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14. ABSTRACT

Work is continuing on the development of infrasound techniques that can be used to improve detection, location and discrimination capability for atmospheric nuclear explosions at International Monitoring System (IMS) infrasound monitoring stations. In particular, we are continuing to focus on the detection of atmospheric explosions in the distance range from about 500 to 4500 km. We note that good detection capability in this distance range is essential to ensure that the global IMS infrasound network has acceptable monitoring capability, including good capability for the detection of explosions that occur over the vast open ocean areas in the Pacific, Indian and Southern Oceans. This investigation has therefore been primarily concerned with a detailed study of the properties of infrasound generated by regional and distant atmospheric explosions and the development of techniques that can improve detection capability for regional and distant sources at infrasound monitoring stations. The database for this study has been expanded to include, in addition to data from IS05 Hobart, Tasmania and IS07 Warramunga in northern Australia, all data from IMS infrasound station IS04 Shannon in southwest Australia, and also data from a number of portable infrasonic array experiments carried out in eastern and northern Australia.

We are continuing to study the influence of the spatial correlation properties of infrasound from distant explosions on the detection capability at IMS infrasound monitoring stations. These studies show that a low degree of correlation between signals at different array elements at frequencies above 0.5 Hz is clearly a significant problem for the detection of infrasound from distant sources at monitoring stations with a small number of widely separated array elements. We also find that the degree of spatial correlation of infrasonic signals, even from sources in the same distance range, is quite variable, which may reflect seasonal variations in waveguide structure and variations in source characteristics. A technique has been developed that allows a direct comparison of the predictions from spatial coherence theory with array averaged coherence observations at all azimuths for any specified infrasonic array configuration.

A high-sensitivity portable infrasonic array has been deployed at a number of sites in the Australian region during the second year of this project. The first experiment with this portable array was carried out at a location between IS05 Hobart and IS07 Warramunga in order to assess the combined detection capability of these neighbouring IMS stations for surface mining explosions in the distance range from 1000 to 2000 km. Three additional experiments have been carried out using the portable array at locations in the Northern Territory and northern Queensland. These experiments were designed to provide data that will assist with the positive identification of local and distant infrasonic sources observed at IS07 Warramunga.

Work has also started on the identification of the fundamental physical processes that result in background noise at IMS infrasound stations. These processes include both infrasonic and sub-sonic noise sources. It is clear that any technique that will improve signal-to-noise ratios (even by a factor of two) will significantly improve the monitoring capability of the IMS infrasound network. We recognize that wind-generated turbulence is usually the most significant source of background noise at infrasound monitoring stations and we have therefore started experimental work on techniques that will reduce the influence of wind-generated noise at frequencies in the principal infrasound monitoring passband.

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Sponsored by Air Force Research Laboratory

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OBJECTIVES

The primary goals of this research project are

- To identify problems with the detection, location, and discrimination of atmospheric nuclear explosions and
- To develop techniques using infrasound technology that will improve detection, location, and discrimination capability for nuclear explosions in the atmosphere.

Since this project is primarily concerned with the detection capability of the global IMS infrasound network, this research continues to be focused on an investigation of the properties of infrasonic signals observed at typical IMS monitoring stations. The average separation between nearest neighboring IMS infrasound stations is 1920 km in the Northern Hemisphere and 2020 km in the Southern Hemisphere. The distances between stations on opposite sides of the vast open ocean areas in the Southern Hemisphere may, however, exceed 7000 km. Stations that monitor the vast open ocean areas in the Southern Hemisphere therefore need to have good detection capability for explosions that occur at distances of at least 4000 km. This project is therefore focused on monitoring capability for atmospheric explosions at distances in the range from about 500 to 4500 km.

