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SNOW COVER EFFECTS ON IMPULSIVE NOISE PROPAGATION IN A FOREST

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1. ABSTRACT

The amplitude and waveform shape of atmospheric acoustic pulses propagating horizontally over a seasonal snow cover are profoundly changed by the air forced into the snow pores as the pulses move over the surface. This interaction greatly reduces the pulse amplitude and elongates the waveform compared to propagation above other ground surfaces. A comparison of experimentally observed blank pistol shot waveforms with waveforms theoretically calculated using a rigid porous media model for the snow and ground can be used to determine the snow cover properties. By varying the source and receiver positions during the experimental measurements, the spatial variations in snow properties near the edge of a forest were sampled at the site of the 1995 Norwegian winter blast tests. An inversion procedure that automatically matches the observed waveforms revealed a very shallow area of snow, just inside the forest, caused by the warming effect of the trees which absorb and reradiate solar energy. These acoustic measurements were in agreement with direct depth measurements and snow pit observations. The waveform inversion procedure is able to accurately determine the snow cover conditions even in the highly variable region at the edge of the forest.

2. INTRODUCTION

The interaction of sound energy with the ground is important in understanding noise propagation through the atmosphere[1-3]. It affects predictions of traffic, industrial, and blasting noise levels, and is important in mitigating and assessing environmental impacts of military activities. The presence of a snow cover has a large effect on acoustic pulse propagation, causing increased attenuation and marked waveform changes compared with propagation over grassland[4]. Snow cover characteristics change not only as a result of deposition from storms or melting during thaw periods, but continually metamorphose as a result of temperature gradients within the snow[5]. In addition, local variations in snow properties on scales of decimeters to meters induced by trees or because of drifting or wind scouring cause variations in the acoustic response.

This paper reports on small-scale measurements that were undertaken during the 1995 Norwegian Trials specifically to examine the effect of snow cover properties on acoustic pulse propagation and to determine the acoustic properties of the snow covers during these trials. Analysis of the experimental waveforms shows that they are effected by and contain much useful information on the local physical properties of the snow cover, and can be used to remotely measure these properties.

3. EXPERIMENTAL PROCEDURE

The experimental approach was to directly determine the snow's acoustic response by recording pulses that had traveled short distances (30-250 meters) horizontally above the snow cover in the forest. To record the pulses, three microphones were placed on the snow surface 90 meters apart. The first microphone was located at the edge of the forest of 15-m-tall trees; the other sensors were progressively deeper inside the forest. Three source (pistol) locations were used, one outside and to the south of the forest, and two within the forest. This combination of source and receiver locations gave multiple propagation paths within the forest that could be separately analyzed.

A handheld .45 caliber blank pistol fired 1 m above the snow surface was used as the source of the acoustic waves. The acoustic pulses were monitored using Globe Model 100C low frequency microphones and Bruel & Kjaer Type 4165 microphones located at the snow surface at distances up to 240 m away from the source. A Bison Model 9048 digital seismograph, triggered by a microphone located near the pistol, was used to record the waveforms at a sampling rate of 4-kHz per channel. The bandwidth of the measurements is estimated as 5 - 500 Hz and is limited mainly by the source output. The physical properties of the snow cover, including depth, density, grain size and type, and permeability were measured at several locations during the acoustic experiments.

4. WAVEFORM INVERSION

If the ground or snow surface acoustic properties are known (or assumed), then theoretical acoustic pulse waveform shapes can be calculated using the following procedure[4, 6-8]. For a monofrequency source in the air and a receiver on the surface, the acoustic pressure P a slant distance r away from the source is given by

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

where P_0 is a reference source level, 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[9-11] 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 of the ground. A rigid-frame porous medium model[12] is used to determine the impedance Z and the image source term Q. Then the received pressure, corrected for the source excitation and instrument response, can be determined at each frequency. An inverse Fourier transform is then used to construct the theoretical waveform in the time domain. In the ground impedance model, the snow is represented as a single layer with frozen soil beneath[13].

