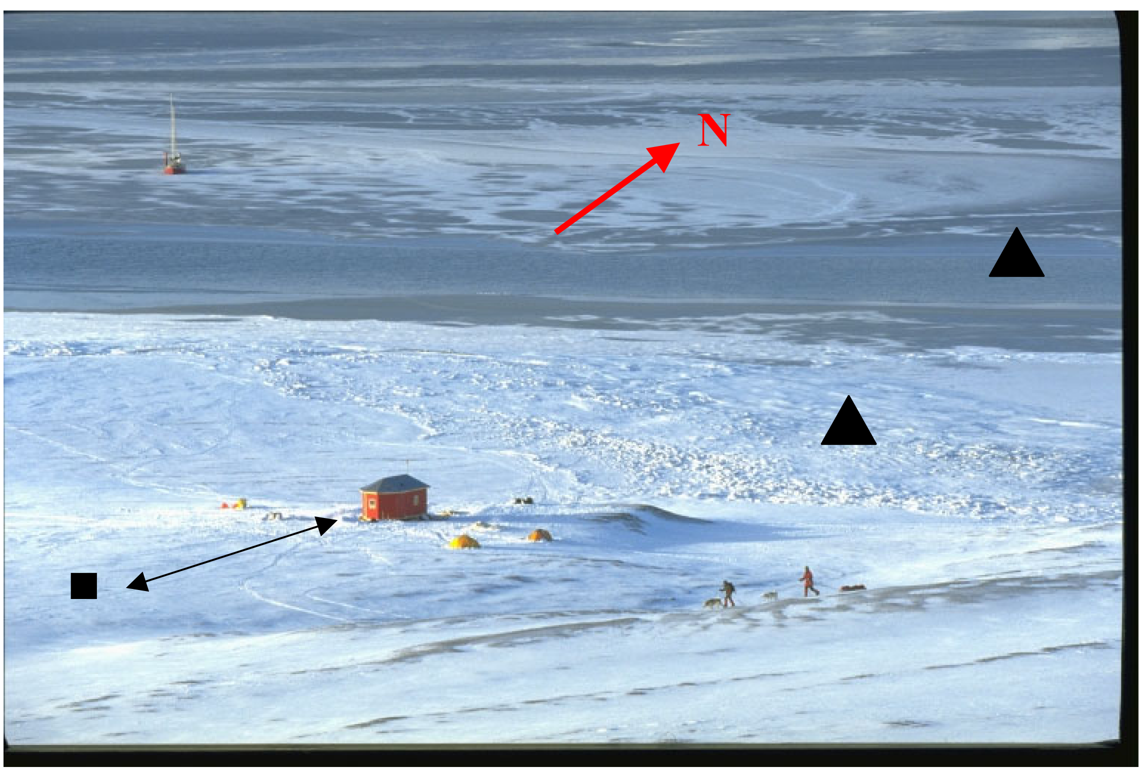


Figure 2: Hourglass Bay. Measurements with were carried out at the black box, while shots were fired along the black line. Ambient noise measurements were carried out at the triangles. Photograph by John Dunn, Arctic Light.

2. Theory

Although a method of calculating pulse shapes based on an empirical model of ground impedance[7] has been developed[8-11] and works well for grass-covered ground, we have included a more complicated, but physically based, model of ground impedance[6] in our calculations to give better agreement with observed measurements for snow[1,5]. This model gives increased accuracy at low frequencies compared to the empirical model.

We briefly outline the procedure for calculating theoretical acoustic pulse waveforms from a known (or assumed) surface. For a mono-frequency source (with frequency ω) in the air and a receiver on the surface, the acoustic pressure P at a slant distance r away from the source is given by

$$\frac{P}{P_0} = \frac{e^{ikr}}{r}\left(1+Q\ \ \right)\ e^{-i\omega t}, \tag{1}$$

where P_0 is a reference source pressure, k is the wave number in air, and Q is the image source strength representing the effect of the ground. At high frequencies ($kr >> 1$), Q can be written as[12-14]

$$Q = R_P + (1 - R_P)F(w), \tag{2}$$

where R_P is the plane wave reflection coefficient, F is the boundary loss factor, and w is a numerical distance, all of which depend on the specific impedance $Z(\omega)$ of the ground. By determining the image source strength Q_n at the nth frequency f_n, the corresponding response amplitude $\hat{P}_n$ can be written as:

$$\hat{P}_n = \frac{P_0}{4\pi\ r} S_n W_n \left(1+Q_n\right) e^{i2\pi\, f_n r/c}, \quad n = 0, 1, 2, \ldots N-1 \tag{3}$$

where S_n and W_n represent the source and instrument effects at the nth frequency and c is the speed of sound in air. An inverse FFT,

$$P_m = \frac{1}{N}\sum_{n=0}^{N-1} \hat{P}_n e^{-i2\pi\, mn/N}, \quad m = 0, 1, 2, \ldots N-1 \tag{4}$$

is used to construct theoretical pulse waveforms in the time domain. An explicitly layered model of the ground must be used to represent thin snow covers[15] using (omitting the frequency subscripts),

$$Z = Z_2 \frac{Z_3 - iZ_2 \tan k_2 d}{Z_2 - iZ_3 \tan k_2 d} \tag{5}$$

where d is the snow layer thickness, k_2 is the wave number in the snow layer, and Z_2 and Z_3 are the impedances of the snow layer and substratum, respectively[16].