RESEARCH ACCOMPLISHED

Introduction

The research in this project is based on a detailed study of signal and noise properties derived from infrasonic data recorded at Australian IMS monitoring stations and data recorded during a number of carefully designed portable infrasonic array experiments. This work is divided into two separate, but closely linked, investigations. The first part is concerned with an ongoing investigation of the properties of infrasonic signals recorded at typical IMS stations, with emphasis on problems associated with the detection, location, and discrimination of regional and distant atmospheric explosions. These results are used to determine techniques that will improve existing infrasonic array designs and currently used analysis procedures. It has been noted (Christie et al., 2005a, b) that the optimum analysis passband for the detection of infrasound from distant explosions is generally centered on frequencies below 1.0 Hz. Up to this point, it has been tacitly assumed that the optimum passband for the detection of a 1-kT explosion at distances in the range from 1000 to 4500 km is centred at or above 1.0 Hz. However, research carried out to date shows that signal components with frequencies of 1 Hz or higher may have eroded away completely when the source lies at distances of more than 1500 km. In this case, the optimum detection passband usually extends from about 0.4 to 1.0 Hz. In some cases, especially when only thermospheric waveguide propagation is possible, detectable infrasound components from distant explosions are found only at frequencies below 0.1 Hz. The detection capability at an infrasound monitoring station is also found to be critically dependent on array design. Two specific problems can be identified: a) spatial aliasing of higher frequency signals and b) problems with signal coherence between array elements. Spatial aliasing of higher frequency signals has been extensively studied in recent years and the use of arrays with eight or nine elements has largely eliminated this problem. The results from the continuing investigation of signal coherence are proving to be surprisingly complex. It is clear, however, that the low degree of signal coherence between array elements at some existing larger-aperture 4-element infrasound monitoring stations will severely limit detection capability for infrasound generated by regional and distant explosions. Some of the results from the survey of signal coherence properties are described below.

The second part of this project is focused on a detailed study of the physical processes that generate infrasonic background noise and the development of techniques that will improve the signal-to-noise ratio for infrasonic signals from regional and distant atmospheric explosions. Detection capability at many infrasonic monitoring stations is limited by background noise usually associated with wind-generated turbulent eddies in the atmospheric boundary layer. Wind-generated noise is a particularly significant factor in the case of monitoring stations located in open exposed environments with little protection from the ambient winds. However, background noise at infrasonic monitoring stations is not limited to turbulent-eddy-generated micropressure fluctuations; there are also a number of other significant sources of background noise ranging from continuous or semi-continuous infrasonic signals to longer period noise components of unknown origin. It is clear that any technique that will reduce the effective background noise level at an infrasound monitoring station has the potential to significantly improve the monitoring capability of the global infrasound network. We have now started experimental work on the development of new techniques, which we hope will lead to a significant reduction in background noise in the primary monitoring

passbands. A brief description of the results of a preliminary experimental investigation of a potentially useful noise reducing technique is presented below.

IMS Infrasonic Stations, Temporary Infrasonic Arrays, and Explosion Sources in the Australian Region

Five IMS infrasonic monitoring stations are located on Australian territory. Two of these stations, IS05 Hobart and IS07 Warramunga have been in operation and certified for some time. IS04 Shannon in southwest Australia has recently been certified and data from this station is now being analyzed continuously in conjunction with data from IS05 and IS07 in an attempt to detect, locate, and identify all significant explosions in the Australian region. Work on the construction of a 4th Australian station, IS06 Cocos Islands, is underway and it is anticipated that the last Australian station in the IMS network, IS03 Davis Base in Antarctica, will be established in late 2007. The locations of the three certified infrasonic stations on the Australian mainland, along with the location of the most important open-cut mines are shown in Figure 1. The locations of the New South Wales bolide on 5 December 2004 and the Manam Volcano explosion on 27 Jan 2005 are also shown on this map, along with the location of a 0.027-kT chemical explosion at the Woomera Test Range. The analysis of infrasonic waves generated by these three events has provided considerable insight into the properties of infrasonic waves from distant sources. Only the most significant open-cut mines and mining areas are shown in Figure 1. A large number of smaller mines have been omitted since explosions at these mines tend to be of lower yield and signals from these explosions are usually detected only at local or near-regional distances.

