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VARIATION OF TURBULENCE EFFECTS ALONG A PROPAGATION PATH

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Impulsive sound is a revealing way of probing turbulent effects as changes to the pulse waveform represent the influence of the meteorological conditions over a short interval. When the wind speed is appropriately measured the propagation time can be accurately predicted. Even when a successful prediction of the pulse propagation time is achieved, efforts to quantitatively link changes in the pulse amplitude, waveform and spectrum to wind speed fluctuations have been largely unsuccessful. To be reported here are the results from a recent experiment in which four microphones, each accompanied by an anemometer, were placed 5m apart along the wind direction. The use of 5m spatial regimes allows a detailed monitoring of the wind structure and the observation of progressive changes in the pulse waveform. Scattering between and from outside the line of microphones is investigated and the results are related to possible models of sound propagating in a turbulent field.

INTRODUCTION

Recently,[1] a large number of measurements have been made to ascertain the way meteorological conditions alter the waveform of an acoustic pulse as it propagates through the atmosphere. While significant changes to the peak height and waveshape are observable at distances as short as 16m, the measurements do not correlate with simultaneously measured fluctuations in the wind speed. In an attempt to elucidate the problem, a series of microphones and anemometers were positioned along the mean flight path, using a spacing of only 5m, to allow the evolution of the pulse waveform to be studied. After briefly reviewing some of the earlier data about pulse propagation in the atmosphere, this 5m linear array data will be considered and interpreted in terms of possible models.

PULSES PROPAGATING IN A FLUCTUATING WIND

The discussion in this section relates to propagation along the direction of the wind, between a source and receiver 16m apart and 2m above grassland. Pulses were produced by detonating a shot-shell primer into a 1m length of tube, the open end of which acted as the source.

Because of their well defined leading edge, the travel time of a pulse over a distance of d = 16m from source to receiver can be measured quite precisely. When compared with predictions using the speed of sound in still air and the measured wind speed, reasonable agreement is obtained, especially if four anemometer measurements along the flight path are used, in conjunction with a quadratic fitting routine, to calculate the mean speed[2].

