Acoustic Pulse Propagation Over a Seasonal Snow Cover

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ABSTRACT

The absorption of sound energy by the ground has been studied extensively because of its importance in understanding noise propagation through the atmosphere. Snow is of interest in this regard because it is the most absorptive naturally occurring ground cover. To quantify the effect of snow, measurements of acoustic pulse propagation were conducted in the 5- to 500-Hz frequency band over various snow covers and over snow-free grass and frozen ground. Blank pistol shots fired 1 m above the snow surface were the source of the acoustic pulses, and geophones and microphones arranged in a linear array were used to record the resultant waveforms. The peak pulse amplitudes decayed much faster with distance over snow than over snow-free grass; an order of magnitude difference in the sound pressure levels was recorded after 100 m of propagation. The acoustic waveforms were also markedly changed after propagating over snow, with broadened pulses and enhanced low frequencies. The pulse shapes and peak amplitude decay rates were successfully predicted theoretically using a layered, rigid-frame, porous medium model of the snow. The effective flow resistivity of the snow was determined by matching theoretical and observed waveforms, and this method gives promise of becoming a useful method of estimating the intrinsic permeability of the snow.

INTRODUCTION

The propagation of sound through the atmosphere is controlled by a number of factors, including meteorological conditions, source characteristics, absorption, and ground conditions. For low frequency, horizontally propagating acoustic waves traveling short distances, ground absorption is usually the most important parameter, and it has been studied extensively (Embleton et al. 1976, Sabatier et al. 1986, Embleton and Daigle 1987, Attenborough 1988) because of its importance in practical applications such as predicting sound levels produced by traffic or industrial noise, artillery firing, construction blasting, and other sources. Snow represents an extreme case in the study of ground absorption, because it is by far the most absorptive naturally occurring ground cover.

Acoustic propagation above snow has been studied rather infrequently (Ishida 1965, Gubler 1977, Embleton et al. 1983, Nicolas et al. 1985 and references therein). Most studies used continuously emitting sources (tones from loudspeakers) at high frequencies and short ranges, which provide transmission loss estimates but do not allow details of the acoustic waveforms to be observed. Because of the high frequencies employed in these experiments, the propagation ranges were limited to less than 15 m, and were usually 1–2 m. Although these measurements gave some useful information, Sommerfeld's review (1982) has pointed out that the lack of long-range acoustic measurements was a noticeable gap in the field. Apparently, only Gubler (1977) previously made impulse measurements over snow; he reported only the amplitude decay rates observed and did not make waveform comparisons.

The approach taken for the experiments reported in this paper was to use broadband impulses as the source of the acoustic waves, so that the wave amplitude, shape, and frequency content could be accurately measured as the wave propagated horizontally above a snow layer. First, a long-range experiment (propagation distances up to 274 m) was conducted to directly compare summer (grass) and winter (snow) conditions. Then, additional experiments were conducted over various snow covers to quantify the variations expected in New England seasonal snow covers. Work on different snow covers continues each winter. Theoretical calculations matching the observed waveforms show that the snow depth and permeability are the most important parameters controlling the waveform appearance, and that measurements of acoustic pulses have the potential to provide a relatively simple method of determining the snow cover's permeability in situ, a measurement that is currently difficult to make (Chacho and Johnson 1987, Sommerfeld 1987).

In the next section, the experimental measurements are presented. The following section discusses the method used to predict the pulse waveforms expected after propagation along an absorbing boundary and compares theoretical and observed waveforms. The predicted and observed amplitude decay as a function of range is also presented. A discussion of measurements over a number of different snow covers is followed by a summary.

EXPERIMENTAL MEASUREMENTS

For these experiments, a loud, repeatable sound source was needed, and after some experimentation, 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 Globe model 100C low-frequency microphones, having a flat response in the frequency band of interest, that were arranged on or near the snow surface various distances away from the source. The data were recorded digitally, using either a Geosource DSS-10 or a Bison 9048 seismic recording system. The bandwidth of the measurements is estimated as 5–500 Hz and is limited mainly by the source output.

For all of the measurements, 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, along with wind, temperature, and relative humidity values.

