SOURCE LOCALIZATION IN THE PRESENCE OF ATMOSPHERIC TURBULENCE

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ABSTRACT

Statistical results of experiments carried out over flat grassland and aimed at testing a system for locating a stationary source over a range of 250m at frequencies between 100 and 3000 Hz in the presence of a realistic atmosphere are described. A ground effect inversion and localization algorithm (GEILA) has been employed to determine the source location. A nine-element microphone array system was used for the acoustical measurements. The elements were arranged as three vertically-separated sets of three microphones at 0.1, 1 and 3 m height. Wind velocity and temperature were measured simultaneously with the complex sound pressures at different heights up to 10m. To investigate the statistical distributions of source locations under the prevailing refraction and turbulence conditions, the complex pressure spectra have been obtained from Fourier Transform of different lengths of the time varying signals at each microphone. Successive periods of 1-sec, 5-sec, 10-sec or 2-min have been used respectively. For each resulting complex pressure spectrum, there is a corresponding measured sound velocity profile. The complex pressure spectra have been used in the GEILA algorithm to determine the source location. It has been found that the statistical distributions of the source locations deduced from acoustical measurement data depend significantly on the length of the samples.

INTRODUCTION

L'Esperance and his co-workers presented a set of meteorological and acoustical data related to an experimental study of the effects of atmospheric turbulence on outdoor sound propagation[1]. They have found that although an average sound velocity profile over a long period provides reasonable predictions under some circumstances, better agreement with experimental data is obtained by using the profiles measured over a very short time intervals.

This paper is concerned with localization of elevated sources in the presence of an unknown realistic atmosphere. Statistical results of experiments carried out over flat grassland at the University of Hull sport field using a nine-element array system are presented. For various meteorological conditions, measurements of instantaneous wind velocity and temperature profiles were recorded simultaneously with complex acoustical pressure received at each microphone of the array system. The effectiveness of the Ground Effect Inversion and Localization Algorithm (GEILA)[2] developed previously for deducing fixed source co-ordinates over various periods of time at a range of 250 m is demonstrated.

GROUND EFFECT INVERSION AND LOCALIZATION ALGORITHM

The ground effect inversion and localization algorithm (GEILA) makes use of a multi-element microphone array system, which is equivalent to three vertical arrays, each containing several microphones arranged arbitrary-triangularly, see Figure 1.

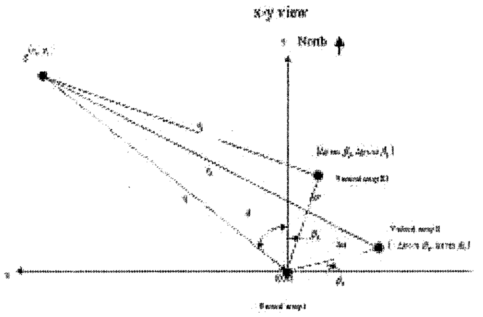

Figure 1. x-y view of acoustic measurement system.

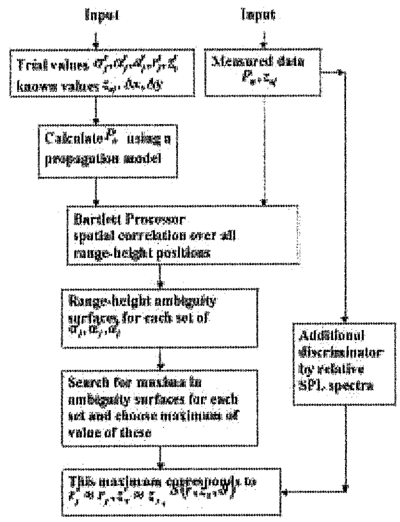

Figure 2. Block diagram of the GEILA.

A matched field processing method matches complex acoustic pressure spectra received simultaneously on each microphone with those predicted by a propagation model for a grid of possible source positions in range and height. Because the required output is the source location, the values deduced for ground parameters and sound velocity gradient are 'effective' values rather than true values.