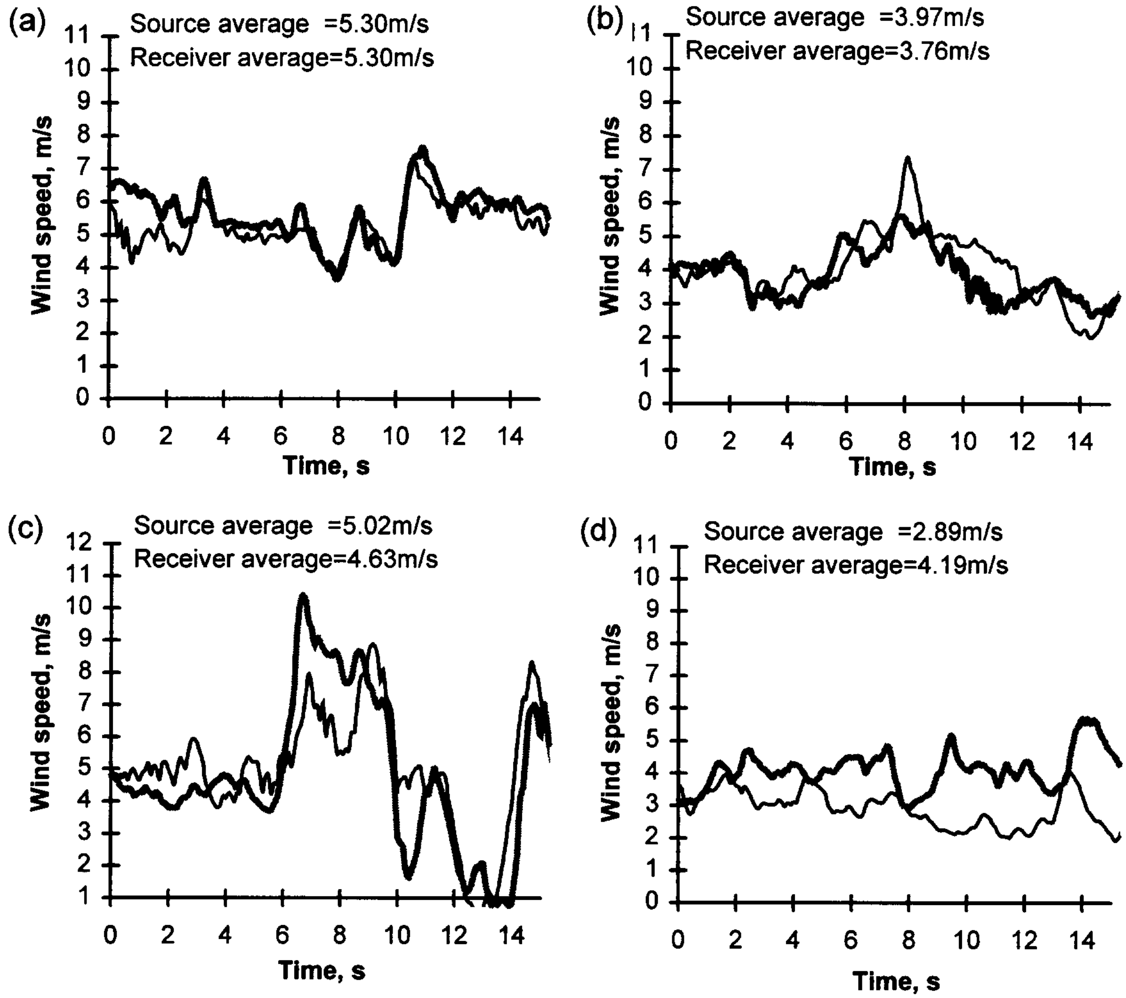

Fig. 1 Comparison of wind speed time traces for four cases determined from anemometer readings at the source, thin lines, and at the receiver, thick lines.

If time traces 20 seconds in duration are recorded at both the source and receiver positions, then Taylor's hypothesis[3] that the wind pattern moves with a constant velocity, implies the time traces should overlap when one is shifted in time by $\Delta t = d/v_0$, where in this case v_0 is the average wind speed over 20s. Some 200 cases were studied, four examples being shown in Fig.1, where the thin and thick lines represent the traces obtained at the source and receiver respectively. Also shown are the average values calculated from the two data sets. The agreement between the two time traces, after shifting, is excellent in case (a). For cases

(b) and (c) the two traces agree well, although at some instants the two traces differ by over 2m/s and if a pulse was travelling during such an interval there would be considerable uncertainty in the appropriate wind speed. Note that the average values differ by only 0.4m/s, which is less than the mean deviation of 0.6m/s for all 200 cases. Case (d) shows little agreement, with a marked difference between the 20s averages. Overall, approximately 84% of the measurements were similar to (b) and (c) while types (a) and (d) each occurred in 8% of cases.

Outdoors, turbulence can cause the height of the pulse to increase or decrease compared to that recorded at the same distance indoors. When the number of pulses is plotted as a function of pulse height, a symmetric histogram is formed, which broadens as the wind speed increases and is the same for upwind and downwind propagation[2]. Ensemble averaging groups of many hundreds of waveforms, taken in mean wind speeds ranging up to $10ms^{-1}$, has shown that the *average* waveform is the same and, indeed, is the same as that obtained *indoors* where there is no wind. Consequently, when analysing data, it is convenient to normalise all values against the average indoor pulse.

To remove shot-to-shot variations, a reference microphone is placed close to the source, and the main data adjusted for any small variations in the corresponding reference peak height.

When the observed changes in peak height or pulse energy are plotted against parameters involving the wind speed, no correlation is observed[4]. The simplest meteorological parameter tested was the difference between the mean wind speed occurring at the source and receiver over the 47ms flight time of the pulse, Fig.2(a). As another example, data were plotted only for pulses where it was judged that the wind speed pattern had propagated with a constant velocity, such as in the cases of (a)-(c) of Fig.1. The wind speed pattern was integrated and plotted against the restricted acoustic data, Fig.2(b), but even this approach failed to improve the correlation.