The acoustic behaviour of the soil or snow is specified by the impedance Z_2 and wave number k_2, which are used in equations (5) and (2) to find the theoretical waveform. We use Attenborough's four-parameter model of ground impedance[6] to calculate these parameters. The four input parameters are the effective flow resistivity σ, the porosity Ω, the pore shape factor ratio s_f , and the grain shape factor n'. The snow depth d and the substrate properties are also required in a layered model.

An exponentially decaying source pulse $S(t)$ of the form

$$S(t) = P^{+}\left(1 - t/t_{+}\right)e^{-t/t_{+}}, \tag{6}$$

is used as the starting waveform in all of the blast wave calculations. In equation (6), P^{+} is the positive peak overpressure, t the time, and t_{+} the duration of the positive overpressure. This pulse shape is sometimes known as a Friedlander waveform. It has been previously used in blast wave calculations[5] and is used in the ANSI standard blast noise estimation method[17]. A value of $t_{+} = 1.5$ ms was selected to represent the blast wave for the cases presented here, and all calculations began with this source pulse. The overpressure was normalized to $P^{+} = 1$, since only waveforms were of interest in this study. The waveform of the source is shown in section 4.

The acoustic pulse calculation method can be used to calculate the pulse shape for a blast if the geometry (source and receiver heights and propagation distance) and ground properties (parameters needed for Attenborough's rigid-porous ground impedance model) are known. The calculation method assumes that the atmosphere is homogeneous. The method can also be used in a waveform inversion procedure to estimate the unknown ground parameters that produce a measured waveform. In this procedure, the geometry and some of the ground parameters (discussed below) are known and are fixed at a constant value in the inversion calculations. Pulses are calculated using equations (1) – (6) using assumed starting values of the unknown parameters, and the calculated waveforms are directly compared with the observed waveforms[1]. The unknown parameters are varied in a systematic way using an iterative search procedure[18] until good agreement is obtained.

For our rigid-porous medium calculations, the grain shape factor n' was set to 0.5, corresponding to spherical grains, and the porosity $\Omega = 0.62$ was determined from the measured average density, 350 kg m^{-3}, of the entire snow cover. We fixed the pore shape factor ratio s_f at 0.8 for dry snow[1]. Parameters for the frozen gravel beneath the snow[1] were fixed at $\sigma = 3000$ kPa s m^{-2}, $\Omega = 0.27$, $s_f = 0.73$, and $n' = 0.5$. Only the effective flow resistivity σ of the snow and the snow depth d were varied in the inversion procedure.

Waveform inversion to determine the snow parameters was performed independently for each source-receiver distance. We compared calculated and observed pulses using time-aligned, normalized waveforms.

3. Meteorology

Hourglass Bay (76 24 N, 87 48 W) has a high-Arctic climate where winter temperatures can be as low as –50 ^{o}C. Precipitation is low, and periods with high wind result in a hard, wind packed snow layer. Air temperature, wind speed and direction and air pressure were measured through the winter at 5 m above ground. During some experiments, temperature at ground was measured as well. Automatic Weather Stations (AWS) from Aanderaa Instruments were applied for these measurements. The instrument unfortunately malfunctioned in mid January 2000, and from then on observations were taken manually with a Davis weather station.

Figure 3 shows weather data for December 1999. The combination of high wind speed and low temperature is different to conditions experienced by snow covers studied before[1]. It is also obvious that calm weather conditions, which are required for the acoustical measurements, are not frequent.

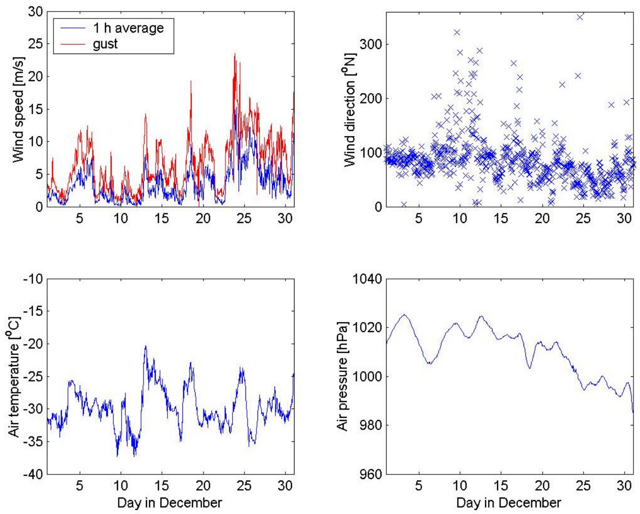


Figure 3: Weather data from Automatic Weather Station in Hourglass Bay, December 1999. Average air temperature over the month was –29.7 ^{o}C, while average wind speed was 3.6 m/s.

4. Methods

A Norsonic unit Nor-121 (Fig. 4 A) with a Nor-1211 microphone with reference direction in the axis of symmetry (0^{o}) (Fig 4 B) was used for acoustical measurements. For vibration measurements on the snow surface, Mark's L-15 dual coil geophones were used (Fig 4 C).

Sampling frequency was 12 kHz, fixed by the instrument. Since only one microphone was available, the experiment was carried out by shooting at several distances from 10 to 200 m from the source (Fig. 5). The shots were fired with intervals of less than one minute. Since ground conditions were rather homogeneous and weather conditions calm during the experiments, we assume this approach to cause only minor errors.

