# THE USE OF ARRAYS OF ELECTRONIC SENSORS TO SEPARATE INFRASOUND FROM WIND NOISE

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Sponsored by Army Space and Missile Defense Command

Contract No. DASG60-00-C-0061

## ABSTRACT

With current technology for near simultaneous detection of multiple signals it is possible to replace the pipes with arrays of individual sensors. With such arrays it is not only possible to average the pressure signals over an extended area, as is done with the pipe arrays, but to combine the signals in innovative ways to preferentially cancel the wind noise. A three axis orthogonal array with 10 sensors in each arm has been constructed and used to study the correlation of the wind noise as a function of distance in the vertical and two horizontal directions. The rugged all weather sensors are of original design and require no external power source. Measurements have been made for wind speeds from 4 to 7 meters per second and at three different sites.

The frequency dependent correlation of the wind noise over a range of wind velocities and atmospheric and environmental conditions in the downwind direction varies as $\exp(-3.2x)\cos(2\pi x)$, and the crosswind correlation varies as $\exp(-7.4y)$, where x and y are the sensor separations in wavelengths in the downwind and crosswind directions, respectively. The correlation of pressure signals from sensors in the vertical arm of the array decreased with sensor separation approximately twice as fast as those from the horizontal arms that were on the ground. For two of the sites studied, over a limited range of wave numbers, the spectra of the varying velocity as measured 3 meters off the ground demonstrated the characteristics of the inertial sub-range. Over the same range of wave numbers the pressure spectra obeyed the –7/3 power law.

## OBJECTIVE

The objective of this research is to improve techniques for detecting infrasound in the presence of wind noise. Current wind noise filters generally use extensive pipe arrays with multiple ports to average pressure signals over an extended area.[1-3] Because sound travels approximately 100 times faster than wind, pressure ports in the pipe arrays can be separated far enough to get random signals from the wind and still get coherent signals from sound. If the pressure variations due to the wind are incoherent, the averaging process will reduce the noise pressure by a factor of $1/n^{1/2}$. If the pressure due to wind noise is not coherent, this averaging is not applicable. The goal of this research program is to replace the pipe arrays and ports with individual rugged sensors. Optimum spacing and numbers of sensors requires that correlation of pressure under different conditions is understood. To study correlation an array of rugged infrasound pressure sensors has been constructed and used to determine the spatial correlation of wind noise.

## RESEARCH ACCOMPLISHED

### The Infrasound Sensors

The infrasound sensing capsules are constructed by cementing piezoelectric bimorphs on each side of a metallic ring. A voltage is generated between the conducting coating of the ceramic and a metal backing plate that is proportional to the pressure bending the bimorphs and is independent of frequency from 0 Hz up to frequencies approaching the resonant frequency of the bimorph. For the 3.5 cm bimorphs used here the resonant frequency was 1.5 kHz.

These sensors are sensitive to changes in temperature as well as pressure. In order to compensate, two capsules have been constructed with the ceramic surface turned outward on one and inward on the other. When wired in series, the changes due to pressure add and the changes due to differential expansion cancel. The pair of capsules is then potted in polyurethane. To further insulate the sensors from temperature fluctuations in the atmosphere, the potted sensors have been wrapped in fiberglass and housed in capsules made of two inch, schedule forty, PVC pipe with end caps. Each of the end caps has 26 holes 1/16 inch in diameter. When temperature compensated and housed in this way, temperature fluctuations ordinarily encountered in the atmosphere produce a negligible signal for frequencies above 0.1 Hz. A total of thirty transducers were individually calibrated and the outputs corrected so that all had the same sensitivity to within + or- 3%. Their phase response was constant and uniform to + or - 0.1 radian between 0.1 Hz and 10 Hz.

Widely different results are reported for pressure spectrum measurements in turbulence [4]. One must always be concerned that intrinsic pressure fluctuations are being measured and not the interactions of the wind with the sensing element. To study this question further, the pressure sensors employed here have also been tested in the field and shown to be insensitive to orientation relative to wind direction over the frequency range of interest.

### The site for the measurements

The sensors described above were used for five sets of field measurements from Sept., 2001 to Jan., 2003. For the first of these, the sensors were arranged along two directions at right angles to each other with 15 sensors in each arm 0.46 m apart. One of the arms was into the wind and one across wind. The sensors were placed on the ground in a plowed cotton field. The cotton had been harvested and the remaining cotton stalks were approximately 0.7 meters tall.

