

PRELIMINARY ANALYSIS OF MEASURED SOUND PROPAGATION OVER  
VARIOUS SEASONAL SNOW COVERS

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**ABSTRACT**

Measurements of acoustic pulse propagation in the 5- to 500-Hz frequency band were conducted under various snow cover conditions during the 1989–1990 winter in New Hampshire. The objective was to determine the effect of snow cover thickness and other snow properties on the absorption of acoustic pulses. Blank pistol shots were used as the source of the acoustic waves, and geophones and microphones in an 80-m-long linear array served as receivers. Snow thicknesses ranged from 0.05 to 0.35 m, and densities varied from 100 to 350 kg m<sup>-3</sup> during the 10 separate measurement days. Preliminary analysis indicates that the peak pulse amplitude decayed in proportion to  $\sim r^{-1.7}$  for most conditions and that the acoustic-to-seismic ratios varied from about 4 to 15 x 10<sup>-6</sup> m s<sup>-1</sup> Pa<sup>-1</sup>. Theoretical waveforms were calculated for propagation in a homogeneous atmosphere using Attenborough's model of ground impedance. An automatic fitting procedure for the normalized experimental and theoretical waveforms was used to determine the effective flow resistivity of the snow covers, and gave values of 10 to 35 kN s m<sup>-4</sup>, in agreement with earlier results.

**INTRODUCTION**

Absorption of sound energy by the ground is important in understanding noise propagation through the atmosphere. It affects predictions of traffic, industrial, or blasting noise levels, which are becoming increasingly important in mitigating or preventing community noise problems and assessing environmental impacts of various activities. In previous work it has been shown that a snow cover has a large effect on acoustic pulse propagation, causing increased attenuation and marked waveform changes compared with propagation over grassland (Ref. 1). Those measurements were for a single snow cover, so measurements were undertaken during the 1989–1990 winter to investigate additional snow covers and to examine the effect of snow cover thickness and other snow properties on pulse propagation. This paper reports on the experimental approach, preliminary results of data analysis, and first steps towards an automatic inversion procedure to determine acoustically the properties of the snow cover.

**EXPERIMENTAL MEASUREMENTS**

As in previous measurements, a .45 caliber blank pistol held and fired 1 m above the surface was used as the source of the acoustic waves. The receivers were a linear array of 4.5-Hz Mark Products Model L-15B geophones and Globe Model 100C low frequency microphones. Two Bruel & Kjaer Type 4165 microphones were used to record the source pulse. Both types of microphones have a flat response in the frequency band of interest. A Bison Model 9048 recording system was used to acquire 48 channels of data at a 5-kHz rate. The bandwidth of the measurements is estimated as 5–500 Hz and is limited mainly by the source output.

In the fall of 1989, vertical and horizontal component geophones were installed along a relatively flat 80-m-long line. A few geophones were also buried 0.5 m deep in the soil 30 and 60 m away from the location of the source. During the winter, just before each measurement period, geophones and microphones were installed at the snow surface and probe microphones (Ref. 2) were inserted into the snow. A number of pistol shot responses were then recorded, and these sensors were removed after that day's measurements were completed. Only the surface sensors will be discussed in this paper.

On the days that acoustic experiments were conducted, a snow characterization pit was dug and the temperature, density, grain size, and crystal type were determined for each layer present. Snow and frost depths were also recorded.

Meteorological data were collected using a Campbell Scientific Model 21X data logger. Temperatures were measured within the ground and snow and at heights of 0.01, 0.03, 0.1, 0.3, 1, 3, and 5 m in the air. Wind speeds at 1- and 3-m heights were also recorded, along with relative humidity and barometric pressure. Measurements were taken every minute, but averages, variations (minimum, maximum, and standard deviation), and instantaneous values were recorded every 10 and every 30 minutes during the acoustic experiments. Values were recorded every 4 hours during the rest of the winter.

### ACOUSTIC WAVEFORM ANALYSIS

Figure 1 shows the waveforms recorded on nine separate days by the Globe 100C low frequency surface microphones a distance of 60 m from the source. The positive peak amplitudes of these pulses, along with the air temperature, snow depth, and snow density (for the surface layer) are given in Table 1. (Experiment 4 used a different sensor array than the rest of the experiments and has not yet been analyzed.)

TABLE 1. MEASURED AMPLITUDES, ENVIRONMENTAL PARAMETERS, AND BEST FITTING WAVEFORM PARAMETERS FOR THE 1989-1990 WINTER EXPERIMENTS.