Figure 1 compares two sets of acoustic waveforms recorded near Burlington, Vermont, at the same source and receiver locations under summer and winter conditions. In the summer, the site was covered by grass approximately 0.20 m tall. During the winter measurements, a snow cover approximately 0.15–0.32 m deep was present, consisting of five distinct

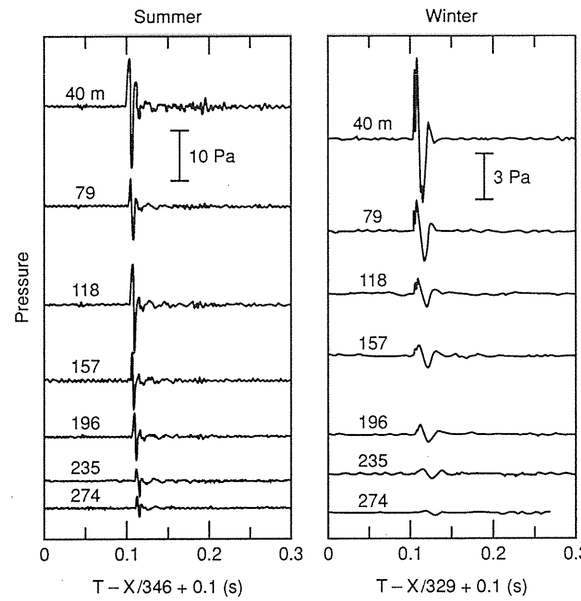

Figure 1. Observed surface microphone waveforms from a blank pistol shot 1 m high in the summer (left) and winter (right), recorded at a site near Burlington, Vermont. The source and receiver locations were identical for both seasons; note, however, that the amplitude scales are different. The different propagation speeds (346 vs. 329 m s^{-1}) are caused by the difference in air temperature (28° vs. –5 °C). The lower amplitudes and broader waveforms in the winter are caused by sound absorption by the snow cover.

layers with densities ranging from 190 to 290 kg m^3. Despite the use of the same source (a .45 caliber blank pistol shot) and identical recording equipment and geometry, the waveforms are quite different in appearance, with the winter pulses lower in amplitude, elongated, and exhibiting enhanced low frequency content. These differences were audible during the experiments, with the pistol sounding as one would expect during the summer, a loud, sharp crack ("bang!"), while in the winter it sounded like a low frequency "whump." The winter pulses also arrived later than the summer pulses, because of the lower air temperature.

The frequency content of two of the signals, for a source-receiver separation of 196 m, is shown in Figure 2. Here, the broadband nature of the summer waveform is obvious, extending from 5 to 500 Hz. In the winter, frequencies above 100 Hz are severely attenuated, but some low frequencies are enhanced. The high frequency losses are caused by viscous and inertial losses as air is forced into the pores of the snow by the pressure pulse. The enhancement at low frequencies is caused by the time delay for the air to

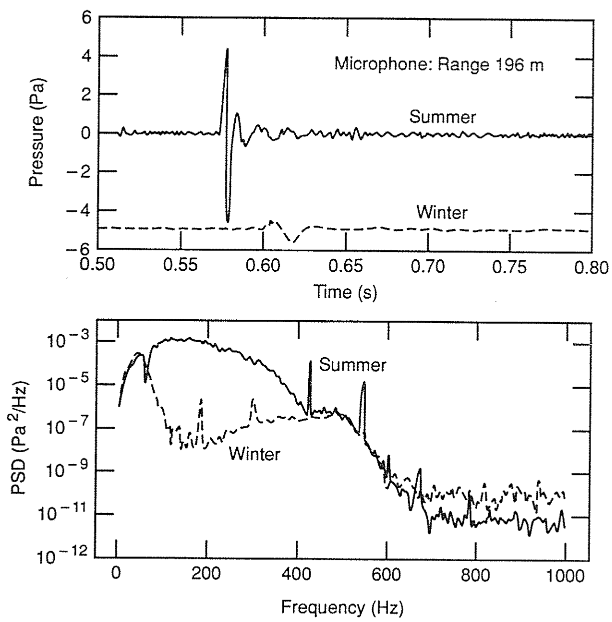

Figure 2. Power spectral density (PSD) as a function of frequency for surface microphones in the summer and winter. The top panel shows the time domain waveforms; the bottom panel shows the power spectra calculated from these waveforms. The source was a blank pistol shot 1 m above the ground and 196 m away from the sensors. A 60-Hz notch filter was used during the recordings, and additional noise peaks are present at harmonics of this frequency. In addition, the slope in the spectra caused by the 500 Hz low pass anti-aliasing filter is visible. Frequencies above 100 Hz are strongly attenuated by the snow cover in the winter.

return from the snow to the atmosphere. This response time depends on the snow thickness and permeability.

