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PREDICTING LOW-LEVEL ACOUSTIC PULSE AMPLITUDES IN AN ATMOSPHERE SUPPORTING WIND AND TEMPERATURE GRADIENTS

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1. INTRODUCTION

Pulse waveforms resulting from explosive discharges, such as a gun-shot or the detonation of plastic explosive above ground, are similar [1] and consist of a rapid compression followed by a lower level but more variable rarefaction. Most gun-shots range from about 100Hz to greater than 10kHz, with maximum intensity occurring at a few kilohertz. An explosive discharge typically has its dominant frequency at a tenth that of the gun-shot. Close to the source the pulse may exhibit non-linear shock effects, however, these become unimportant at greater distances and so are not considered further in this paper.

Attenuation of outdoor sound with distance is often calculated using, say, the Greens Function form of the parabolic equation (GF-PE) technique [2], which has improved computational speed. While incorporating both atmospheric and ground topology effects, it is still relatively time consuming to determine the result at a single frequency and prohibitively so at the several hundred frequency components required to generate a pulse waveform. Consequently, it is still necessary to use less sophisticated techniques to predict pulse amplitudes.

Basically, the procedure is to start with a waveform obtained at a known distance from the source, which is free from ground reflections or any other unwanted signals. This waveform is decomposed into its frequency components by using a fast Fourier transform (FFT) routine then, after appropriately modifying each component, using an inverse FFT to reconstitute the altered waveform. Normally, two waveforms will then have to be added, with an appropriate delay, to determine the effect of the direct airborne sound interacting with the ground reflection.

2. FACTORS AFFECTING OUTDOOR PULSE PROPAGATION

All waveshapes must be corrected for atmospheric absorption, which preferentially reduces the higher frequencies [3]. In what follows, it is convenient to consider excess attenuation as the attenuation in addition to inverse square law spreading and atmospheric absorption.

Close to the ground, the resultant waveform at a distance from the source is the sum of the sound which passes directly to the receiver and that reflected from the surface of impedance, Z. At short distances, the direct and ground reflected components will be separated in time, however, at longer distances they progressively overlap and far from the source will essentially arrive simultaneously. Depending on Z and the geometry, the specularly reflected ray from the ground may be inverted and cancel the direct ray leaving only the non-specular reflection, or ground wave, which dominates at larger distances [1].

Other factors effecting propagation are wind and temperature gradients, which cause the speed of sound to vary with altitude producing curved ray paths. In downwind conditions and often at night time the rays are refracted downwards resulting in multiple bouncing of the rays from the ground and sound focusing, where the excess attenuation can increase by over 10dB. In upwind conditions and often during the day, the rays curve upwards and an acoustic shadow boundary forms. Simplistically, no sound passes the boundary, however, creeping wave theory allows sound to move under the boundary and then radiate upwards into the shadow region. Assuming a linear sound speed gradient, creeping wave theory under predicts the peak level of pulses measured deep inside the shadow zone by tens of dB [4]. Continuous wave measurements have indicated that once the excess attenuation exceeds about 25dB there is no further decrease with distance [5]. The accepted explanation is that the additional sound arises from turbulent scattering in the volume above the shadow boundary. This concept has been confirmed by single frequency PE calculations which include turbulence [6]. However, it is not necessarily obvious that this explanation holds for pulses as the different path lengths between the creeping wave component and sound from the turbulent scattering volume imply a variety of arrival times. Thus one might expect to see fluctuating pulse shapes and changing magnitudes within the shadow zone as the turbulent medium above alters the sound paths. However, this is inconsistent with the experimental observation that the pulse shapes are extremely reproducible inside a shadow zone [4].

Measurements have shown that, even at distances as small as 16m, the amplitude and waveform of pulses can vary significantly due to fluctuations in the meteorological conditions [7]. The second part of this paper reports on a study intended to see how significant the effect of turbulent scattering is in creating delayed components in the pulse.

3. TURBULENT SCATTERING AT 16m

An impulse source was positioned midway between two microphones arranged along the dominant wind direction, as shown in Fig.1. With this geometry, the surface reflected pulse at either receiver M_1 or M_2 is delayed about 1.4ms from the direct pulse, providing a clear interval in which to seek any additional delayed energy scattered by turbulence in the atmosphere. A reference microphone was positioned 50cm from the source in the plane at right-angles to the wind direction. Being close to the source this reference pulse did not experience significant turbulent effects, so its peak value was used to normalise the M_1 and M_2 waveforms for source amplitude variations between shots.