Several sound sources were tested out. Blank 30.06 calibre rifle shots were used in the first part of the experiment series, but these turned out to provide pulses with higher frequencies than expected. The spectra covered the range up to 1-2 kHz, and varied from shot to shot. The duration of the signals turned out to be only 2-3 ms. Thus, it turned out that these signals were not ideal for analysis. Later on 12 gage shotgun shots were used. These turned out to provide lower frequency pulses with most of the energy contained below 300 Hz, and were rather stable from shot to shot. Figure 6 compares pulses from the two sources. The two spectra show that, even if the central frequency of the 30.06 calibre signal is lower than that of the shot gun signal, the 30.06 signal contains more of the higher frequencies. However, some high frequency noise was also present in the shotgun pulses (probably made by the pellets), so that a low pass filter had to be applied for efficient comparison of measured and calculated waveforms. Maximum frequency was set to 1200 Hz, sufficient to cover most of the energy in the original signals (Fig 6). Figure 6 C shows the calculated source pulse (equation 6) as used in the inversions.

Figure 4: A) Nor 121 analyser. See www.norsonic.com.

B) Nor 1211 microphone. See www.norsonic.com.

C) Mark's L-15 dual coil geophone.

Figure 5: The test site in Hourglass Bay, February 2000. The picture is taken from the receiver position (viewing from S towards N), while the rifle or shotgun was fired along a line to the right of the person towards the hut in the background. Thus the shots were fired above an undisturbed snow cover.

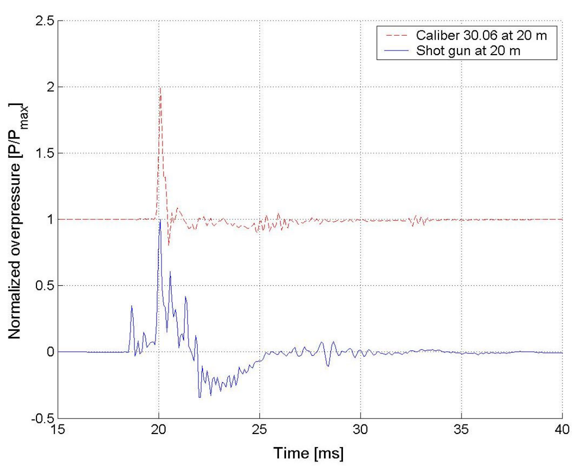
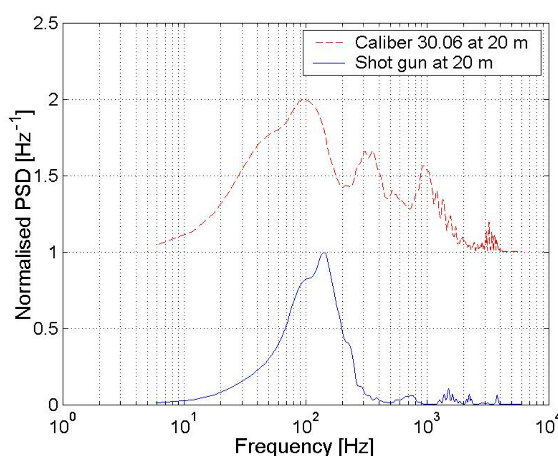
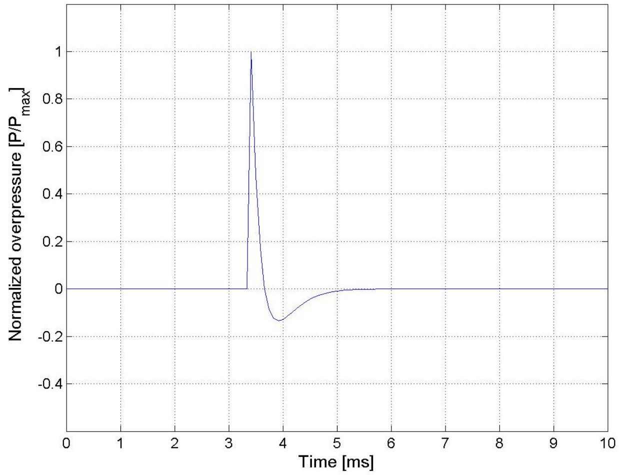


Figure 6: A) Pulses from calibre 30.06 rifle and shotgun at 20 m from source. Shots were fired at 1 m above ground, while the microphone was at the surface.



B) Spectra from calibre 30.06 rifle and shotgun at 20 m from source. Shots were fired at 1 m above ground, while the microphone was at the surface.



C) Source pulse calculated by equation 6, with $t_+ = 1.5$ ms.

5. Snow profiles and ground conditions

Snow characterization during the experiments was carried out according to the *International Classification for Seasonal Snow on the Ground*[19] and presented graphically using the program *SnowPro* from Gasman Industries Ltd. Here we present two snow profiles; one from the beginning (5 November 1999) and one from towards the end of the test period (22 February 2000). Very little precipitation was observed between these two dates. Most of the accumulating snow drifted away from the experiment site subsequently. Thus, the snow depth changed very little, as can be seen in Fig. 8. Symbols and terminology are described in Ref. 19.

The two snow pits were dug in the middle of the test field. Snow depth measurements on other points of the shooting line showed depths varying from 18 to 40 cm, with most values close to 30 cm. Figure 8 shows that except for one thin, hard ice layer observed in the first case, the snow was generally harder in late February than in the beginning of November. This is probably a result of wind effects and metamorphosis in the snow layer. In both cases there was a thin layer (1 cm or less) of fresh precipitation particles on top of the snow cover.