Expt No	Date (1989-1990)	Amplitude, (Pa, at 60 m)	Air temp. (°C)	Snow depth (mm)	Snow density (kg/m <sup>3</sup> )	Flow resistivity (kN s/m <sup>4</sup> )	Change in fitted snow depth (mm)
1	29 Dec	3.1	-12.4	185	170	25	0
2	4 Jan	4.9	3.1	170	260	30	0
3	10 Jan	4.3	1.3	140	280	35	-50
4	19 Jan	17.0	-3.0	50	210	—	—
5	22 Jan	2.0	-5.3	190	100	10	+50
6	31 Jan	2.2	-2.8	350	140	10	0
7	8 Feb	1.9	3.0	280	150	10	+50
8	6 Mar	3.3	-4.0	140	340	35	-50
9	15 Mar	16.1	14.3	0-60	350	—	—
10	12 Apr	16.7	3.2	0	300	—	—

Note: The snow cover was continuous for all of the experiments except for experiment number 4 (9/10 of the ground was covered), experiment number 9 (5/10 covered), and experiment number 10 (no snow).

The two largest arrivals were recorded on days when there was little or no snow cover present, and have amplitudes about five times larger than the pulses recorded when snow was present. The waveforms recorded over snow are all elongated to various degrees, and exhibit relatively stronger low frequency content than those recorded without snow present.

In Reference 1, a method of calculating theoretical acoustic pulse waveforms from known surface properties was developed and verified. The procedure is briefly outlined here. For a monofrequency source in the air and a receiver on the surface, the acoustic pressure a slant distance ( $r$ ) away from the source is given by

$$P/P_0 = 1/kr e^{ikr} (1 + Q)$$

where  $P_0$  is a reference source level,  $k$  is the wave number in air,  $Q$  is the image source strength representing the effect of the ground, and  $e^{-i\alpha x}$  is suppressed. At high frequencies ( $kr \gg 1$ ),  $Q$  can be written as (Ref. 3 and 4)

$$Q = R_p + (1 - R_p) F(w)$$

where  $R_p$  is the plane wave reflection coefficient,  $F$  is the ground wave term, and  $w$  is a numerical distance, all of which depend on the specific impedance  $Z_g$  of the ground. The impedance is itself dependent upon frequency; thus, so is  $Q$ . [The elongation and relatively stronger low frequency content of the measured waveforms in Figure 1 can be explained theoretically by the decrease in  $R_p$  at high frequencies and the

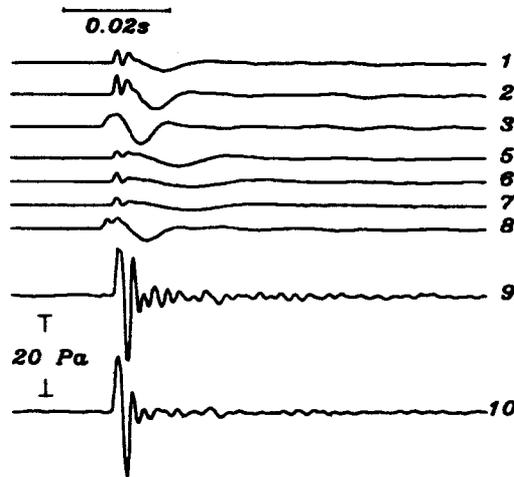


Figure 1. True amplitude, time aligned, low frequency surface microphone waveforms at 60-m range from a .45 caliber pistol shot 1 m high above the snow or ground surface. These waveforms were recorded with the same microphone on nine separate days, and the numbers refer to the measurement days listed in Table 1. The two largest waveforms occurred on days when there was very little or no snow cover present. Note that waveforms 3 and 8 are slightly misaligned in time; the shift is the result of the low frequency portion of the waveform being larger than the direct arrival.

enhancement of  $F(\omega)$  at low frequencies (see Ref. 1, Fig. 4).] By determining  $Q$  over the frequency band of interest, an inverse FFT\* can be used to construct theoretical pulse waveforms in the time domain. Nicolas et al. (Ref. 5) have shown that an explicitly layered model of the ground must be used to represent thin snow covers, and this was done in the calculations presented here using

$$Z = (Z_3 - i Z_2 \tan k_2 d) / (Z_2 - i Z_3 \tan k_2 d)$$

where  $d$  is the snow layer thickness,  $k_2$  is the wave number in the layer, and  $Z_2$  and  $Z_3$  are the impedances of the layer and substratum, respectively (Ref. 6).