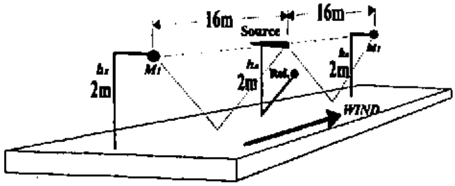

Fig.1: Measurement geometry

Using a similar geometry indoors, with no wind, waveforms from 100 shots were recorded. After adjusting for source variations they were ensemble averaged and contours, located one and a half standard deviations from the mean, calculated at each instant along the time trace. These contours set the range of variation expected from source fluctuations.

Individual pulse waveforms obtained in the middle of a soccer field, with wind speeds varying to over 8 ms^{-1}, were tested to see if scattered energy occurred beyond the indoor deviation contours. The results are shown in Table 1. Incidentally, the range of reference pulse heights measured indoors and outdoors closely agreed and there was no evidence of delayed energy in the tail, indicating that the sound reaching this microphone did not experience significant turbulent effects.

Type of effect	Upwind		Downwind		% Total
	Major	Minor	Major	Minor	
Decreased peak	14	24	11	16	37 (14)
Increased peak	12	16	8	10	26 (11)
Tail peak, upright	5	21	4	15	25 (5)
Tail peak, inverted	5	26	17	31	44 (12)
Unchanged	13		16		16

Table 1: Number of pulses showing changes in waveform (total 178 pulses). Last column gives upwind plus downwind result, with number exhibiting major effect in brackets.

The table indicates that:

- wind direction causes no significant difference.

84% of pulses experience some form of energy change, with 69% showing delayed energy arriving in the tail.

Many of these observations can be explained by the curved ray path situations sketched in Fig.2, noting that the received waveshape may result from multiple events.

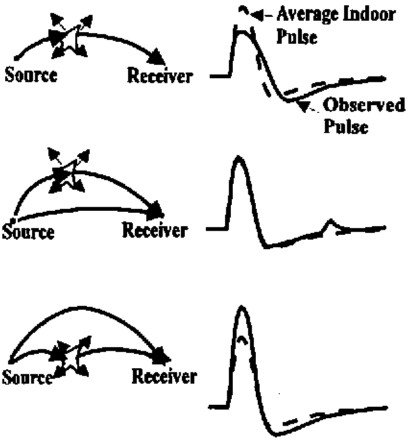

Fig.2. Possible scattering paths and associated waveshapes.

Decreased main peak: Energy is scattered out of pulse along the propagation path

Small peak in tail: Energy is scattered into the tail of the pulse from some point outside the direct propagation path, resulting in two components arriving at receiver with slight delay.

Increased main peak: A special case of above, where scattered and direct energy arrive with negligible delay, thereby increasing height of pulse.

The most difficult case to explain is when there is an inverted peak in the tail, as occurs in about 44% of cases, since this requires some mechanism to invert the original waveform. A possibility is a backscattering mechanism, involving an angle change approaching 180°, however, this should also occur in the reference pulse. No such delayed energy was observed in 89 reference waveforms investigated. All the delayed pulses occurred within a time of 1.3ms from the onset of the main peak, suggesting that the maximum divergence from the direct path between source and receiver is not more than 0.43m, indicating that the major scattering effect is essentially a forward scattering mechanism. Generally, the size of the scattered components diminished very quickly as the delay increased. Of the reduced peak waveforms recorded, 72% also exhibited delayed scattering in the tail while it occurred in 74% of the increased amplitude waveforms. It was observed that reduced amplitude peaks were consistently wider while the enhanced peaks were narrower than the indoor peak.

In conjunction with the above data, a 20s long wind speed trace, centred on the gun shot, was recorded at the source and receiver positions and the mean wind speed determined from both traces. If the atmosphere is 'frozen', as required by Taylor's model of turbulence [9], then when one trace is shifted according to its mean wind speed, the two traces should overlap. After appropriately shifting the receiver trace, only 50% of the data fitted this requirement. Representative wind speed traces recorded when the five types of scattering occurred are shown in Fig.3, where the time for a frozen wind pattern to move from source to receiver is shown by two vertical lines.