CALCULATING ACOUSTIC WAVEFORMS

Albert and Orcutt (1990) developed and verified a method of calculating theoretical acoustic pulse waveforms from (assumed) known surface properties. The procedure is briefly outlined here. For a monofrequency source in the air and a receiver on the surface, the acoustic pressure a distance r away from the source is given by

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

where P_0 is a reference source level, k is the wave number in air, and Q represents the effect of the ground. At high frequencies ($kr >> 1$), Q can be written as

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

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_2 of the ground. These expressions are known as the Weyl–van der Pol solution, and were originally derived for electromagnetic waves early in this century. The impedance is itself dependent upon frequency; thus, so is Q. By determining Q over the frequency band of interest, then multiplying by the source excitation and the instrument response, an inverse Fourier transform can be used to construct theoretical pulse waveforms in the time domain. Nicolas et al. (1985) 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 the expression (Brekhovskikh 1980)

$$Z = \frac{Z_2\left(Z_3 - i\, Z_2 \tan k_2 d\right)}{\left(Z_2 - i\, Z_3 \tan k_2 d\right)}$$

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 layer and substratum, respectively.

The impedance Z_2 and wave number k_2 of the snow were calculated using Attenborough's (1985) rigid-frame porous medium model. This model uses four parameters to describe the porous medium: the effective flow resistivity σ (which, at zero frequency, is equivalent to the dynamic viscosity η divided by the permeability k_0), the porosity Ω, and two parameters describing the microstructure, a grain shape factor n' and a pore shape factor ratio s_f. For all of the calculations, the grain shape factor and the pore shape factor ratio s_f were set to 0.5 and 0.8, respectively, values that are consistent with Buser's (1986) and Attenborough and Buser's (1988) fitting of impedance tube measurements of snow. The porosity was determined from the measured snow density, and the effective flow resistivity σ was varied until the calculated waveforms agreed with the measured waveforms.

Examples of the measured and best-fit calculated waveforms for grass and snow are shown in Figure 3. The model has been able to match these waveforms of quite different appearance. For grass, the best fitting flow resistivity was 200 kN s m^{-4}, corresponding to a permeability of about 0.88×10^{-10} m^2, while for snow the flow resistivity used was 20 kN s m^{-4}, $k_0 \approx 8.7 \times 10^{-10}$ m^2.

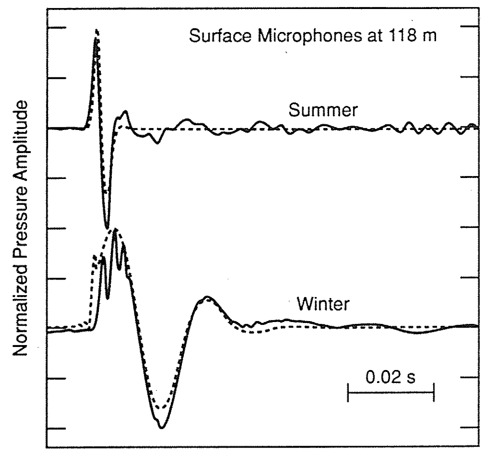

Figure 3. Comparison of normalized waveforms for pulse propagation over grassland and snow for a range of 118 m. The solid lines are the waveforms recorded by surface microphones, and the dashed lines are waveforms calculated using Attenborough's (1985) model of ground impedance. The observed peak amplitudes were 9.1 Pa in the summer and 0.91 Pa in the winter. For the calculated waveforms, an effective flow resistivity σ_e of 200 kN s m^{-4} was used in the summer. In the winter, a value of 20 kN s m^{-4} was used, along with a snow layer depth of 0.15 m.