The impedance  $Z_2$  and wave number  $k_2$  of the snow were calculated using Attenborough's (Ref. 7) four-parameter model. For all of the calculations, the grain shape factor  $n'$  was set to 0.5 and the pore shape factor ratio  $s_f$  was 0.8. The porosity  $\Omega$  was determined from the measured density of the snow, and the effective flow resistivity  $\sigma$  was allowed to vary.

A new result presented in this paper is a method of comparing calculated and observed acoustic pulse waveforms. A suite of waveforms were calculated and the best fitting waveform was selected under the  $L_1$  norm criterion (i.e., the sum of the absolute value of the differences between the calculated and observed waveforms over a fixed time window). A least squares criterion, the  $L_2$  norm, was avoided because it heavily weights, and tries to reduce, the maximum misfit. Since the source pulse in the calculations is an assumed one, and not actually measured, I wanted to allow for errors in this assumed pulse to be ignored while accurately fitting the overall, low frequency portion of the measured waveforms accurately.

Eight theoretical waveforms were calculated to fit the observed waveform at  $r = 60$  m using the measured snow thickness and porosity, with the effective flow resistivity  $\sigma$  varying from 5 to 40  $\text{kN s m}^{-4}$ . Then, for the best  $\sigma$ , four additional waveforms were calculated, with the snow thickness changed by  $\pm 0.05$ - and  $\pm 0.1$ -m increments from the measured thickness to see if the fit could be improved. An example is given in Figure 2.

**\*Fast Fourier Transform**

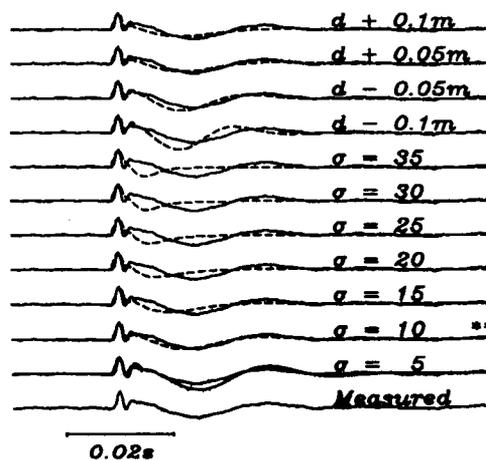


Figure 2. Comparison between normalized measured and calculated waveforms for experiment number 6 (see Table 1) at a range of 60 m. The solid lines are the measured waveform; the dashed lines are calculated waveforms with the indicated effective flow resistivities  $\sigma$ . The measured snow depth  $d$  was 0.35 m. Stars mark the best fitting waveform.

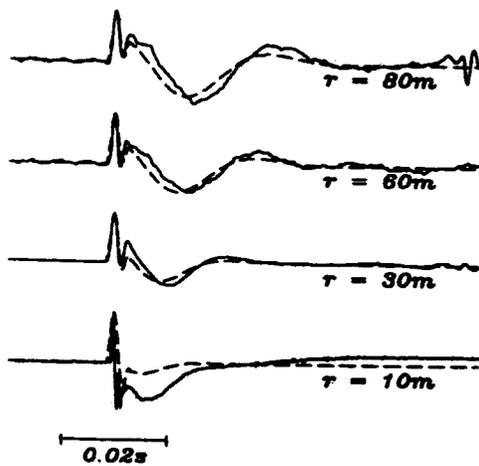


Figure 3. Comparison between normalized measured (solid) and calculated (dashed) waveforms for experiment number 6. The waveforms at all the ranges were calculated using the parameters from the fitting procedure at 60 m. At 10-m range, a Bruel & Kjaer Type 4165 microphone 0.3 m above the snow was used (and the measured waveform shows some evidence of being clipped); the other measurements were made with Globe Model 100C low frequency microphones on the snow surface.