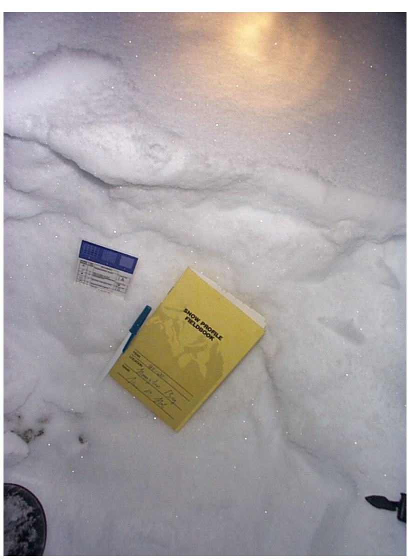


Figure 7: A) Snow pit on 5 November 1999. B) Snow pit on 22 February 2000.

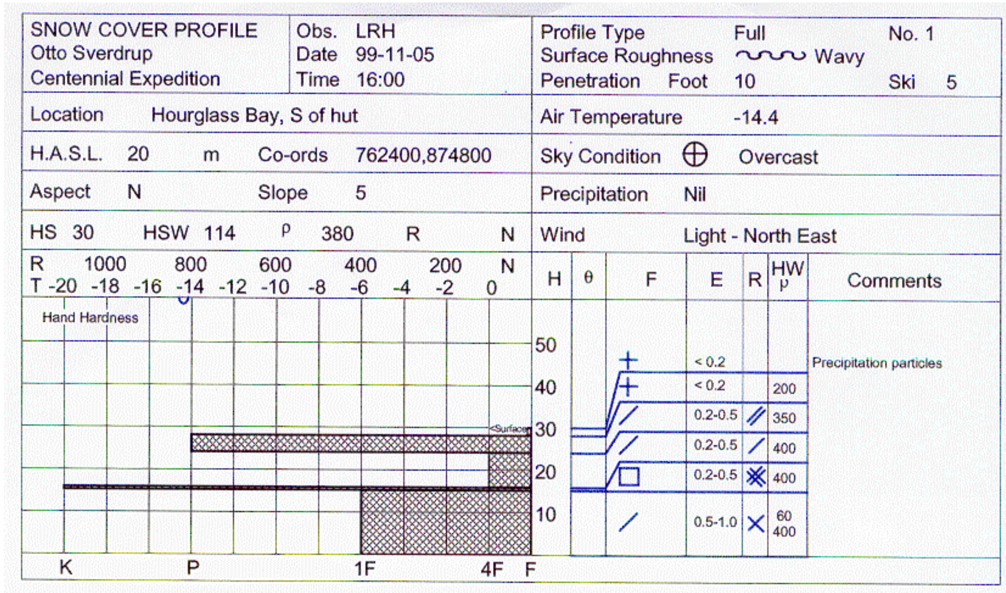
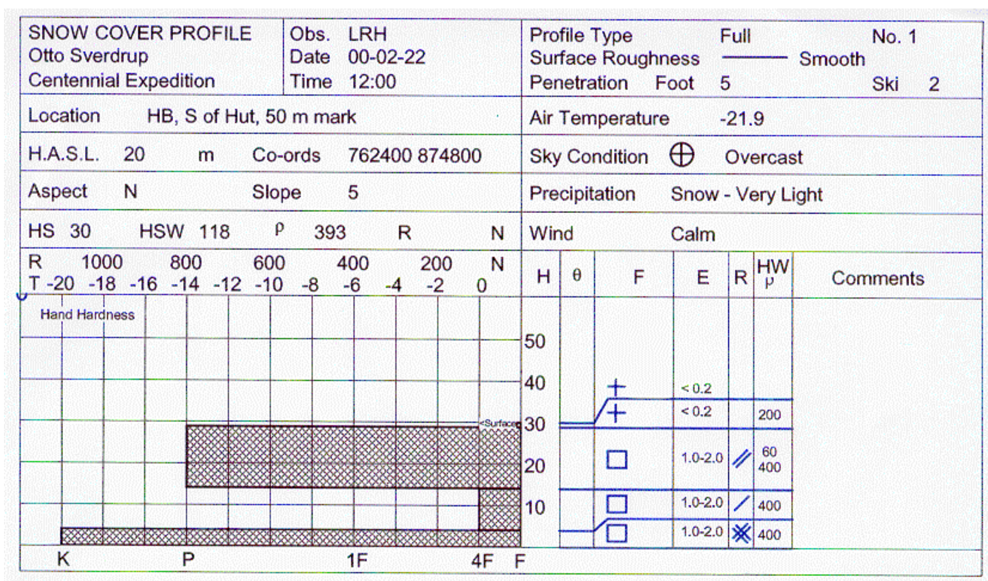


Figure 8: A) Snow cover profiles from 11 November 1999. Symbols and terminology as described in Ref. 19.



B) Snow cover profiles from 22 February 2000. Symbols and terminology as described in Ref. 19.

Surface penetration depth of ski and foot was also shallower later in the season. It is apparent from Fig. 8 that the average snow crystal size increased over the winter, a well-known phenomenon[20-22]. The ground under the snow turned out to be gravel with average size of 3-4 cm. It was frozen on top, so that we assume it to have a much higher flow resistivity than the snow. Figure 7 shows the snow pits and the gravel under the snow.