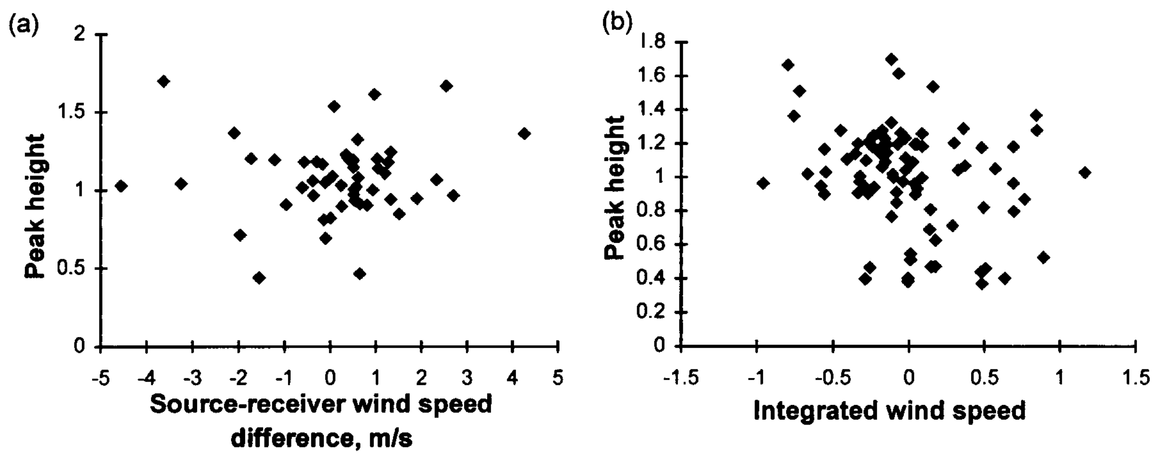

Fig. 2 Examples of attempts to find a wind speed parameter that correlates with the pulse peak height.

By analysing individual pulse waveforms into their Fourier components and dividing by the corresponding components of the average indoor pulse, the change in amplitude and phase can be observed. The amplitude ratio of individual indoor pulse components deviates only marginally from unity while the phase variations are typically within ± 0.5 radians of zero over the frequency range, Fig.3(a). Outdoors, the phase changes are often similar in size to the indoor values, the most extreme case being shown in Fig.3(c). However, the amplitudes can differ by a factor of two at some frequencies, Fig.3(b)-(d). Attempts to generate the observed pulse waveforms by manipulating bands of frequencies, that is by amplifying, attenuating and/or altering the phase were largely unsuccessful[4] as a multiplicity of filtering processes were required to generate the wide range of observed shapes.