In the case of a fixed single source, using trial values of ground impedance σ'_j and α'_j and sound velocity gradient a'_j, the range and height ambiguity function is computed according to[3,4]

$$A_j(r_j, z_s) = 10\log\left|\frac{1}{M}\sum_{m=1}^{M}\frac{\left|\sum_{n=1}^{N} P_m(f_m, r_j, z_s, z_{nj}) P_e^*(f_m, r'_j, z'_s, z_{nj}, a'_j, \sigma'_j, \alpha'_j)\right|^2}{\sum_{n=1}^{N}|P_m|^2\sum_{n=1}^{N}|P_e|^2}\right|^2, \quad j = 1,2,3 \qquad (1)$$

where z_{nj} is the nth microphone of the jth vertical array, f_m is the mth single frequency, r_j is the horizontal range between a source and the jth vertical array

$$r_j = \sqrt{(x_j - x_s)^2 - (y_j - y_s)^2}\,. \qquad (2)$$

The P_m represents the measured pressure due to a source $S(r_j, z_s)$ and P_e represents the estimated pressure for source co-ordinates $S'(r'_j, z'_s)$. The superscripts prime and asterisk denote trial value and complex conjugate respectively. Ambiguity surfaces corresponding to each set of trial values include several maxima. The maximum of these is compared with the corresponding maximum from all ambiguity surfaces and the maximum of these maxima is chosen. When the trial values of range and height are closest to the true values of the range and height then the ambiguity function will have its maximum value i.e. in a correctly matched environment, $P_e \approx P_m$ and $r'_j \approx r_j$ and $z'_s \approx z_s$. GEILA determines the position of the source in the horizontal plane by finding the range from each of the three arrays. The source azimuth ϑ can be determined by solving the following equations numerically

$$\vartheta = \frac{\pi}{2} - \arctan\left(\frac{y_s}{x_s}\right), \qquad (3)$$

$$\begin{cases} r_1^2 = x_s^2 + y_s^2, \\ r_2^2 = r_1^2 + \Delta r^2 + 2r_1\Delta r \sin(\vartheta - \beta_x), \\ r_3^2 = r_1^2 + \Delta r^2 - 2r_1\Delta r \cos(\vartheta + \beta_y) \end{cases} \qquad (4)$$

where $\Delta r = \Delta x = \Delta y$ is the known separation between arrays. Figure 2 shows a block diagram of the GEILA algorithm.

DESCRIPTION OF THE EXPERIMENTS

The acoustical measurement system arrangement is shown in Figure 1. The separations between the three arrays were $\Delta x = \Delta y = 20\,\mathrm{m}$ and $\beta_x = \beta_y = 0$. Each array consisted of three microphones separated vertically at heights of 0.1, 1.0 and 3.0 m above the ground. An Electro-Voice loudspeaker was used as a source and placed at heights of 10, 5 and 2 m respectively during the experiments. The range between the source and the vertical array I was $r_1 \approx 250$ m. The acoustic signals were white noise and multiple tones between 100 and 3000 Hz. Meteorological measurements were made simultaneously with the acoustical measurements. The meteorological equipment mast was fixed near vertical array I. Wind speed and direction and temperature were measured using three sonic anemometers at altitudes of 2, 5 and 10 m simultaneously. All the signals received by the microphones and anemometers were recorded simultaneously on a 16-channel digital tape recorder. These recordings have been analysed in the laboratory using PC based card, software and the GEILA algorithm. In order to reduce the running time of the GEILA, trial values of impedance parameters were obtained from a short-range measurement at the propagation site using a local source and receivers

STATISTICAL RESULTS

In processing the data, it is assumed (1) that the atmosphere was vertically stratified, (2) that sound velocity profiles were linear, (3) that these sound velocity profiles fluctuated about their mean values in the presence of turbulence and (4) that there was an instantaneous sound pressure spectrum corresponding to each instantaneous sound velocity profile.