6. Measured and calculated pulses

As described in the previous section, snow conditions, and depth in particular turned out to be rather constant over the experiment period from October 1999 to April 2000. We had expected some heavy snow falls over the winter, but it turned out that most of the precipitation came in September. After

September, most of the local accumulation was caused by snow drifting. However, on the experiment site, no obvious drifts were observed.

Figure 9 A) shows spectra measured 22 February 2000, from 30 to 200 m from source (shotgun). The spectra are shifted from higher to lower frequencies with distance. Figure 9 B) shows the corresponding low pass filtered pulses, where high frequency noise has been removed. The main difference from earlier studies of softer snow covers, is that the negative phase is longer and much more shallow in the case studied here. Other data collected during the wintering show very similar features.

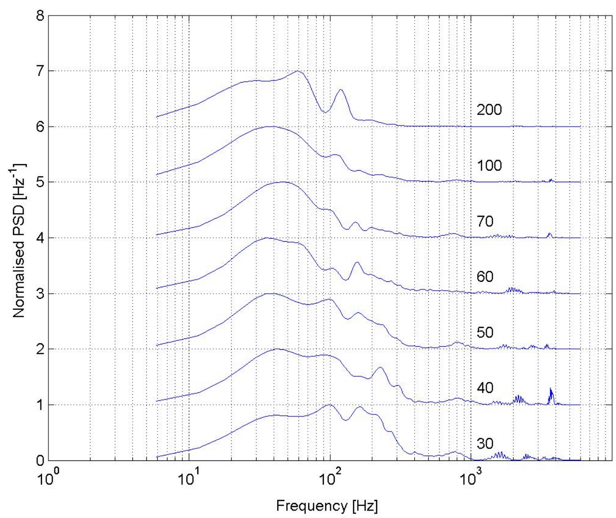
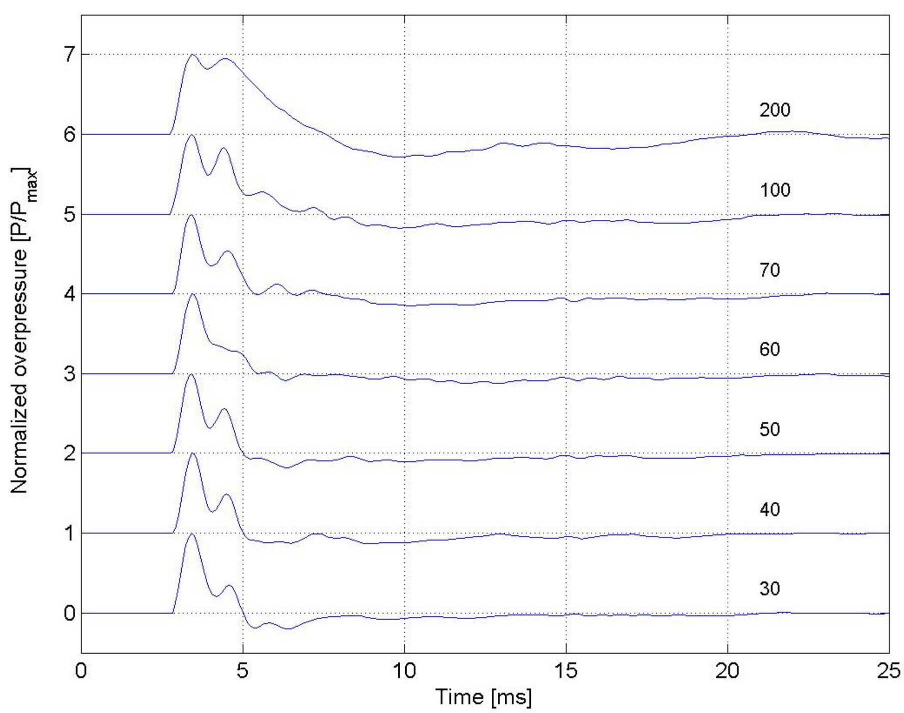


Figure 9: A) Spectra from Hourglass Bay 22 February, 1100 to 1110 local time (1700 to 1710 UTC).



B) Low pass filtered signals (maximum frequency = 1200 Hz) from 30 to 200 m. Hourglass Bay 22 February, 1100 to 1110 local time (1700 to 1710 UTC).