For the other four sets of measurements, 28 of the sensors were arranged in a three dimensional rectangular array. An ultrasonic anemometer was mounted 3 meters off of the ground about 0.5 meters from one of the pressure sensors on the vertical arm of the array. This anemometer and the three dimensional array was deployed at four different sites. The first was on a junction of service roads between 20-acre catfish ponds. The second was a sod field. Measurements were taken at this site on two different days. The third was a disked field in the Mississippi delta. The fourth site was at a different place in the same cotton field where the first measurements were made approximately one year earlier.

**The average response of each arm in the array**

The power spectral density of the pressure variations for each of the three arms of the array for each of sites 3, 4 and 5 is plotted in Fig. 1.

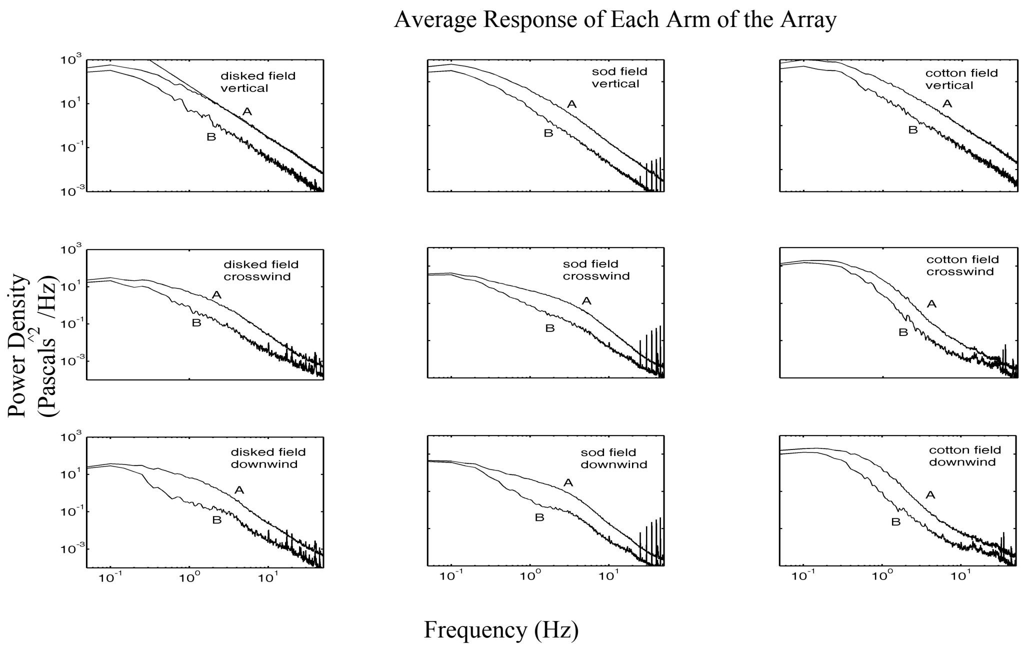


**Figure 1. The power density spectra of the varying pressure as measured by each arm of the array at each of three sites. Curves A were obtained by averaging the spectra from nine sensors in each arm. Curves B were obtained by taking the spectra of the average signal from the same nine sensors.**

The top curve (A) in each figure is obtained by calculating the spectrum of time signals from each of the nine sensors in the arm and then averaging these spectra. The lower curve (B) is obtained by averaging the time signals from the nine sensors and then calculating the spectrum of this average. For curves B, if the sensors are far enough apart so that their signals are uncorrelated, averaging the time signals should divide the noise power density by the number of sensors. This is seen to be the case for the vertical arm signals at all three sites for frequencies above approximately 1 Hz. For the two horizontal arms that are on the ground the wind noise at the higher wave numbers is reduced to where the spectra are influence by background sound. Since the sound is at least partially correlated over the arm of the array averaging the time signals reduces the power level by less than the 1/n factor.

The average spectrum for the nine sensors in the vertical arm that are from 2 feet to 18 feet off the ground has very nearly a $-7/3$ slope. This is illustrated by the straight line plotted through the data for vertical arm in the disked field. For the horizontal arms on the ground, the surface boundary reduces the turbulence and causes a deviation of the spectral slopes from $-7/3$. The spectra for the cotton field data differ significantly from the other two sites. The noise level in the vertical arm is greater and the shape of the spectra for the two arms on the ground is different. The pressure levels at frequencies in the neighborhood of 0.3 Hz are increased while those around 3 Hz are decreased.