Figure 3 shows example spectrum levels of white noise and background noise, and of multiple-tones and background noise measured at different times during the experiments. The acoustic pressure was sampled every 2 minutes. It is noted that a much better signal-to-noise ratio was obtained with multiple-tones than with white noise.

The short-range measurement data obtained at this site can be described well by Attenborough's two-parameter ground impedance model[5] with $\sigma_e = 4.6 \times 10^4$ MKS rayls m^{-1} and $\alpha_e = 960\,\mathrm{m}^{-1}$. Figure 4 shows examples of comparisons between measured short-range level difference spectra and calculation using these two parameters. This makes it possible to reduce the range of trial values of ground impedance in the algorithm, i.e. the parameter ranges $\sigma_i' = 1.0 \times 10^4 \sim 10.0 \times 10^4$ MKS rayls m^{-1} and $\alpha_i' = 800 \sim 1000\,\mathrm{m}^{-1}$ were used. It should be noted that GEILA does not need prior knowledge of impedance data, however the use of these trial values based on the short-range measurement can reduce the running time of GEILA greatly.

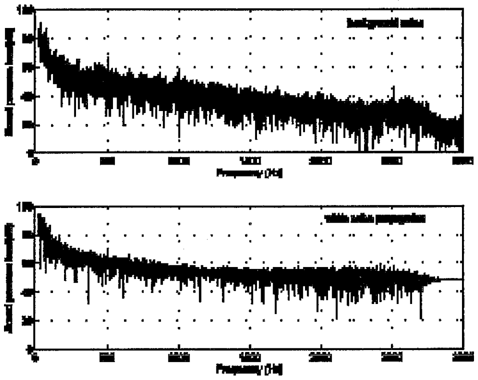

Figure 3(a) Examples of levels of white noise and background noise.

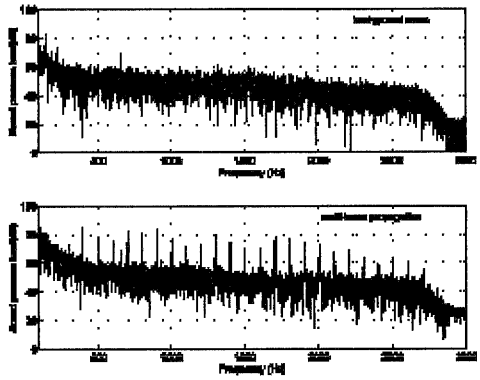

Figure 3(b) Examples of levels of multiple tones and background noise.

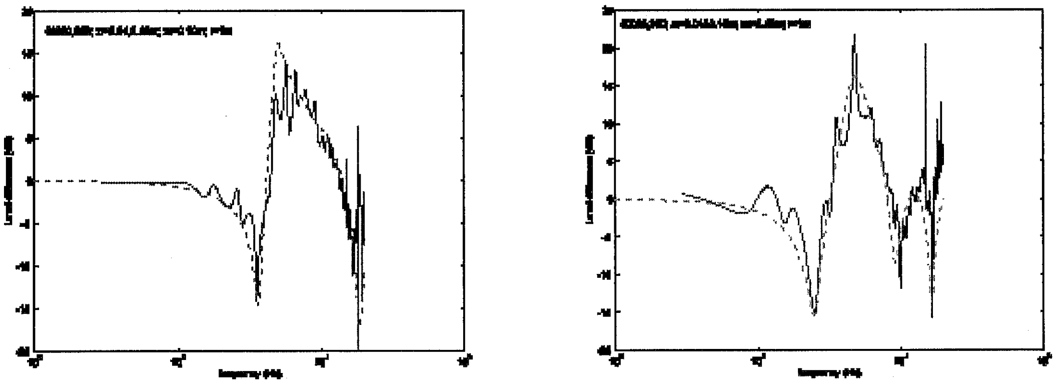

Figure 4. Comparisons of measured short-range level difference spectra with predictions using Attenborough's two-parameter impedance model.