Attenborough's theoretical model[12] is used to determine the ground impedance Z for the calculations in this paper. The four input parameters needed by the model 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. For all of the calculations in this paper, the grain shape factor n' was set to 0.5 corresponding to spherical grains, and the porosity Ω was determined from the measured density of the snow. Parameters for the frozen soil below the snow were fixed at σ = 3000 kN s m^{-4}, $\Omega = 0.27$, s_f = 0.73, and $n' = 0.5$.

The experimental data were analyzed using an inversion procedure that attempts to directly match the observed and calculated microphone waveforms. The source and receiver locations, soil parameters, and the porosity of the snow were measured and are fixed values in the calculations while the snow's effective flow resistivity σ, depth d, and pore shape factor ratio s_f are varied to match the observed waveforms. A simplex iterative search procedure[14] was used to determine the best waveform fit. The algorithm minimized the absolute value of the difference between the observed and calculated waveform over a fixed time window. The algorithm moved smoothly and directly to the solution in all cases; restarts with different initial values led to the same solution. In this inversion procedure, the snow cover is treated as a single layer, and the sound attenuation caused by the vegetation in the forest is ignored or implicitly included in the ground effect in the calculations since it is very small at these short propagation distances and low frequencies[15].

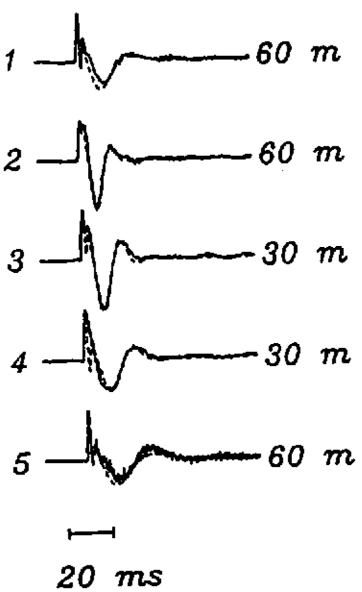

Fig.1. Normalized blank pistol shot waveforms for the forest experiment. Measured (solid line) and automatically-calculated (dashed line) waveforms are shown. The waveforms are in order from a propagation path just outside the forest (No.1) to the deepest path within the forest (No. 5).

5. RESULTS FROM THE NORWEGIAN TRIALS, 1995

Fig. 1 shows the observed normalized pressure waveforms recorded by the surface

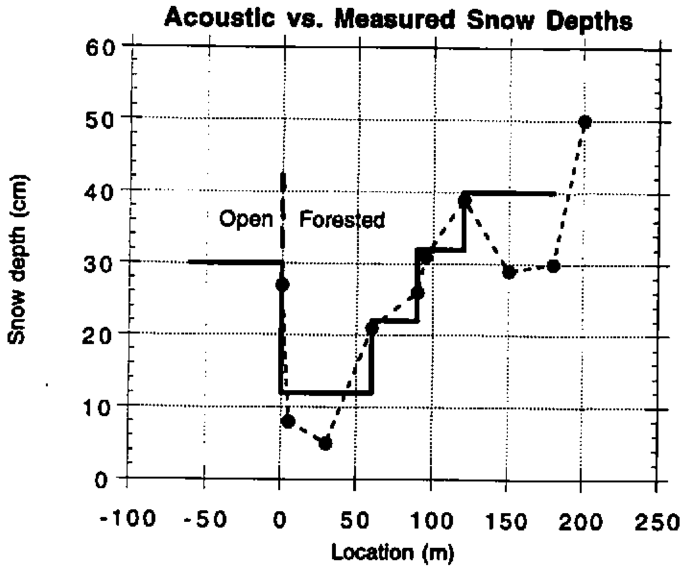

Fig. 2. Comparison of snow depths measured directly with a meter stick (filled circles with dashed lines) and acoustically via waveform inversion (solid lines extending over the actual propagation path).

microphone for five short propagation paths in the forest. The differences in the recorded waveforms are caused by the different path lengths and by changes in the snow cover properties along the propagation path. This figure also compares the measured and calculated waveforms, and the waveform agreement, achieved automatically using the inversion procedure described above, is very good in all cases.