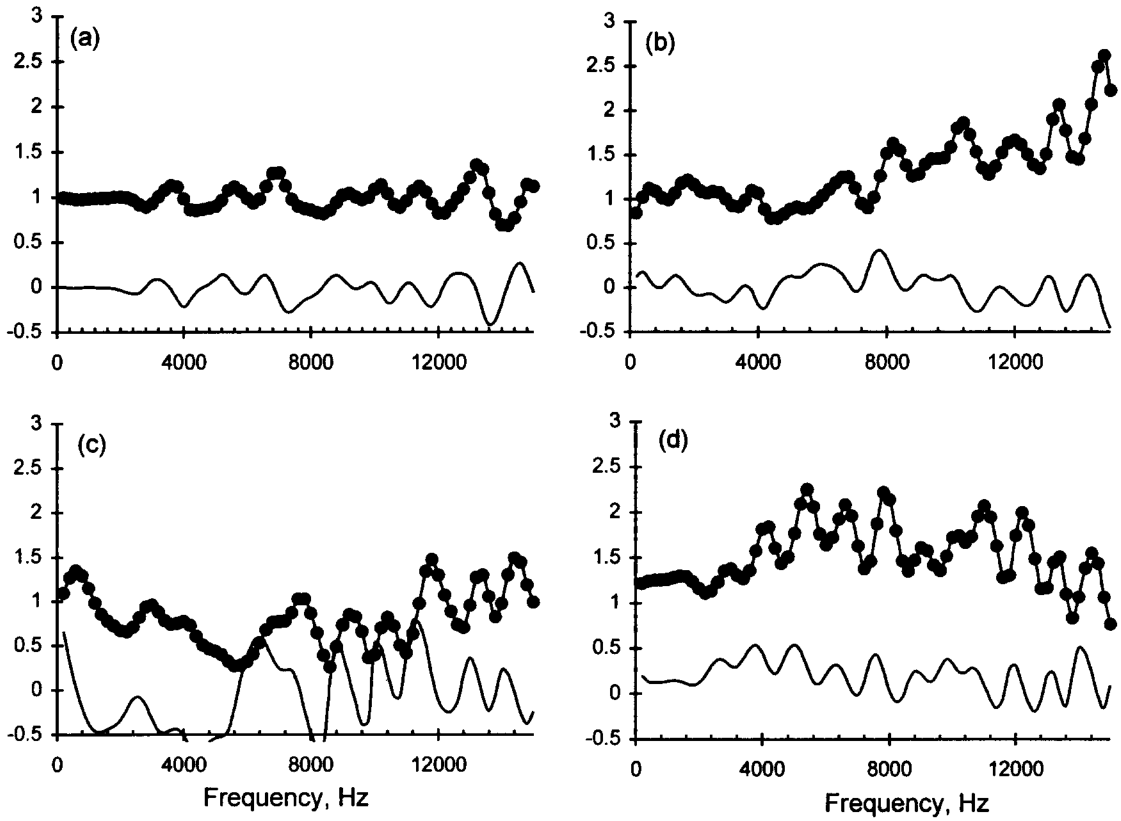

Fig. 3 Transfer functions for (a) an indoor pulse and (b) to (d) outdoor pulses. The dots represent amplitude information while the thin lines are the phase variation.

LINEAR ARRAY MEASUREMENTS

In an attempt to obtain even more detailed information about the pulse shape changes, a set of measurements were taken with an array of microphones placed only 5m apart. Each microphone was accompanied by an anemometer, and was slightly offset, Fig. 4, to avoid distorting the propagating waveshape. Testing the geometry indoors, where the pulse shapes were very reproducible, showed that removing, say, M1 did not affect the waveform at the more distant microphones.

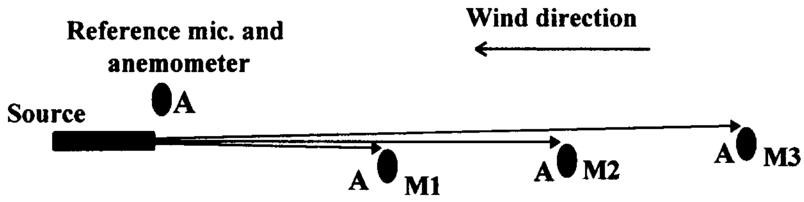

Fig. 4 Plan view of the microphone and anemometer positions used in the array experiment.

Long time traces of the wind fluctuations were recorded at each anemometer position. The earlier study, Fig.1, indicated that Taylor's hypothesis was generally adequate over distances of 16m. By using shorter distances and more anemometers, it was anticipated that an even more reliable wind speed profile would result. The profile was deduced by projecting forward, and also backward, from each measuring site along the array. Fig. 5 shows these predictions for six cases. In general the profiles agree quite well, suggesting that the predicted spatial wind speed variation are reasonable estimates. There are cases, (b), (d), and (e) where significant differences occur, however, even in these cases both estimates indicate a speed change has occurred, although at a different position along the array. Also superimposed on Fig. 5 are the measured peak heights at each position, after normalising against the reference pulse amplitude. There is little change in the peak height with distance in either cases (a) or (b) although in (b) quite marked variations in the wind speed occur around the 5m microphone position. A significant increase in peak height is apparent by 15m in case (d), yet there is almost no wind speed fluctuation evident after the 10m position. A drop in the wind speed before 10m position in (e) could be associated with the decreased height recorded at this distance but there is no equivalent explanation for the further decrease recorded at 15m. In case (f) the peak height increases at 10m but has dropped by the 15m position. Overall, there is no obvious, consistent pattern in the wind traces which explains the behaviour of the peak value.

The corresponding pulse waveforms recorded at the 5, 10 and 15m positions are presented in Fig. 6. Note that in this figure we are considering shape changes that occur subsequent to the 5m position. Thus the effects are independent of possible waveform changes at the source. While the peak value changes only slightly in cases (a) and (b), there are more significant alterations to the waveform. The initial peak disappears then reappears in (a) whereas in (b) a marked reduction has occurred in the trailing edge while propagating between the 10 and 15m positions. In the same region, the start of the pulse has been reduced in (c) and enhanced in (d), although the wind traces are relatively flat around these sites in both cases. Even though the distances involved with these experiments are only a few meters, the waveforms are consistent with the earlier observations obtained over 16m indicating that peaks which have

- an enhanced height are usually narrower,
- a reduced height are generally broader.