Figure 5 shows examples of the variations of wind speed and temperature with height above the ground surface during the trial. The range of sound velocity gradients deduced from the wind speed and temperature gradients were $a = 2 \sim 5 \times 10^{-4}\ m^{-1}$. The wind direction varied between $\psi_w = 35 \sim 107.68^{\circ}$ with respect to the North.

GEILA matches the complex acoustic pressure obtained simultaneously at each microphone of the arrays with the estimated ones for source location. The largest values of the ambiguity functions should be given when the estimates for range and height approximate to the actual source co-ordinates. In the case of slow fluctuations in complex sound pressure, good agreement between the sound level difference spectra predicted using the values deduced from GEILA and the measured data can be achieved usually when the sound pressure data were sampled over a period of 2 minutes. An example of the comparisons is shown in Figure 6. In Figure 6, the deduced source co-ordinates were $z_s' = 10.4$ m and $r_1' = 240$ m (compared with actual values of 10 m and 250 m respectively). The estimated by-products of GEILA are $a' = 3 \times 10^{-4}\ m^{-1}$, $\sigma_1' = 6 \times 10^{4}$ MKS rayls m^{-1} and $\alpha_1' = 800\ m^{-1}$. The level difference spectrum was between the sound pressure received at $z_r = 1$ and 3 m.

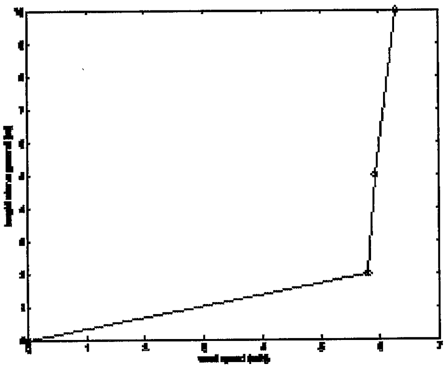

Figure 5(a). Example of measured wind speed gradient.

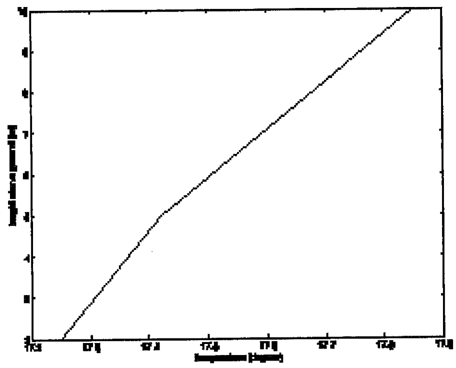

Figure 5(b). Example of measured temperature gradient.

However, in the cases of rapid fluctuations in the complex sound pressure, the predicted sound level difference spectra using the deduced values from GEILA may disagree with the measured data, see Figure 7. Figure 7 shows comparisons between the sound level difference spectra predicted using the values deduced from GEILA and the measured data with different sampling intervals. For the same raw data, the complex acoustic pressure was sampled over periods of 1-second, 5-second, 10-second, and 2-minute respectively. Each sampled *instantaneous* complex sound pressure spectrum was used in the GEILA algorithm to determine the source location. The averaged source co-ordinates deduced from GEILA were $z_s' = 10$ m, $r_1' = 250$ m and the meteorological values are same as those in Figure 6. The level difference spectra in Figure 7 were between the sound pressure received at $z_r = 0.1$ and 3 m. It has been noted that better agreement was found by using shorter sampling intervals. The statistical distributions of the source locations deduced from acoustical measurement data depend significantly on the frequency with which the complex sound pressure is sampled.