Fig. 2 compares the snow depths that were determined directly (using a meter stick) with those determined acoustically from the automatic waveform inversion. The depths also show good agreement, even in this area where the natural snow depths are rapidly changing.

The snow properties show rapid spatial changes at the forest edge because of changes in snow accumulation and ablation caused by differences in the radiation conditions and by interception of snowfall by the forest canopy[16]. At the forest edge (0 - 50m), some of the snowfall is intercepted by the canopy and never reaches the ground. Since the edge is south-facing, solar radiation also directly reaches the snow, but more importantly, it illuminates the dark tree trunks, which absorb and re-radiate the heat much more efficiently than the high albedo snow surface. The interaction of solar radiation with the trees caused significant melting and compaction of the older snow cover. In this area, only very shallow snow cover was present, mostly the result of a snowfall only a few days before the measurement period.

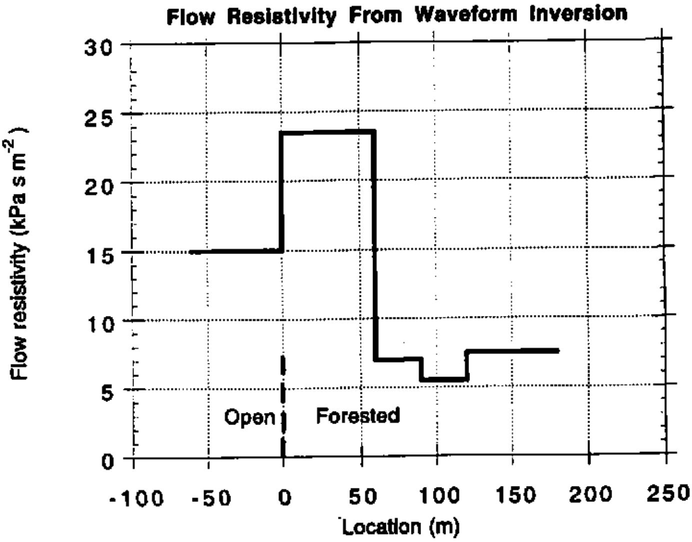

Fig. 3. Effective flow resistivity of the snow cover determined from automatic waveform inversion.

Deep within the forest, the canopy intercepts some of the falling snow and much of the solar radiation. The snow cover is even thicker here than in the open area because the reduced solar radiation has been unable to cause melting or compaction. These vegetative effects on the snow cover properties are further discussed in [16].

Fig. 3 shows the effective flow resistivity determined from the waveform inversions. Again, there are large changes near the forest edge, and these changes reasonably follow expectations based on the radiation effects discussed above. For example, the highest flow resistivity, corresponding to the lowest snow permeability, occurs just inside the forest where the greatest compaction and consolidation of the snow cover has occurred. The effective flow resistivity values range from 6 to 28 kPa s m^{-2}, in agreement (with corrections for differing definitions of effective flow resistivity) with previous outdoor [1, 2, 4, 13, 17, 18] and laboratory [19, 20] measurements on snow.

The pore shape factor ratio s_f value determined by the waveform inversion was 0.8 for the all of the forest measurements. This value agrees with previous measurements on dry snow covers[4].

After the forest measurements, a similar pistol shot experiment was conducted in a nearby open field. Unfortunately, these measurements occurred after and during a heavy rainfall. Although the waveform inversion procedure correctly determined the snow properties, the acoustic properties of the saturated snow cover in the open field were so different from the snow properties during the forest experiments that a comparison of the two data sets to determine the acoustic effect of the forest vegetation would not be valid.

6. CONCLUDING REMARKS

The measurements reported in this paper have shown the large effect of a dry snow cover on acoustic pulse propagation, and have demonstrated that acoustic waveform inversion can accurately determine spatial and temporal variations in snow properties. These acoustic waveform inversion results are important not only for their application to this particular test site, but also because they indicate that acoustic techniques have promise for more general applications. With some additional development, these methods can provide accurate remote assessment of surrounding conditions and can track temporal and spatial changes in those conditions.

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