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FOREST SOUNDINGS: INTERPRETATIONS OF PRESSURE WAVEFORMS OF EXPLOSIONS AT DISTANCES OF UP TO 20 KM

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1. INTRODUCTION

Measurements of the sounds from detonations of plastic explosives were made over a two week period in September, 1994, in the Finnskogen region (60°51′N 12°05′E) of Norway. Several technical groups participated in this exercise with the overall goal of learning how sound propagates in a forested region. In support of this goal, acoustic, seismic, and meteorological data were collected in a large scale collaborative effort. For a fairly comprehensive overview, see Ref. [1].

At site 112 microphones were placed in a vertical array at heights 30 m, 16 m, 8 m, 4 m, 2 m, and 0 m above ground level and recorded on a multichannel recorder. The purpose of this paper is to report on acoustic observations at recording site 112, the northernmost station on the test range.

2. IDEALIZATIONS

In studies of explosions, it is common to refer to a rapid, positive change in pressure as a shock. When an "ideal" explosion wave travels past a microphone, the shock signal is first, followed by a relatively slow decrease in pressure below ambient pressure. The pressure then begins ascent toward its ambient value. Bursts in free air produce such signals, and theories exist to model the attributes of these waves, which seem to work well over a wide variety of distances and explosive masses.

In the presence of reflecting surfaces, the surfaces tend to produce replicas of the model free-air burst, delayed in time, and perhaps modified in some way by the reflection surface. Highly non-linear waves permit the incident and reflected waves near the surface to combine into a single front. An important case occurs in propagation close to a natural ground surface, where the ground reflection path is only slightly delayed in comparison to the line-of-sight path from source to receiver. If the ground is very hard, the (over) pressure is essentially doubled throughout the waveform, with the appearance of distinct shock fronts if the direct and reflected paths are separated. On the other hand, porous ground at low grazing angles reflects low frequencies in phase with the incident wave and reflects high frequency components out of phase with the incident wave. The combined result of direct and reflected pressures is a sharp, needle-like signal, followed by a sinusoid.

The effects of atmospheric refraction, scattering by the forest, hillsides, and by atmospheric turbulence are substantially more complicated, though of great interest. It is likely that these processes are responsible for signals which did not match the classical expectations of the free-air burst or the ground-reflected burst.

3. OBSERVATIONS

In the figures, pressure measurements of blast events (shots) numbered 71, 77, 105, 159, 161, 167, 168 and 186 are shown. This is not a complete catalog of the measurements, but is shown to give an impression of the variety of effects observed at site 112. The distances printed in the graph titles are the distances from the blast, the mass indicated is the mass of C-4. The time pressure axes are shown only for scale; time 0 does not correspond to the detonation time. The pressure signals are progressively shifted higher in pressure to distinguish them from one another, so that the top signal corresponds to the highest microphone. The measurements were insensitive to signals below 0.1 Hz, so the measured pressure preceding the blast arrival is usually very close to 0 Pa.

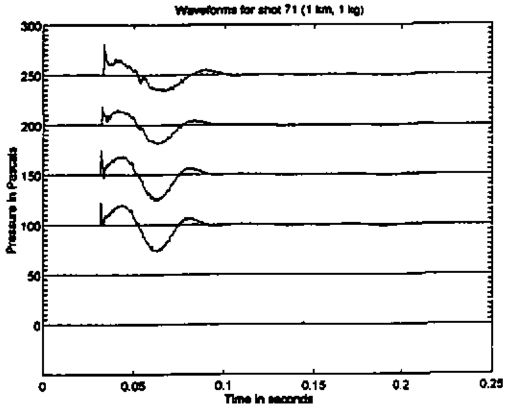
4. INTERPRETATIONS

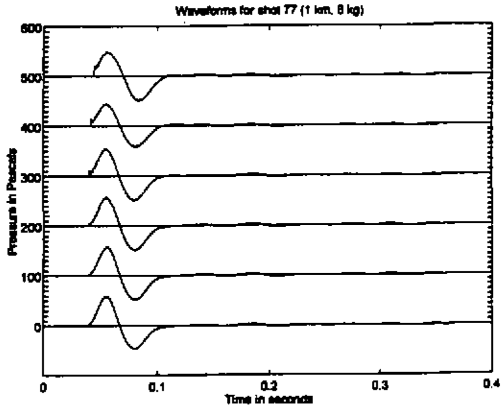
4.1 General Features. Microphones aloft generally measured more high-frequency variation, whereas microphones closer to the ground display more smoothly varying pressure signals. Shots 159 and 167 show this effect.