When the source height was 10m, and the sound pressure data were sampled over a period of 10 seconds, the source location results and corresponding standard deviations deduced from GEILA using frequencies from 400 to 2500 Hz are: $r_1' = 240 \pm 30$ m, $r_2' = 250 \pm 27$ m, $r_3' = 240 \pm 30$ m, $z_s' = 10.4 \pm 1.5$ m, $\sigma_e' = 2.5 \pm 1.5 \times 10^4$ MKS rayls m^{-1}, $\alpha_e' = 850 \pm 50$ m^{-1}, $a' = 3.0 \pm 1.2 \times 10^{-4}$ m^{-1}, and $\vartheta' = 87 \pm 25°$ from the North. When the source height was 5m, and the sound pressure data were sampled over a period of 10 seconds, the source location results and corresponding standard deviations deduced from GEILA using frequencies from 400 to 2500 Hz are: $r_1' = 242 \pm 24$ m, $r_2' = 260 \pm 30$ m, $r_3' = 240 \pm 25$ m, $z_s' = 4.4 \pm 2.5$ m, $\sigma_e' = 3.2 \pm 2.5 \times 10^4$ MKS rayls m^{-1}, $\alpha_e' = 850 \pm 50$ m^{-1}, $a' = 2.9 \pm 1.4 \times 10^{-4}$ m^{-1}, and $\vartheta' = 78 \pm 30°$ from the North. When the source height was 2m, and the sound pressure data were

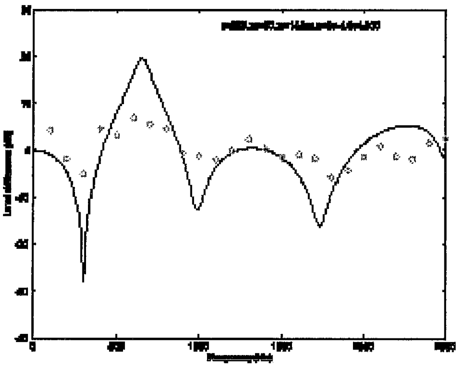

Figure 6. Comparison of level difference spectra between the prediction using the values deduced by average overall results from GEILA and the data of complex pressures sampled over a period of 2 minutes. $z_r = 1$ and 3 m.

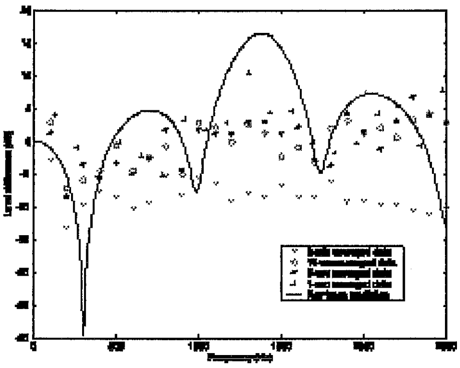

Figure 7. Comparison of level difference spectra between the prediction using the values deduced by average overall results from GEILA and the data with various sampling lengths. The parameters are same as Figure 6, but $z_r = 0.1$ and 3.0 m.

sampled over a period of 10 seconds, the source location results and corresponding standard deviations deduced from GEILA using frequencies from 400 to 2500 Hz are: $r_1' = 245 \pm 35$ m, $\alpha_e' = 900 \pm 50\ \mathrm{m}^{-1}$, $a' = 2.8 \pm 1.0 \times 10^{-4}\ \mathrm{m}^{-1}$, and $\vartheta' = 74 \pm 28^\circ$ from the North. $r_2' = 260 \pm 30$ m, $r_3' = 242 \pm 30$ m, $z_s' = 2.4 \pm 1.0$ m, $\sigma_e' = 3.7 \pm 2.5 \times 10^4$ MKS rayls m^{-1},

SUMMARY

The effectiveness of GEILA algorithm for deducing the location of a stationary source at a range of 250 m over flat grassland in a realistic atmospheric environment has been investigated. The source locations deduced from the acoustical measurement data depend significantly on the length of successive time domain samples used in the algorithm. The relatively shorter sample length is found to give better results. However, this is being investigated further. Also it has been demonstrated that the sound velocity gradients deduced from the meteorological data during the experiment and the acoustical data were comparable.

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