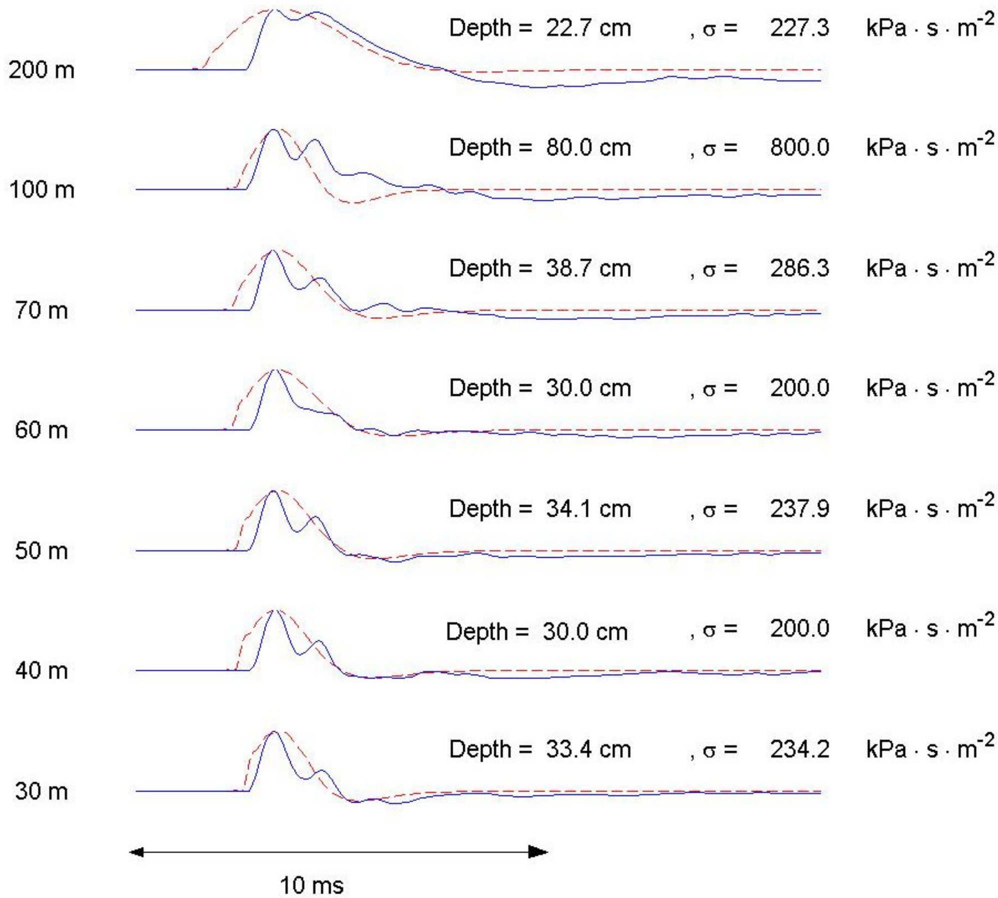


Figure 10: Comparison of measured and calculated pulses from 30 to 200 m on February 22, 2000. Blue solid lines are calculations, while red dashed lines are measurements. The measured data are the same as in Fig. 9. The estimated depth and flow resistivity is show for each range.

Figure 10 reveals that the inversion method provides depths and flow resistivities within a reasonable range except for the result at 100 m, which is clearly erroneous. The results must be seen as average values for the snow between source and receiver, and thus some variation between the cases can be expected. The curve fits are not as accurate as some observed earlier[1,5], but the inversion method has not been tested on this type of snow covers before.

Measurements of ground vibrations were carried out the same way as the acoustic measurements. Unfortunately, the geophones provided too low voltage for the NOR 121 to produce reliable results in most cases. Only at the shortest distances (10 and 20 m), were the results mostly meaningful. One set of measurements is presented here, but is not used in any analysis.

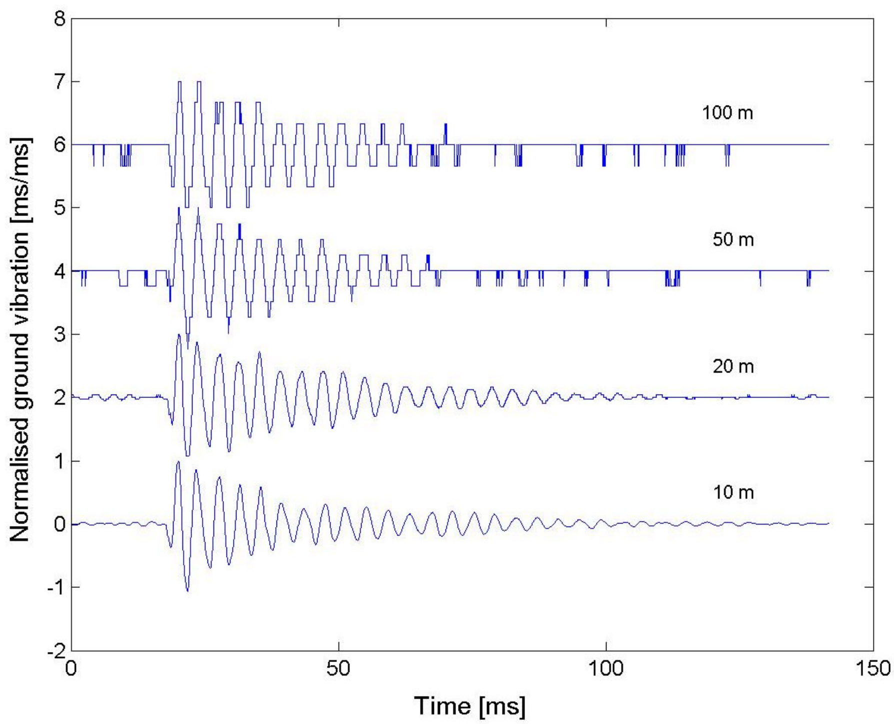


Figure 11) Snow surface vibration as measured on 22 November 1999, 1130 local time (1730 UTC).

AMBIENT NOISE MEASUREMENTS

On behalf of US Army Cold Regions Research and Engineering Laboratory (USACRREL), some measurements of ambient noise spectra were carried out during the wintering in Hourglass Bay. The data will be used for comparison with ambient noise data from areas with more vegetation and a different climate in New England, USA. The idea with the project is to obtain information of typical background noise levels for a range of environments and weather situations, and to look at the effect of different environmental factors such as vegetation and snow on the ground. Information of background noise is important when estimating total environmental noise. The intention of the project is also to correlate the variation in background noise spectra with local weather conditions.