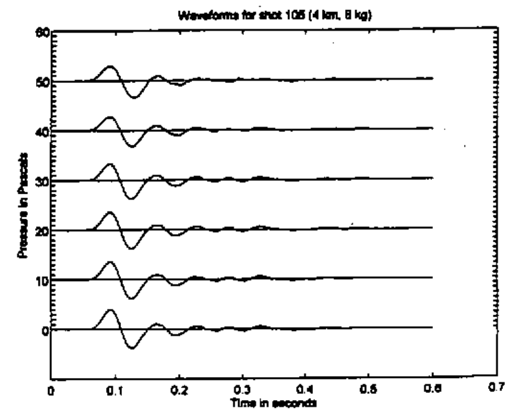
Near ground microphones often display pressure doubled signals, when compared to microphones above. For shot 159, the first signal feature is about 6 Pa at the ground and about 3 Pa at 30 m. The peak-to-trough variation in shot 168 at time 0.2 s is 7.5 Pa at 30 m and 1.35 Pa at the surface. On the other hand, for the same shot, the positive-going feature at 0.5 s is 0.4 Pa at both microphones.

4.2 Tilted Wave Fronts. By comparing the relative times of the signals received by the array, we can infer the angle of arrival of individual waves which passed. A number of signals were measured whose arrival came first at the highest microphone (shots 159, 161, 167 and 168 in the figures). For shot 159, the angle of arrival was 11.3 degrees above the horizon. For shots 167 and 168 arrival angles were about 10 degrees above the horizon. Somewhat surprisingly, some blast waves arrived first at the lowest microphone (shot 71), and in at least one case the signal arrived first at 8 m (shot 77). In shot 71, the lag at 30 m may indicate lower sound speeds with increasing height (implying upward refraction).

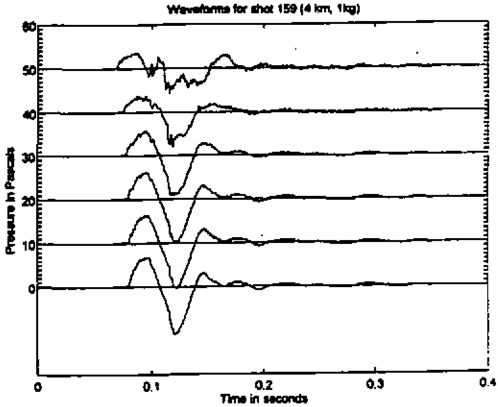
4.3 Separate Paths. In many cases where the propagation was from longer distances, the additional features in the observed signals arrived at angles different from the arrival angle of the first feature. This is evident in shots 167 and 168, where the second feature arrived horizontal to the ground 0.27 s after the onset of the first blast signal. These waves probably traveled along separate paths in the atmosphere.


Waveforms for shot 71 (1 km, 1 kg)
Pressure in Pascals
Time in seconds
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25

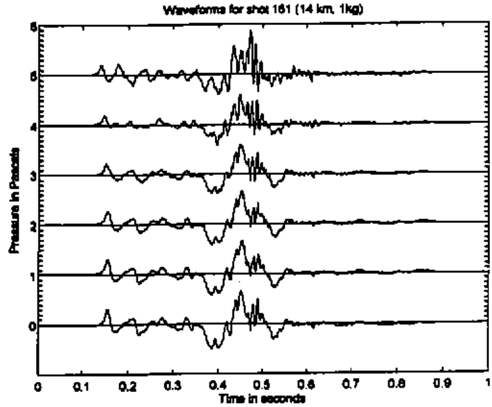

Waveforms for shot 77 (1 km, 8 kg)
Pressure in Pascals
Time in seconds
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4


Waveforms for shot 105 (4 km, 8 kg)
Pressure in Pascals
Time in seconds
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

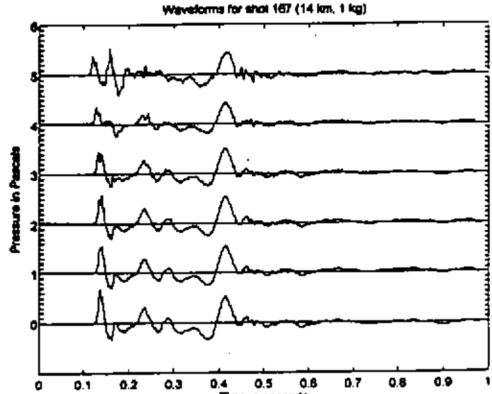
Waveforms for shot 159 (4 km, 1kg)