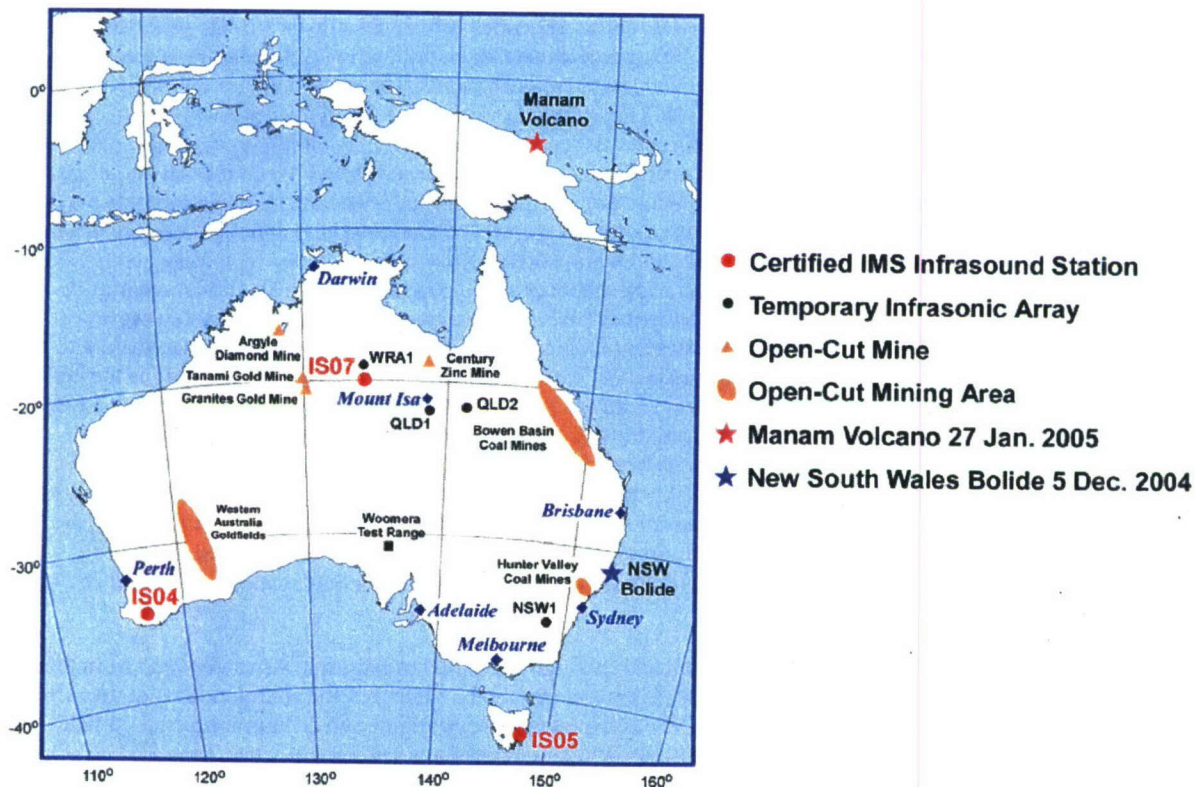


Figure 1. Map of the Australian region showing the locations of certified IMS monitoring stations IS04, IS05, and IS06, the locations of the most significant open-cut mines and open-cut mining regions, the sites of temporary infrasonic arrays (NSW1, WRA1, QLD1 and QLD2) used in this study, and the locations of the 0.027 kT chemical test explosion on 20 September 2002 at the Woomera Test Range, the explosive eruption of Manam Volcano on 27 January 2005 and the New South Wales bolide on 5 December 2004.

A 4-element high sensitivity portable infrasonic array has been constructed and deployed at a number of experimental sites as shown in Figure 1. The sensor used at each array element is a Chaparral Physics Model 5 microbarometer with specifications that exceed those required for IMS infrasound monitoring stations. Data is recorded on RefTek 24-bit model 130-01 digital recorders. Power is supplied at each array element by a solar power system and time is maintained to within 5 microseconds using independent GPS clocks. The portable array is usually deployed in a slightly irregular centered triangle configuration with an aperture of about 300 m. Noise reduction is achieved by connecting four 15-m porous hoses, arranged in a spiral configuration, to the inlet manifold on each microbarometer. Results from the portable array experiments are used to identify sources, to extend the database for the study of infrasonic wave properties to new sources and source distances, to measure the properties of background noise, and to test procedures that can be used to minimize background noise. NSW1 in New South Wales was installed to evaluate the performance of IS05. WRA1 was located near Warramunga to identify local sources at IS07. QLD1 was established near Mount Isa to observe infrasound generated by a large industrial mining complex and QLD2 was installed midway between the coal mining region in the Bowen Basin and IS07.