In the Arctic, particular sources such as sea ice cracking, blowing snow and frozen ground cracking can be assumed to be present. Here, only some samples of the collected data are included. Data from one case is presented. On February 9, 2000, a sequence of measurements was undertaken 500 m North-East of the cabin 1500 to 1530 local time (2100 to 2130 UTC). Measurement series of 5 to 7 min were carried out at the following positions:

- Case 1: On land, microphone buried just under snow surface.
- Case 2: On land, microphone 1 m above snow surface
- Case 3: On ice, microphone just at snow surface.
- Case 4: On ice, microphone just under snow surface.

The average wind speed was 10 m/s from NE and the air temperature was –30 °C with clear sky conditions. There was light snow drifting in the lowest meter above ground. The sampling interval for these measurements was 0.5 sec. Figure 12 shows that the unweighted Sound Pressure Level (SPL) for each case, does not vary much with time. I.e., for the four different cases the SPL seems to oscillate around a rather constant running average. However, the average SPL for case 2 is about 20 dB higher than for case 4.

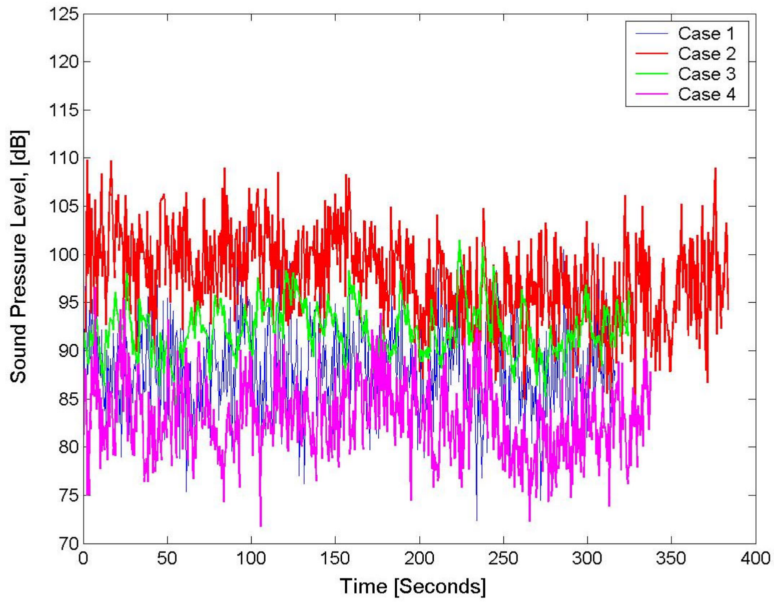
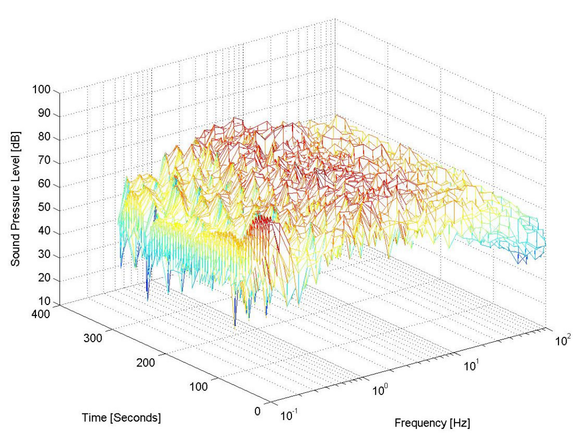


Figure 12: Sound pressure levels as measured on February 9.

Figure 13 shows the variation of the spectra with time for the four cases. For frequencies above 100 Hz, there are clear differences from case to case, while for frequencies below 100 Hz the four cases are much more similar. For case 3 and case 4, some spike in the spectra are visible. These are probably associated with cracking in the ice along the shore. The cracking was caused by tidal changes, and was clearly audible during the measurements.



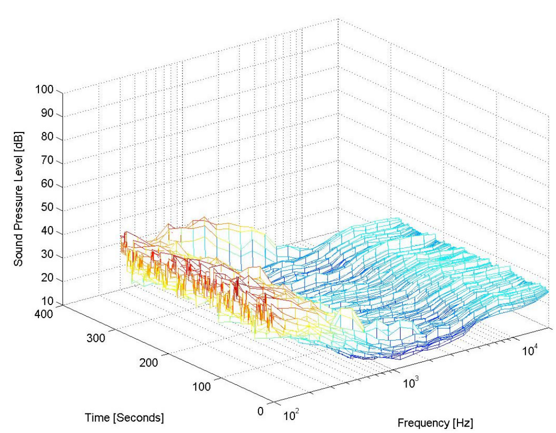
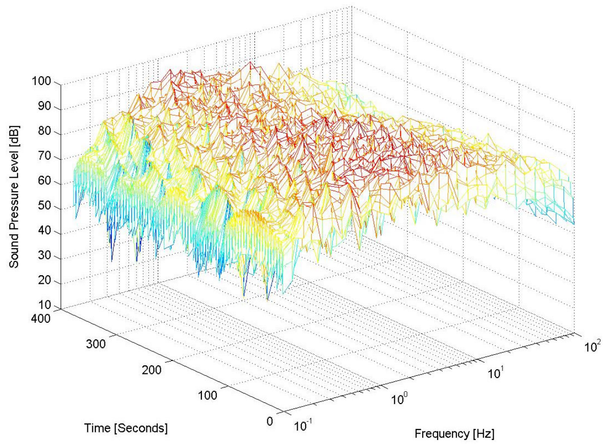
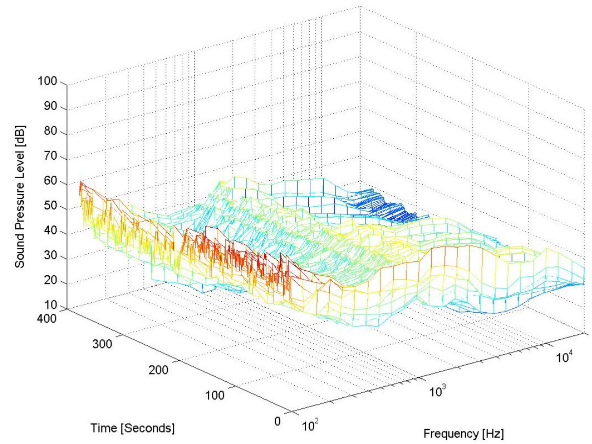