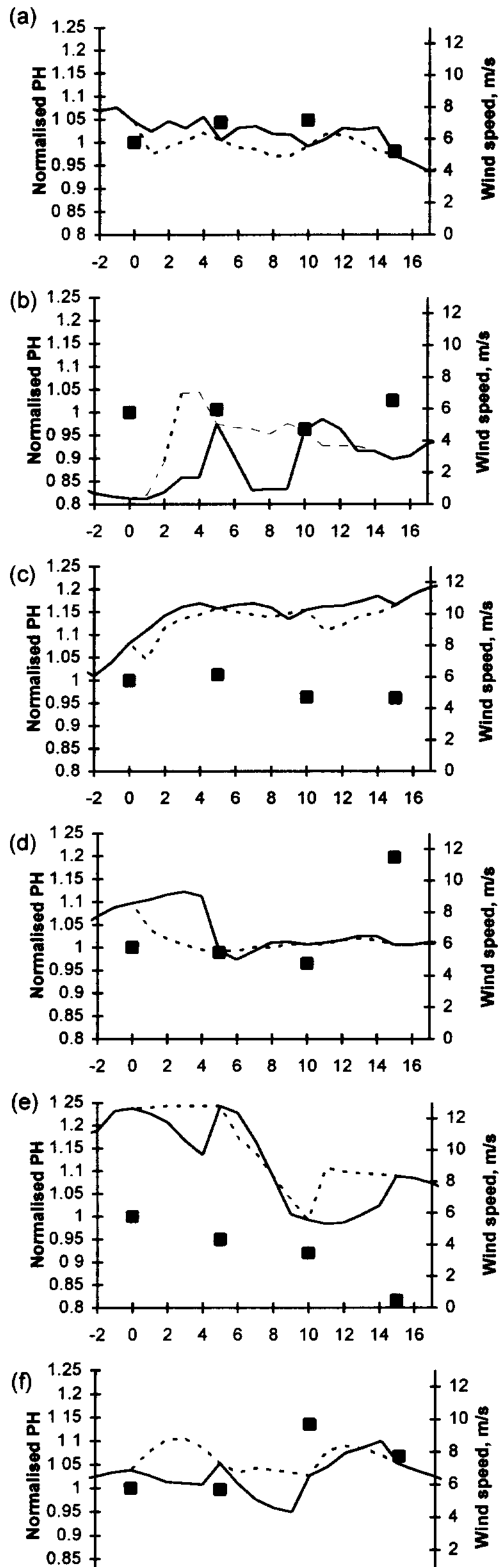

Fig. 5 Wind speed profiles and peak heights

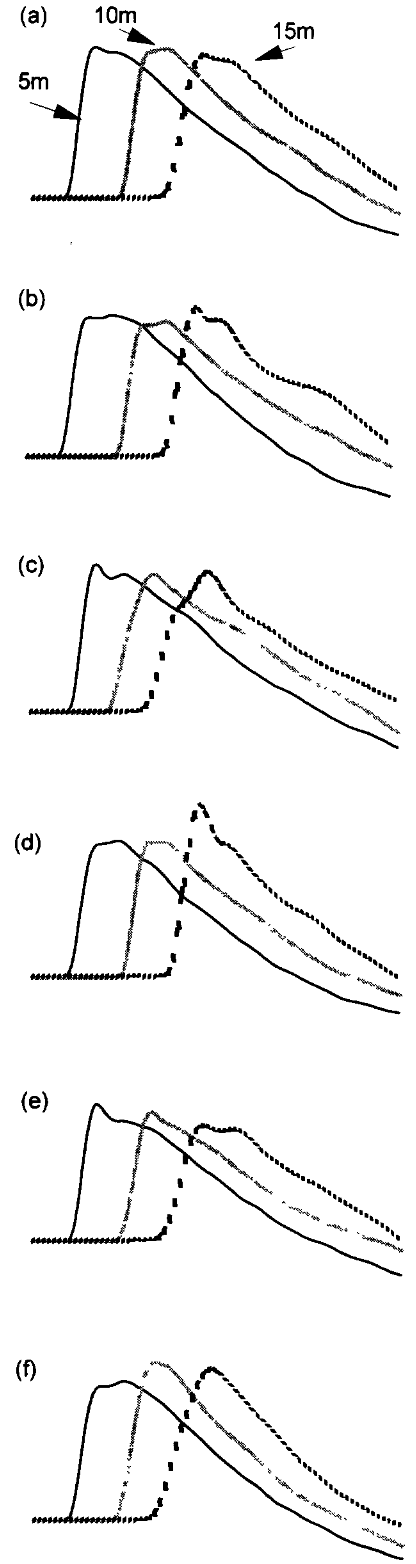

Fig. 6 Pulse waveforms recorded at 5, 10 and 15 m.

POSSIBLE MODELS TO EXPLAIN THE OBSERVATIONS

Scattering from regions off the direct path has been observed in the tail of the pulse.[4] However, the delays of 0.1ms or less associated with changes occurring in the head of the pulse, and the short propagation distances involved in these measurements, limit the turbulent mechanisms to ones essentially along the direct path.