For the disked field and sod field, averaging the signals from the downwind arm produces greater than 1/n noise reduction for wave frequencies between about 0.5 and 5 Hz. This can be explained by assuming that the turbulent pressure field has a periodicity. When the convection velocity carries this periodic field across the downwind arm of the array, for wavelengths comparable to the length of the array arm, signals from different parts of the array will be out of phase and cancel out in the averaging process.

**Correlation studies**

Fig. 2 A and B shows the correlation as a function of lag time for signals from 5 sensors in the downwind and

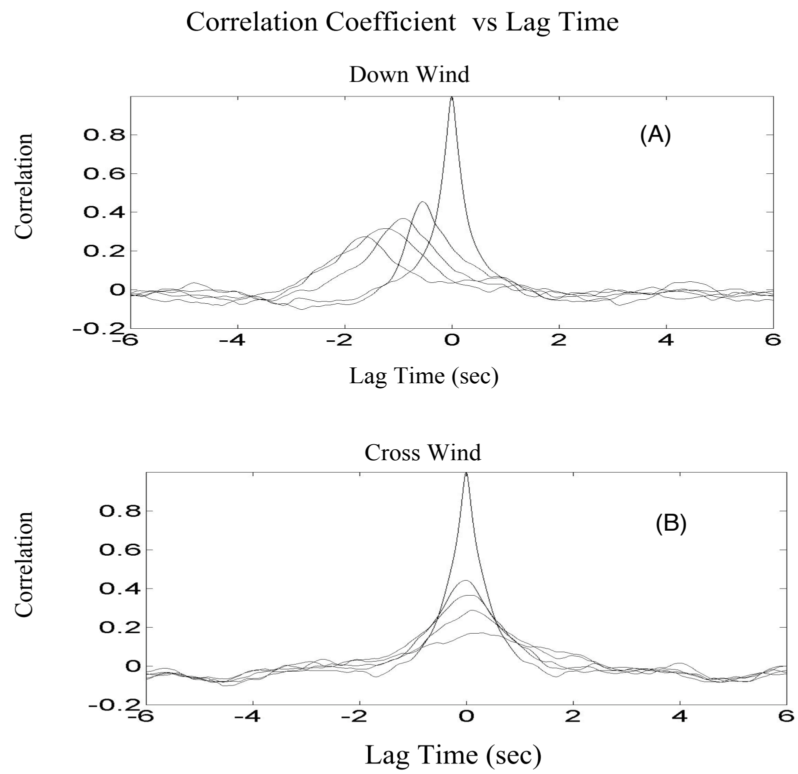


**Figure 2. The Correlation coefficient versus the lag time for signals from 5 sensors in (A) the downwind arm of the array and (B) the crosswind arm of the array. For the crosswind arm the sensors are separated by 2 feet (61 cm.), and for the downwind arm, they are separated by 4 feet (122 cm.)**

crosswind arms of the array respectively for the disked field data. Plotting the correlation at zero lag time versus sensor separation in these two figures gives the decrease in correlation with distance in the crosswind and downwind directions. Plotting the peak heights versus lag time for the downwind arm gives the decrease in correlation with time at a fixed position in the turbulent pressure pattern. As has been pointed out by Bass, Raspet and Messer[5], the average wind velocity should equal to the slope of the plot of the sensor separation versus lag time.