The detection characteristics, array configurations, and background noise properties of IS04 Shannon, IS05 Hobart, and IS07 Warramunga differ substantially. IS04 is located inside one of the tallest forests in Australia (trees to a height of more than 60 m) dominated by giant kari trees. The array elements are well sheltered from the ambient winds and noise levels tend to be quite low at most times of day. It is worth noting that the noise levels in the low-frequency monitoring passband from about 0.03 to 0.1 Hz are significantly lower on average than the levels observed at other IMS infrasound monitoring stations. Microbaroms generated by storms over the Southern Ocean tend to have large amplitudes and can be detected in the data at any time of day. Surf noise is seen on occasion at frequencies above 1 Hz. Longer period semi-continuous auroral-generated infrasonic signals are also observed at IS04 from time to time. The low-noise conditions at IS04 suggest that this station will play a valuable role in the monitoring of the open ocean regions in the South Indian and Southern Oceans. The noise conditions at IS05 in Tasmania are not nearly as good as those found at IS04. This station is located in a fairly open eucalypt forest which provides some shelter from the ambient winds, but noise levels tend to be relatively high at all times of day and to vary significantly from one array element site to the next. High frequency noise associated with surf activity along the eastern coast of Tasmania is frequently observed. As with IS04, microbaroms generated by intense storms over the Southern Ocean tend to have high amplitudes, but, in contrast with IS04, microbaroms cannot be detected at all times due to relatively high levels of background noise. Numerous local explosions generated by mining activity on the island of Tasmania have been detected. However, it is a matter of some concern that signals from large mining explosions on the Australian mainland are seldom detected at IS05. This may be due to the relatively high levels of background noise at IS05. It may also be due to the fact that most signals from sources on the Australian mainland can only propagate to IS05 in a thermospheric waveguide. IS07 at Warramunga in the Northern Territory is located in a semi-desert environment. Some protection from the ambient winds is provided by long grass, bushes and a few small trees, but wind-noise levels are almost always high during the daytime. Winds in the boundary layer are decoupled from the surface shortly after sunset with the rapid development of an intense radiation inversion. Noise levels therefore tend to be very low at night except when the radiation inversion is destroyed by thunderstorm activity or by propagating highly nonlinear mesoscale solitary waves and internal bore wave disturbances (Christie, 1989). Highly nonlinear gravity waves of this type are frequently observed at IS07 but have not been identified in the data from IS04 and IS05. They probably occur with reasonable frequency at IS04 Shannon, but only rarely at IS05 Hobart.

The array configurations and responses for IS04, IS05, and IS07 are compared in Figure 2. As can be seen from this illustration, the overall aperture of each of these arrays is approximately the same, but the configurations of the array elements differ substantially. The array elements at IS07 Warramunga are configured in a "high-frequency" small aperture triangular sub-array enclosed by a larger aperture "low-frequency" triangular main array. This configuration is typical of the array configurations used during the early stages in the construction of the IMS. IMS arrays that are currently being installed are usually configured in the form of a small aperture tripartite sub-array centered inside a larger aperture pentagon array, a design with very good side-lobe suppression characteristics. It is not always possible to install an IMS monitoring station with an ideal array configuration. The somewhat unusual array configurations at IS04 and IS05 have been installed to accommodate local conditions at each of these stations. The array response for all of the IMS arrays on the Australian mainland is quite good with fairly reasonable side-lobe suppression. Spatial aliasing will not be a problem except in the case of higher frequency signals with low signal-to-noise ratios. In this case, the technique described by (Kennett et al., 2003) can be used to minimize spatial aliasing and lower detection thresholds.