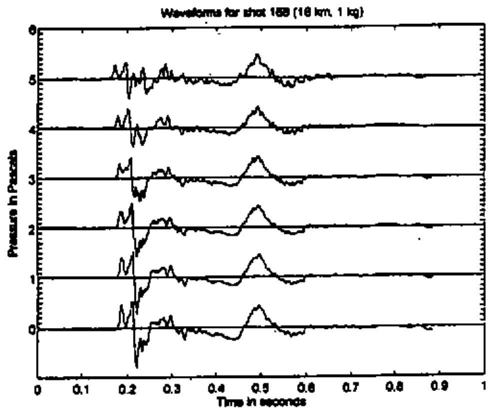


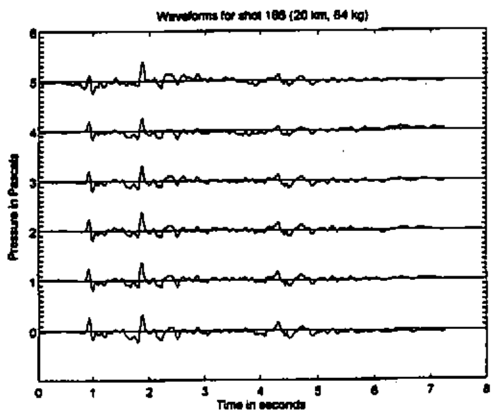
Waveforms for shot 161 (14 km, 1kg)



Waveforms for shot 167 (14 km, 1 kg)







4.4 Time symmetry. Occasionally, signals showed features which were somewhat symmetrical in time. No explanation for this is entirely reasonable, but the existence of a scattering process that returns a (partly) time-reversed replica of the incident wave is not too far-fetched. The sum of the incident and scattered field at nearly equal amplitudes would posses the desired symmetry and would maintain symmetry at any path length separation. Signals that display some time symmetry are shot 159 (symmetry about 0.12 s), shot 167 (about 0.28 s), shot 161 (about 0.45 s), shot 186 (about 1.4 s). To achieve time reversal, the hypothetical process needs only to progressively retard the phases of higher frequency wave components. In the signals shown here, the filter must act on the approximate frequency band 2 Hz to 40 Hz. It remains a challenge to construct a filter with the appropriate characteristics and identify the responsible time-symmetry scattering process.

4.5 Jet sounds. Under conditions producing an unusually strong inversion, distinct sounds were observed for some time following the arrival of the primary blast sound. Each primary blast sound apparently originated from the South (the correct azimuth of the source) at no more than 5 degrees above the horizon. It was similar to many other sounds we had heard in prior measurements, a simple "boom." The primary blast sound was followed in time by three "jet sounds" each lasting 4 to 6 s, swept first along an arc across the sky from the SW to NW, then sweeping from the SE to NE, and finally from the NW to NE (apparently behind us). The jet sounds were reminiscent of the sound of an overflight of a high-speed (subsonic) jet aircraft. The apparent angle of arrival was clearly noticed, well-defined and persisted at approximately 30 degrees above the horizon throughout each sound. The occurrence of the jet sounds coincided with each blast at short range, but were not observed from distances beyond 4 km. These sounds were audible for 25 s to 30 s amounting to path lengths 8.3 km greater than the 1 km and 2 km direct paths to the primary blasts. Where did these sounds go before we heard them?

The strongest proposal for the origin of the jet sounds has come from Geoff Kerry, who claims to have witnessed similar sound scattered from the edge of a forest. This has substantial merit as the cause of the sounds, as there are a number of lakes and rivers in the region of our site, all forming tree-lines. Nevertheless, a single jet sound lasting 6 s demands scattering from a tree-line whose first and last sounds travel over paths differing in length by 2 km.

5. FURTHER WORK

We plan to use the measured meteorological parameters and ground impedances as inputs to the Fast Field Program and compare the predicted and measured spectra. In February, 1996, we participated in a similar set of measurements at the same location in the presence of snow cover. The analysis of that data will be forthcoming.

1 R. L. Guice and G. M. Ogg, "Data collected during NOR94/1A, 'Low frequency sound propagation over a forested region, Summer trials'" Fortifikatorisk Notat/95, Applied Research Association (August, 1995).