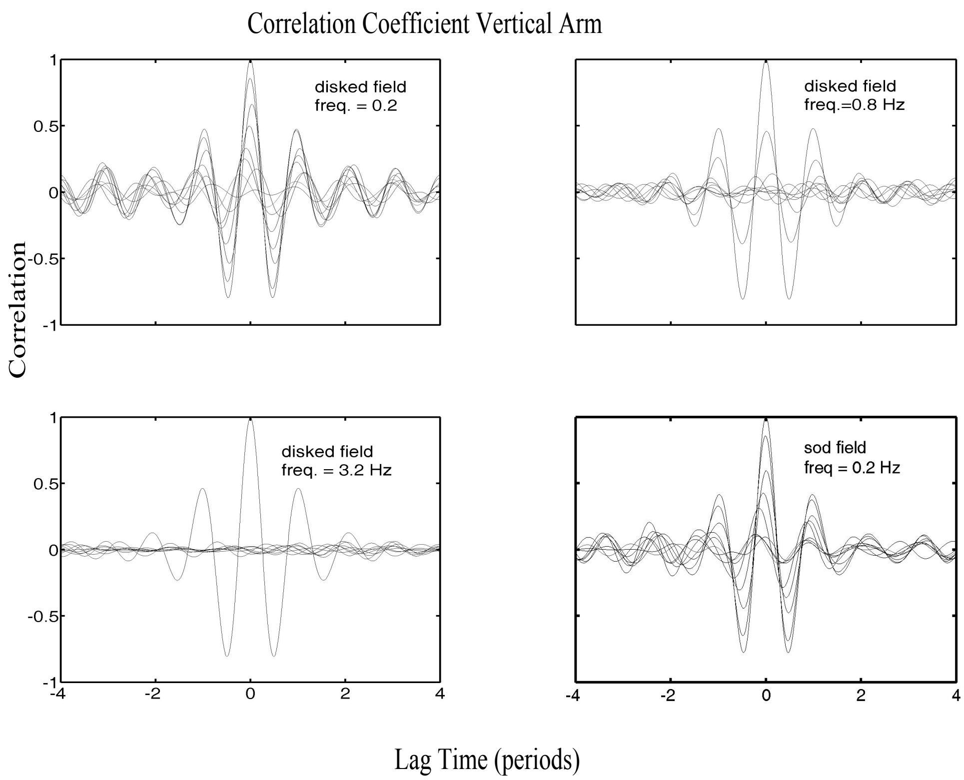


**Figure 3. Single frequency correlation versus lag time in periods for varying pressure signals from eight sensors in the vertical arm of the array.**

It is interesting to examine these correlation curves as a function of frequency. Figs. 3 A, B, and C show the correlation of the signals at three different frequencies from eight sensors in the vertical arm of the array for the disked field data. The sinc function shape of the correlation curves is characteristic of the correlation of narrow band of frequencies. The lag time has been normalized by dividing by the period of the filtered signal. This gives the same shape to curves at different frequencies. As the frequency is increased from 0.2 Hz in Fig 3A to 3.2 Hz in Fig 3C the rate of decrease in correlation with distance rapidly increases to where at 3.2 Hz there is negligible correlation even between the adjacent sensors separated by only 0.6 meters. Fig 3D gives the curve for the same sod field. The correlation at the two sites is very similar.

Nearly 40 years ago J. T. Priestley [6] made narrow band pressure correlation measurements in the frequency range 0.008 to 1 Hz. for wind speeds ranging from 2.1 to 7.2 m/sec. He used six pressure sensors to study the dependence of the correlation on the downwind and crosswind separation of the sensors. He determined, in agreement with earlier studies, that the narrow band correlation coefficients in the down wind and cross wind directions are given by

$$R(\text{downwind}) = e^{-\alpha x} \cos(k_1 x), \quad (1)$$

and

$$R(\text{crosswind}) = e^{-\beta y}, \quad (2)$$

with x and y the down wind and cross wind separations. Priestley found that, though the convection velocity given by ($2\pi *F/k_1$) was highly dependent upon meteorological variables, the functional relationships between alpha, beta and $k_1$ were remarkably independent of them. (F was the center frequency of his filtered signal and $k_1$ chosen to fit his data.) He obtained

$$\alpha = 0.33 * k_1^{1.28}\ \text{m}^{-1}, \quad \text{for } 0.5<1/k_1< 50. \quad (3)$$

$$1/\beta = 0.84*(1/\alpha)^{0.74}\ \text{m}, \quad \text{for } 3< (1/\alpha) < 500. \quad (4)$$

Fig 4 is a plot of the correlation at zero lag time between sensors in the downwind arm of the array versus the sensor

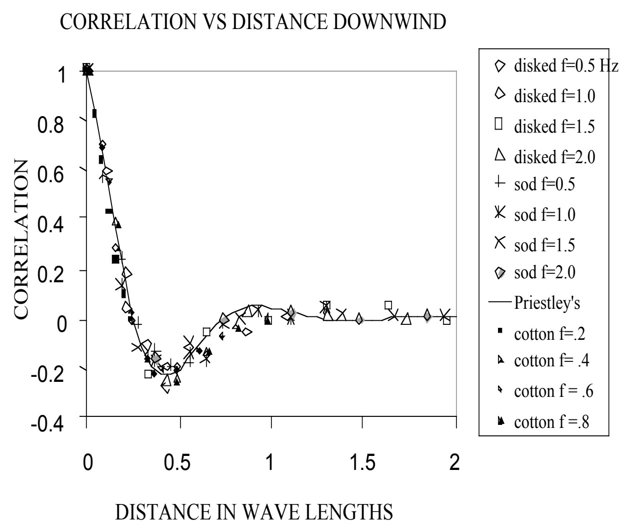


**Figure 4. Correlation of the varying pressure signals versus the sensor separation in wavelengths in the downwind direction. The data are for four different frequencies and for three different sites as designated in the legend. The solid curve is the fit to Priestley's data taken at much lower frequencies in 1964.**