In principle, suitable filtering can yield the observed pulse shapes, although there is no evidence of any consistent grouping which would help explain the behaviour. Some frequencies require an amplification factor of two. It is hard to imagine any scattering or filtering mechanism that would produce this enhancement. If one visualises a filter being placed where the wind speed profiles shown in Fig.5 differ, then there should only be a change in waveform after such a difference. This is not the case, as is evident for example in Figs.5(d) and 6(d) where a filter about 2m would have no effect between 10m and 15m.

Inspection of many wave shapes suggests that often the energy is being shifted in time within the peak. Two examples are the 15m pulses shown in Fig. 6 (b), where energy from the trailing edge region has apparently moved to the very peak, and in (e), where the peak energy has been spread into the tail, broadening the waveform. Other wave shapes show comparable trends. Scattering from regions well away from the direct path will result in changes later in the pulse, whereas the effects observed in the head of the pulse must be attributed to turbulence along the line of flight.

One picture which enables the observed shape changes to be generated is to assume that the resultant pulse is formed by the summation of a large number of "pulselets" with different delays as they come from different parts of a finite volume source region. These pulselets would travel along slightly different paths to the receiver. Assuming that the atmospheric conditions can change very markedly with distance across the beam of pulselets, or rapidly

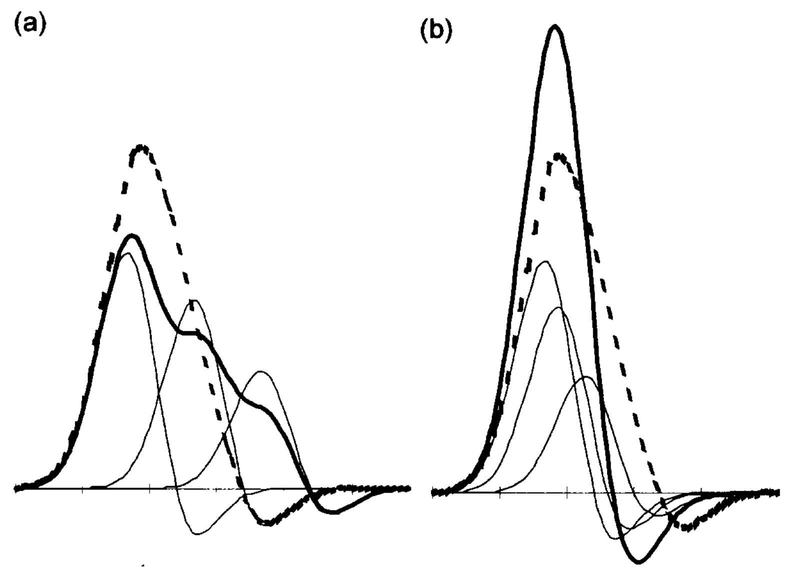

Fig.7. Examples of the three pulselet model: (a) where the arrival time of each pulselets has increased resulting in a wider, reduced height pulse than the norm shown dashed, and (b) where reduced delays have resulted in a narrow, enhanced pulse.

with time, then some will experience different turbulent effects. They may be sped up or slowed down compared to the other components, depending on the particular turbulence they experience. By shifting the pulselets appropriately, all the observed pulse waveforms can be generated, Fig. 7. The changes observed within the 0.5ms duration of the pulse head argues for small rapidly changing regions of turbulence, which are clearly not detectable by the anemometers used in this study.

CONCLUSION

This investigation used relatively small propagating distances to study the changes in pulse waveform as a function of the wind fluctuations. Even though the wind speed profile could be reasonably well inferred along the flight path, there was no consistent evidence linking any measured meteorological effect to the observed changes in the pulse. Using commonly available hot wire anemometers, even when only 5m apart, would appear to be inadequate to measure the velocity field required to explain the acoustic observations. The short 5m propagating distance implies that turbulence along the path, rather than scattering from more distant regions is responsible for the observed changes in the pulse head. Treating the turbulent atmosphere as a filter which scatters out or delays appropriate frequency components has limited validity, as no consistent behaviour has been observed which would allow classification of the transfer functions into distinct groups. Further, a mechanism producing enhancement of some frequencies by a factor as great as two is difficult to visualise. A model treating the pulse as the superposition of a range of pulselets, each of which can experience individual amplitude and delay changes, is consistent with the observations. Such pulselets may arise by the distributed nature of a finite source, however, this aspect requires further investigation.

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