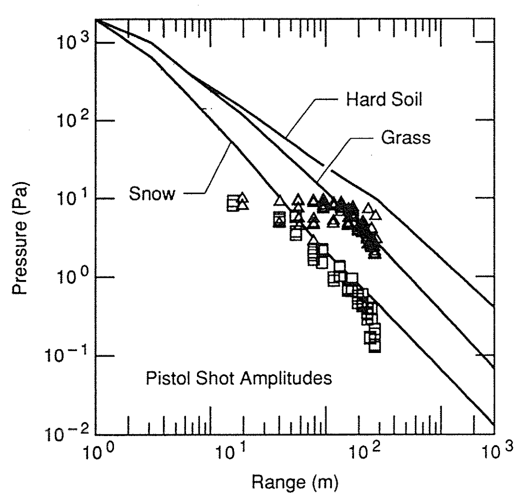

Figure 4a. Plot of first arrival amplitude vs. distance from the source for pulse propagation over grassland (triangles) and snow (squares), as measured by surface microphones. The lines are amplitudes calculated using effective flow resistivities of 1820 (hard soil), 200 (grass), and 20 kN s m^{-4} (snow). The flat trend in the microphone amplitudes at the shorter ranges is the result of exceeding the dynamic range of the microphones (see text).

The amplitude decay as a function of range can be determined by least squares fitting of the data from the surface microphones to

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

where r is the propagation distance in meters, $A(r)$ is the peak amplitude in pascals at range r, $A(r_0)$ is the source amplitude at a reference distance r_0, and α is the distance attenuation exponent. If the ground were a perfectly rigid surface, a value of $\alpha = 1.0$ would be expected from spherical spreading of the wavefront; higher values of α indicate absorption of energy by the ground surface.

Figure 4 compares the peak sound pressure levels measured as a function of range in the summer and winter (symbols), along with theoretically calculated levels (lines). Figure 4a shows the measurements made with microphones located on the grass or snow surface. In the summer, 92 measurements were made with microphones. The plot shows that the short-range microphone measurements were clipped until the propagation range exceeds 100 m; then the amplitudes match those calculated for grass quite well. In the winter, only a few of the 56 microphone amplitudes, those for ranges less than 40 m, may be clipped. The observations agree with the absolute amplitudes and with the decay rate calculated for snow.

Because of the microphone clipping problem, surface geophones were also used to compare the summer and winter amplitudes (Fig. 4b). These sensors re-

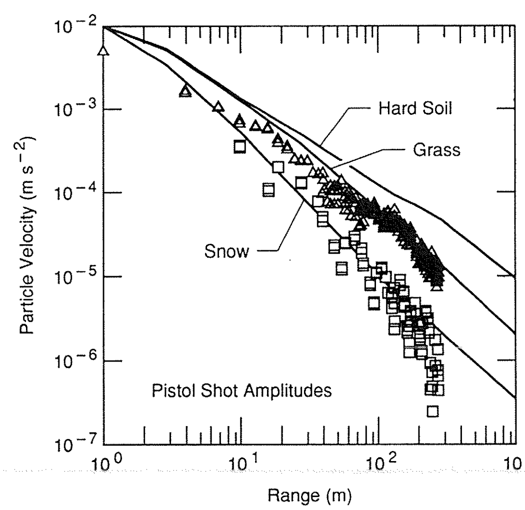

Figure 4b. Plot of first arrival amplitude vs. distance from the source for pulse propagation over grassland (triangles) and snow (squares), as measured by surface geophones. The lines are amplitudes calculated using the same parameters as for Figure 4a.

spond to the direct air pulse that propagates in the atmosphere and couples locally into the ground. The calculated pressure amplitudes were converted to particle velocity using an estimated source amplitude of 2 kPa at 1 m and the measured acoustic-to-seismic coupling ratio of 6×10^{-6} m s^{-1} Pa^{-1}. The summer levels are larger than those measured in the winter, and decay proportional to $r^{-1.2}$ vs. $r^{-1.9}$. The theoretical and observed decay rates are in good agreement.

SNOW COVER VARIATIONS

To investigate the variations in acoustic propagation above a snow cover, an additional series of measurements was conducted over the course of a winter at Hanover, New Hampshire (Albert 1990). At this site, the propagation distance was more limited than in the previous experiment. Example waveforms recorded on seven separate days by surface microphones 60 m from the source are shown in Figure 5 (solid lines). Once again the waveforms recorded over snow are all elongated to various degrees, and exhibit relatively stronger low frequency content than those recorded without snow present. These observations were automatically fitted with theoretical waveforms (dashed lines), leading to the effective flow resistivity and permeability estimates given in Table I.