separation in wavelengths. Data for the disked, sod, and cotton fields for a number of frequencies have been plotted on the same graph. The data for each site have been averaged not only for all runs at the site, but also for all pairs of sensors with the same separation. The wavelength was determined by dividing the convection velocity by the frequency of the filter. However, since the sensors are on the ground, the anemometer measurement of the velocity made 3 meters above the ground is inadequate. Instead the convection velocity for the three sites was adjusted to make the data fit Eq. 1. These velocities were 2.8, 3.3, and 3.0 m/s for the disked, sod, and cotton fields respectively. The velocities obtained in this way were approximately equal to those obtained from the plot of the sensor separation versus the lag times at which the maximum in the correlation occurs. The average velocities for the three sites measured with the anemometer 3 meters above the ground were 6.2, 6.7, and 5.9 m/s respectively.

To within experimental error, the correlation is seen to be a function of the separation divided by the wavelength independent of frequency, wind velocity (over the limited range of velocities measured) and even the terrain. frequency dependent. The $\alpha$ value used to draw the curve in Fig. 4 corresponds to Priestley's $\alpha$ as calculated from Eq 3 with a wave number of 4.7m $^{-1}$. This is the highest wave number for the data plotted in Fig. 4. approximately 2 m/sec. The distance in the direction of the wind is the time times the average wind velocity.

## CONCLUSIONS AND RECOMMENDATIONS

The conclusions can be summarized as follows:

1) Noise power reduction produced by averaging signals from individual sensors varies as 1/(number of sensors) when the signals averaged are not correlated.
2) The frequency dependent correlation of the wind noise over a range of wind velocities and atmospheric and environmental conditions varies as exp(3.2x) cos(2$\pi$ x), where x is the sensor separation in wave lengths in the down wind direction. This allows greater than 1/n noise reduction if the aperture of the array is greater than _ wavelength of the pressure variations in the wind. Use of multiple sensors rather than fixed separation ports allows one to take advantage of this cosine dependence to further reduce noise.
3) The correlation as a function of sensor separation for arrays in the crosswind and vertical directions is given approximately by exp(-7 x) for a range of wind velocities and atmospheric and environmental conditions.

## ACKNOWLEDGEMENTS

The help of Chris Clark and Brandon Smith in taking data is gratefully acknowledged. Thanks also go to Drs. Ken Gilbert, Carrick Talmadge, Richard Raspet, and Garth Frazier, for helpful discussions.

## REFERENCES

F. B. Daniels, "Noise-Reducing Line Microphone for Frequencies below 1 cps", J. Acoust. Soc. Am., 31, 529-531 (1959).

S. T. Tenny, B. T. Mays, and J. M. Noble, "A methodology for infrasonic detection and array signal processing," Army Research Laboratory , Security Office, 2800 Powder Mill RD. Adelphi, Md 20783, (1999).

M. A. Hedlin, B. Alcoverro, and G. D'Spain, "Evaluation of rosette infrasonic noise reducing spatial filters," J. Acoust. Soc. Am., 114, 1807-1820(2003).

W. K. George, P. D. Beuther, and R. E. A. Arndt, "Pressure spectra in turbulent free shear flows", J. Fluid Mech.," 148, 155-191(1948).

H. E. Bass, R. Raspet, and J. O. Messer, "Experimental determination of wind speed and direction using a three microphone array", J. Acous. Soc. Am., 97 (1) 695-696 (1995).

Joseph Tant Priestley, "Correlation Studies of Pressure Fluctuations on the Ground Beneath a Turbulent Boundary Layer", *National Bureau of Standards Report, No. 8942*, (1965), also M. S. Thesis, University of Maryland (1965). Joseph Tant Priestley, "Calculation of the Effectiveness of Infrasonic Line Microphones for Reducing Wind Noise", *National Bureau of Standards Report* 9380, (1966).