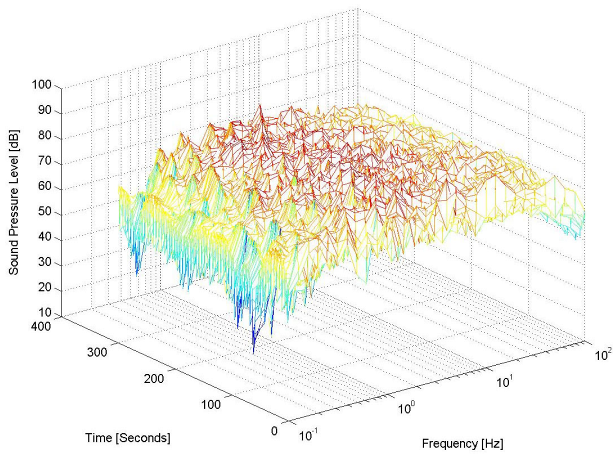
Figure 13: A) Case 1. SPL from 0.1 to 100 Hz. B) Case 1. SPL from 100 Hz to 11 kHz.



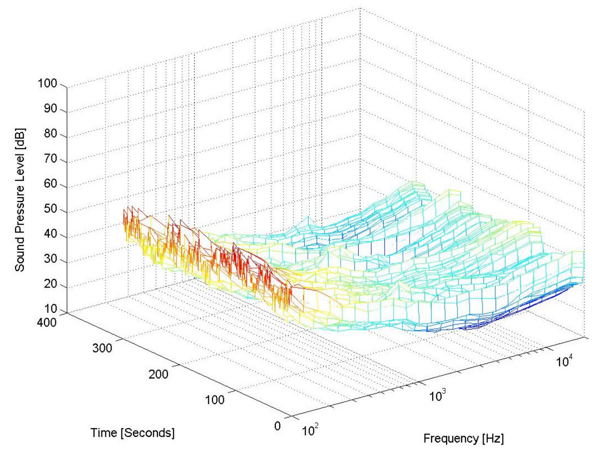
C) Case 2. SPL from 0.1 to 100 Hz.



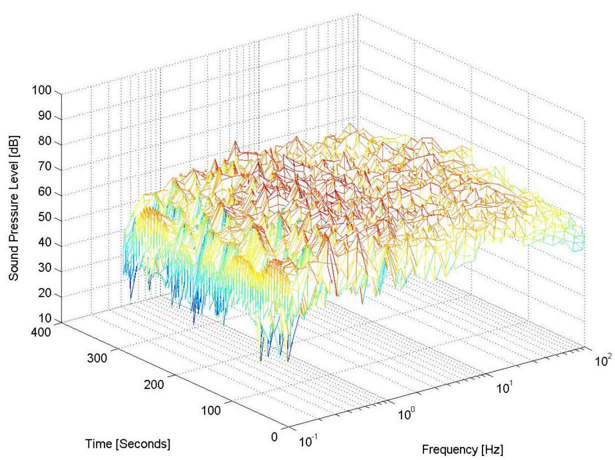
D) Case 2. SPL from 100 Hz to 11 kHz.



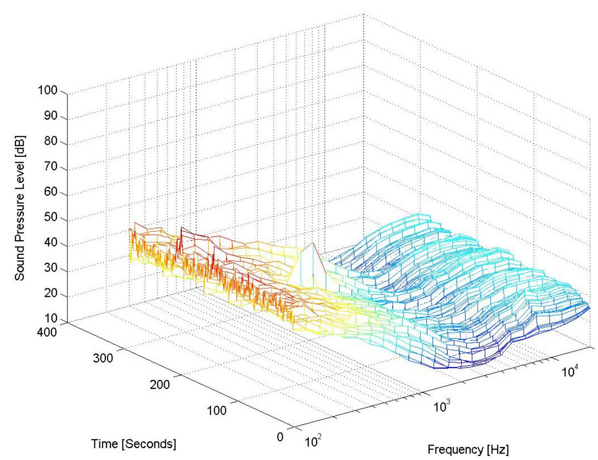
E) Case 3. SPL from 0.1 to 100 Hz.



F) Case 3. SPL from 100 Hz to 11 kHz.



G) Case 4. SPL from 0.1 to 100 Hz.



H) Case 4. SPL from 100 Hz to 11 kHz.

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