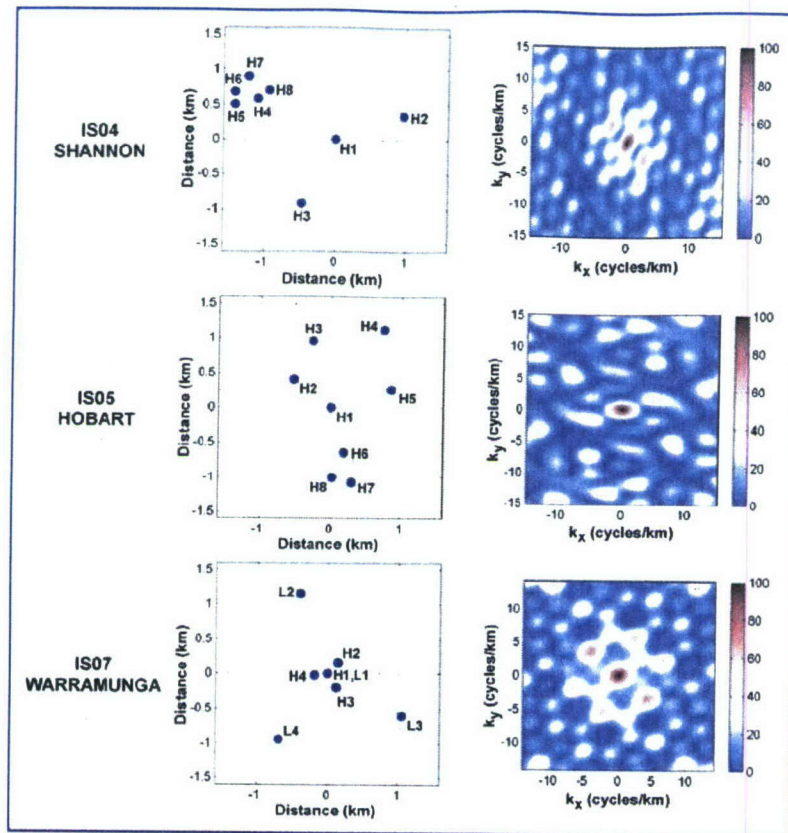


Figure 2. Comparison of the array configuration and response at IS04 Shannon, IS05 Hobart, and IS07 Warramunga. The overall aperture of each array is similar and each array includes both small and large aperture sub-arrays. The array response at all stations exhibits fairly reasonable side-lobe suppression.

Spatial Correlation of Explosion-Generated Infrasonic Signals

The spatial coherence of infrasonic signals has been studied extensively since the pioneering work of Gossard (1969), Gossard and Sailors (1970) and Mack and Flinn (1971) (see also Gossard and Hooke (1975). Mack and Flinn (1971) developed a relatively simple model for spatial coherence as a function of sensor separation and frequency and compared the predictions of this model with observations of relatively long-period infrasonic signals from very large explosions observed at great distances at a large aperture array. The model provided a very good fit to the observed data. Interest in recent years has focused on the spatial coherence of higher frequency infrasonic signals generated by relatively small explosions at distances ranging from a few hundred to a few thousand kilometers. The design of modern infrasound monitoring arrays is critically dependent on the results of these investigations. The first work on this subject was presented by Blandford (1997) in a sophisticated design study based on an extrapolation of the results of Mack and Flinn (1971). Further attempts to apply the theoretical treatment of Mack and Flinn to higher frequency infrasound observations have been reported by Armstrong (1998), Blandford (2000, 2004), McCormack (2002), and Christie et al. (2005a, b). In all cases, the results indicate that the degree of spatial coherence decreases rapidly with increasing frequency and with increasing sensor separation. In particular, the results suggest that a low degree of spatial coherence is likely to be a significant problem for the reliable detection of infrasound from distant sources at frequencies above 1.0 Hz at arrays with large apertures and few array elements. Coherence observations are usually compared with the predicted upper and lower limits defined by the Mack and Flinn theory for sensor pairs aligned normal to and parallel to the wavefront, respectively, as a function of sensor spacing. The measured coherence values generally exhibit large variations. It has been noted by Christie et al. (2005a,b) that the initial results from an on-going investigation of signal coherence at IMS infrasound stations suggest that the optimum passband for the detection of regional and distant explosions is centered below 1.0 Hz.

Here, we extend the observations of signal coherence at IMS infrasound stations and compare the directly observed *array-averaged* correlation coefficients with the array-averaged values predicted by Mack and Flinn theory.