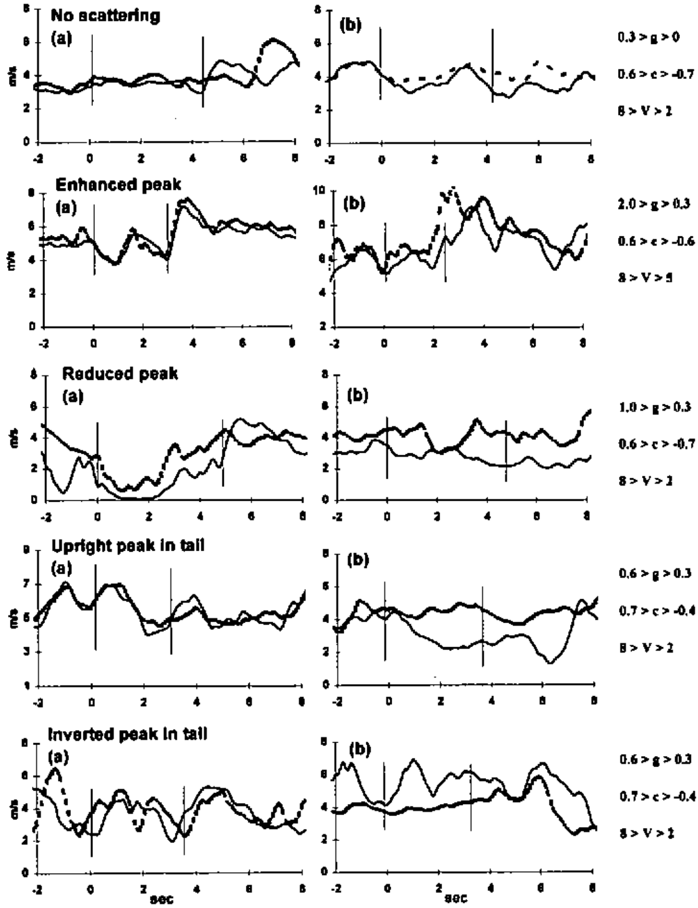

Fig3: Wind speed traces at source (full) and receiver (dashed) for different scattering categories and calculated parameters discussed in text.

In each category, the (a) traces show a reasonable match while the (b) set are typical mis-matches. In order to seek trends, the upright and inverted peak in tail groups do not include data incorporated in the enhanced/reduced peak categories. Tabulated alongside is the range, determined from all members within the category, of three parameters calculated only on the part of the traces between the vertical lines. The maximum wind speed gradient, $\Delta v/\Delta x$ where Δx is the horizontal distance, in each trace has been determined and the average of these for a pair of traces is designated g. This parameter indicates that scattering into or out of the main peak is associated with more rapid changes, while delayed tail peaks occur when smaller gradients are observed. For pulses exhibiting no scattering, the upper limit for the gradient g was $0.3ms^{-1}/m$.

As a measure of the difference between the traces, the parameter D is defined as

$$D=\sum_{0}^{N}\left[\left(\mathrm{v}_{s}-\bar{\mathrm{v}}_{s}\right)-\left(\mathrm{v}_{r}-\bar{\mathrm{v}}_{r}\right)\right]^{2}/N\bar{\mathrm{v}}^{2}$$

where the summation is over the *N* instantaneous minus average velocity values at source and receiver, made non dimensional by dividing by the average velocity for all data. Unfortunately, this parameter does not distinguish between the categories, largely because of the mis-match cases where the atmospheric conditions experienced by the pulse are effectively unknown. The average wind speed, V, suggests there is a preference for enhanced peaks to occur at higher wind speeds. Again an uncertainty exists for the unmatched traces in deciding over what spatial range the change in speed has occurred.

CONCLUSION

By using impulse sounds, individual scattered components have been observed when a pulse propagates through a meteorologically fluctuating medium. The timing of the observed delays suggests that generally the scattering is close to the forward direction. Wind speed data sorted according to the various types of pulse scattering, suggests that wind gradients may be an indicator of the type of scattering. Neither of the other parameters considered proved useful. This is largely because the high percentage of mis-matched cases (about 50%) meant that, even over distances as short as 16m, the meteorological conditions were inadequately known.

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