The acoustically determined permeability values fall within the range of values previously reported in the literature by others using laboratory permeameters (see Fig. 6). Some caution should be associated with the acoustic permeability values, however, because they were calculated using a high frequency determination of the effective flow resistivity. Since the permeability is a static parameter, there may be some bias in the estimate. Experiments are planned to directly compare the acoustically determined permeabilities with directly measured values using a classical flow apparatus (Chacho and Johnson 1987).

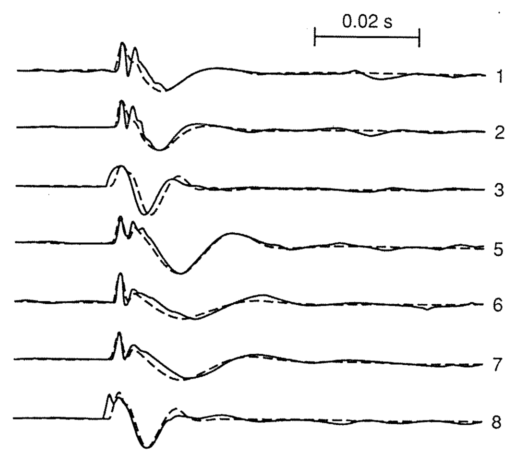

Figure 5. Surface microphone waveforms recorded at 60-m range from a .45 caliber pistol shot 1 m high above the snow surface (solid lines). These waveforms were recorded with the same microphone on seven separate days, and the numbers refer to the measurement days listed in Table I. Calculated waveforms are shown as dashed lines; these automatically fitted waveforms give the effective flow resistivity and permeability estimates listed in Table I. 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.

Table 1. Measured amplitudes, environmental parameters, and best fitting waveform parameters for various seasonal snow covers.

Expt no.	*Date (1989–1990)*	*Air temp. (°C)*	*Snow depth (mm)*	*Snow density (kg/m3)*	*Flow resistivity (kN s/m^4)*	*Estimated permeability ($\times 10^{-10}$ m^2)†*
1	29 Dec	−12.4	185	170	25	6.6
2	4 Jan	3.1	170	260	30	5.8
3	10 Jan	1.3	140	280	35	4.9
5	22 Jan	−5.3	190	100	10	16.8
6	31 Jan	−2.8	350	140	10	16.9
7	8 Feb	3.0	280	150	10	17.3
8	6 Mar	−4.0	140	340	35	4.8

† A value of $\eta = 1.708 \times 10^{-5}$ Pa s for the dynamic viscosity of air at 0°C, with a temperature correction of 5.61×10^{-8} Pa s °C^{-1}, was used to convert the effective flow resistivity σ_e to permeability k_0 using the expression $k_0 = \eta/\sigma_e$.

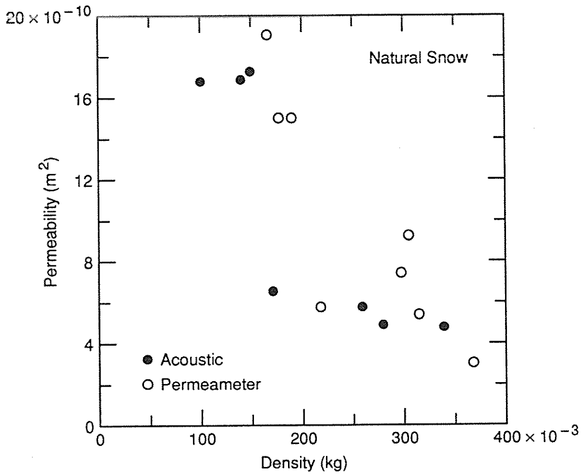

Figure 6. A comparison of the acoustically determined snow permeabilities (filled circles) with those measured using a permeameter (open circles, Sommerfeld and Rocchio 1989) for natural snow.

Values of the range decay constant α for snow range from 1.6 to 1.9 for these snow covers, with higher values (more absorption) corresponding to snow covers with higher permeability values.

SUMMARY

An overview of experimental measurements of horizontally propagating acoustic pulses above seasonal snow covers has been presented. Comparison of pulses propagating over grass and snow shows that the winter pulses exhibit lower amplitudes, elongated waveforms, loss of high frequencies, and higher range decay rates. All these effects can be successfully explained using a rigid-frame, porous medium treatment of the snow cover. Additional measurements show some of the variability in acoustic pulses caused by different physical properties of the snow. It appears that simple acoustic measurements have the potential to provide an accurate measurement of the intrinsic permeability of the snow; this application will be tested during the next winter.

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