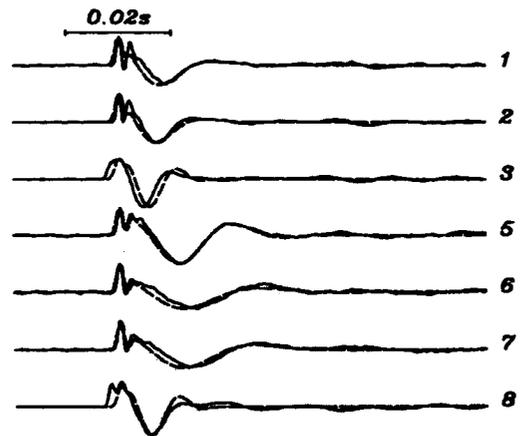


Figure 4. Comparison of normalized measured (solid lines) and calculated (dashed) waveforms at 60 m for propagation over various snow covers. The numbers refer to the experiment numbers given in Table 1, where the best fitting flow resistivities and snow layer thicknesses are listed.

In this case the best fit was obtained for  $\sigma = 10 \text{ kN s m}^{-4}$  and the measured snow thickness. Using these best fit values of  $\sigma$  and  $d$ , more waveforms were then calculated for different propagation ranges. The comparisons between these waveforms and observations are shown in Figure 3, and the agreement is quite good.

All the measured and best-fit calculated waveforms for snow are shown in Figure 4. The fitting procedure has been able to automatically match waveforms of quite different appearance. The last two columns of Table 1 list the effective flow resistivities and snow depths determined using this fitting procedure. In all cases the snow thickness was within  $\pm 0.05 \text{ m}$  of the measured thickness, a reasonable variation considering the variation in the actual snow cover thickness across the propagation path.

### ADDITIONAL ACOUSTIC MEASUREMENTS

The amplitude decay as a function of range was determined by least squares fitting of the data from the low frequency microphones to

$$A(r) = A(r_0) r^{-\alpha}$$

where  $r$  is the propagation distance in m,  $A(r)$  is the peak amplitude in Pa at range  $r$ ,  $A(r_0)$  is the source amplitude at a reference distance  $r_0$ , and  $\alpha$  is the distance attenuation exponent. For the data analyzed so far, the results are given in Table 2. Values of  $\alpha$  for snow range from 1.6 to 1.9, compared with the expected 1.0 from spherical spreading. For the last two experiments, with little or no snow present, the coefficient is around 1.1.

TABLE 2. RANGE DECAY COEFFICIENT AND ACOUSTIC-TO-SEISMIC COUPLING RATIO MEASURED FOR AIR WAVES.

Expt No.	Date	Range decay coefficient $\alpha$		Acoustic-to-seismic coupling ratio, $\text{m s}^{-1} \text{Pa}^{-1}$			
		No. of points	Value of $\alpha$	95% confidence interval	No. of points	Value of coupling ratio	95% confidence interval
1	12-29-90	12	-1.60	$\pm 0.30$	10	4.01	$\pm 1.25 \times 10^{-6}$
2	1-04-90	13	-1.71	$\pm 0.49$	10	6.35	$\pm 5.18$
3	1-10-90	18	-1.69	$\pm 0.22$	15	3.41	$\pm 0.87$
4	1-19-90						
5	1-22-90	8	-1.76	$\pm 0.64$	6	5.10	$\pm 5.03$
6	1-31-90	18	-1.84	$\pm 0.22$	15	15.1	$\pm 2.77$
7	2-08-90	16	-1.91	$\pm 0.36$	13	5.93	$\pm 1.49$
8	3-06-90	18	-1.73	$\pm 0.16$	12	4.27	$\pm 1.07$
9	3-15-90	11	-1.05	$\pm 0.46$	9	6.28	$\pm 2.66$
10	4-12-90	30	-1.12	$\pm 0.19$	25	10.2	$\pm 1.69$

The ratio of induced particle velocity in the snow or soil to incident pressure was determined from the collocated surface vertical component geophones and surface microphones (Table 2). These ratios vary from 3 to  $15 \times 10^{-6} \text{ m s}^{-1} \text{ Pa}^{-1}$ . Note that some of the values have very poor confidence intervals (e.g., experiments 2 and 5). It is hoped that these values will be better determined when all of the data are analyzed.

## CONCLUSIONS

The experiments were successful in obtaining accurate measurements of pulse propagation over a variety of seasonal snow covers. Preliminary values have been presented for the range decay and acoustic-to-seismic coupling coefficients, and more accurate values will be provided when the data analysis is completed. I have also demonstrated a waveform matching procedure that can be used to select the theoretical waveform that best fits the measured data.

Future work will include completing the data analysis, including determination of attenuation coefficients in the snow from the probe microphone recordings, and correlating the acoustic effects with the snow cover properties. A true waveform inversion procedure will also be developed.

## ACKNOWLEDGMENTS

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