Gossard (1969), Mack and Flinn (1971), and Blandford (1997) provide evidence to show that the observed loss of signal coherence along the direction of wave propagation is due to a small variation, $\pm \Delta c$, in wave velocity while the observed loss of coherence along the wavefront is due to a small variation, $\pm \Delta \theta$, in wave azimuth. The coherence parameters Δc and $\Delta \theta$ are range (and probably frequency) dependent. These parameters are adjusted by Mack and Flinn (1971) and Blandford (1997) to fit the observed loss in coherence both along and perpendicular to the wavefront. The precise physical processes that give rise to spatial decorrelation of infrasonic signals remain poorly understood. It seems reasonable, however, to assume that part of the observed decorrelation may be due to the specific characteristics of the source and part is due to scattering associated with wave propagation through an inhomogeneous medium with turbulence and/or small-scale variations in wind speed. Mack and Flinn consider three possible distributions, $F(\mathbf{k}, f)$, for amplitudes in the wavenumber domain, two with symmetrical continuous distributions around a central maximum, and a third with constant amplitudes defined by the windows $\pm \Delta c$ and $\pm \Delta \theta$ in frequency-wavenumber space. As noted by Mack and Flinn, the results for all distributions are essentially the same. Since the precise form of the amplitude distribution in wavenumber space is not known, we shall adopt the basic uniform distribution model proposed by Mack and Flinn (1971). Mack and Flinn obtain an expression for the squared coherency, γ^2 , at a given frequency, f , by integrating the spatial Fourier transform of the wavenumber spectrum $F(\mathbf{k}, f) \neq 0$, and normalizing the result to unity when $|\mathbf{r}| = 0$. The signal correlation, C , between two sensors separated by vector $\mathbf{r}$ is given, at a specified frequency, by the square root of the squared coherency (Blandford, 2000). For convenience, we write the expression for C in the following form:

$$C(\mathbf{r}, T) = \sqrt{\gamma^2(\mathbf{r}, T)} = \sqrt{\left| \frac{\sin(2\pi x \sin(\Delta \theta) / cT)}{2\pi x \sin(\Delta \theta) / cT} \right|^2 \left| \frac{\sin(2\pi y \Delta c / (cT(c + \Delta c)))}{2\pi y \Delta c / (cT(c + \Delta c))} \right|^2} \quad (1)$$

Here, T is period, c is the mean phase velocity and x and y are the components of the vector separation $\mathbf{r}$. The coherence parameters used in this investigation ($\Delta c = 15$ m/s and $\Delta \theta = 5^\circ$) are taken from the results of Blandford (1997) for higher frequency infrasonic waves. Expression (1) can be plotted for $y = 0$ to give the Mack and Flinn limiting curve for the correlation between two sensors at a specified period as a function of sensor separation for sensors aligned parallel to the wavefront. Similarly, a plot of expression (1) with $x = 0$ gives the Mack and Flinn limiting curve for the variation of correlation at a given period as a function of sensor separation for sensors aligned normal to the wavefront.

A useful comparison of observations with the predicted Mack and Flinn limiting curves can be carried out directly when it is possible to find pairs of array elements in a large array separated by a range of distances and aligned along or perpendicular to the wavefront. The method is less useful when the comparison is based on data from a fixed array with a small number of array elements where few, if any, array element pairs are aligned normal and perpendicular to the wave propagation direction. In this case, corrections can be applied to the observed coherences to give estimates of the normal and perpendicular values, but this is a potential source of error. We have therefore decided to use a different comparison method that can be applied directly to any array configuration and which includes a contribution from all array element pairs. The method also allows the theoretical predictions at a specified frequency to be compared directly on the same plot with observed infrasonic wave correlation data corresponding to sources located at any azimuth.

Consider first the azimuthal variation of the signal correlation between two sensors as given by expression (1). The predicted azimuthal variation is plotted in Figures 3a and 3b in polar coordinates as a function of both sensor separation and wave period. The curves shown in Figure 3a correspond to a sensor separation of 1.0 km. As can be seen from this diagram, the degree of anisotropy in the azimuthal distribution increases rapidly as period decreases below 2.0 seconds. This indicates that the dominant contribution to the overall array-averaged correlation coefficient at higher frequencies will come from array element pairs that are aligned more or less in the wave propagation direction and suggests that some array configurations may exhibit azimuthally-dependent detection characteristics. This will be illustrated further in the results presented below. The results presented in Figure 3b for the azimuthal variation of the correlation between two sensors at constant period as a function of sensor spacing are similar in

form to those shown in Figure 3a. The azimuthal distribution is essentially isotropic at a period of 1 second when the sensor separation is less than about 0.3 km and highly anisotropic when the separation is more than about 1.0 km. Again these results suggest that certain array configurations may exhibit detection characteristics that are azimuthally biased at higher frequencies.

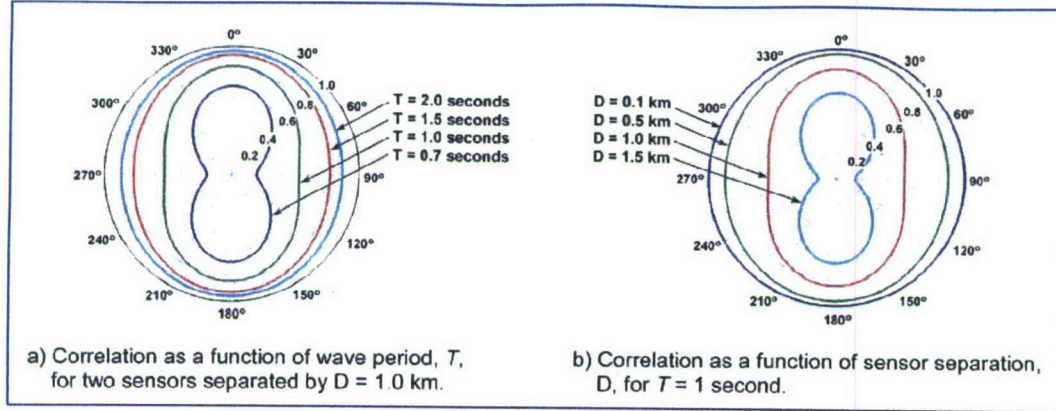


Figure 3. Predicted azimuthal variation of signal correlation between two sensors aligned along the 0° direction as a function of a) wave period, T , and b) station separation, D . The azimuth is the angle between the wave propagation direction and the vector separation between the sensors. $\Delta c = 15$ m/s and $\Delta \theta = 5^\circ$.

The predicted correlation between two sensors for all signal azimuths is specified, at a given period, by expression (1) in a coordinate system where azimuth is measured from the direction defined by the separation vector $\mathbf{r}$. Thus, the predicted correlations for each individual sensor pair in an array can be calculated in a common polar coordinate system where azimuth, ϕ , is measured from geographic north by rotating the azimuthal distribution defined by (1) to the direction of the pair separation vector $\mathbf{r}_{ij}$ in the common coordinate system. The results for each sensor pair, $\tilde{C}_{ij}(\phi, T)$, in rotated coordinates can then be averaged over all pairs of elements in the array to give a predicted normalized array-averaged correlation coefficient for all wave back-azimuths:

$$\bar{C}(\phi, T) = \frac{2}{N(N-1)} \sum_{j>i}^N \tilde{C}_{ij}(\phi, T) \quad (2)$$

The resulting polar distribution of the array-averaged correlation coefficient is a unique characteristic of the array configuration, the parameterisation of Mack and Flinn theory, and the specified period. As noted above, each sensor pair in the array contributes to the predicted normalized array-averaged correlation coefficient for all wave back-azimuth directions and thus the observed normalized array-averaged correlation coefficients from all sources can be compared directly with the theoretical predictions on the same diagram.

Problems with the detection of higher frequency infrasonic signals on large aperture arrays can be illustrated by comparing the Mack and Flinn theoretical predictions with observations of array-averaged correlation coefficients corresponding to explosion-generated infrasonic wave detections on both small and large aperture arrays specified by sub-arrays at IS07 Warramunga. Examples of this procedure are illustrated in Figure 4 for the detection of infrasonic waves from regional and distant sources at a period of 1.0 seconds. The predicted azimuthal distribution of the normalized array-averaged correlation coefficient for a small aperture (~ 300 m) 3-component array defined by IS07 sites H2, H3, and H4 (see Figure 2) is given by the blue curve in each of the polar diagrams shown in Figure 4. Since the individual pair correlation coefficients are uniformly high for all pairs in this small aperture sub-array, the relatively minor azimuthal variations for each individual pair are integrated out in the averaging process leaving an isotropic overall predicted array-averaged correlation coefficient of about 0.94. In contrast, the azimuthal distribution of the predicted array-averaged correlation coefficient for a larger aperture (~ 2 km) three-component array defined by IS07 sites L2, L3, and L4 exhibits significant anisotropy as shown by the solid red curve in Figure 4. In this case, the predicted array-averaged correlation coefficients are less than the detection threshold.

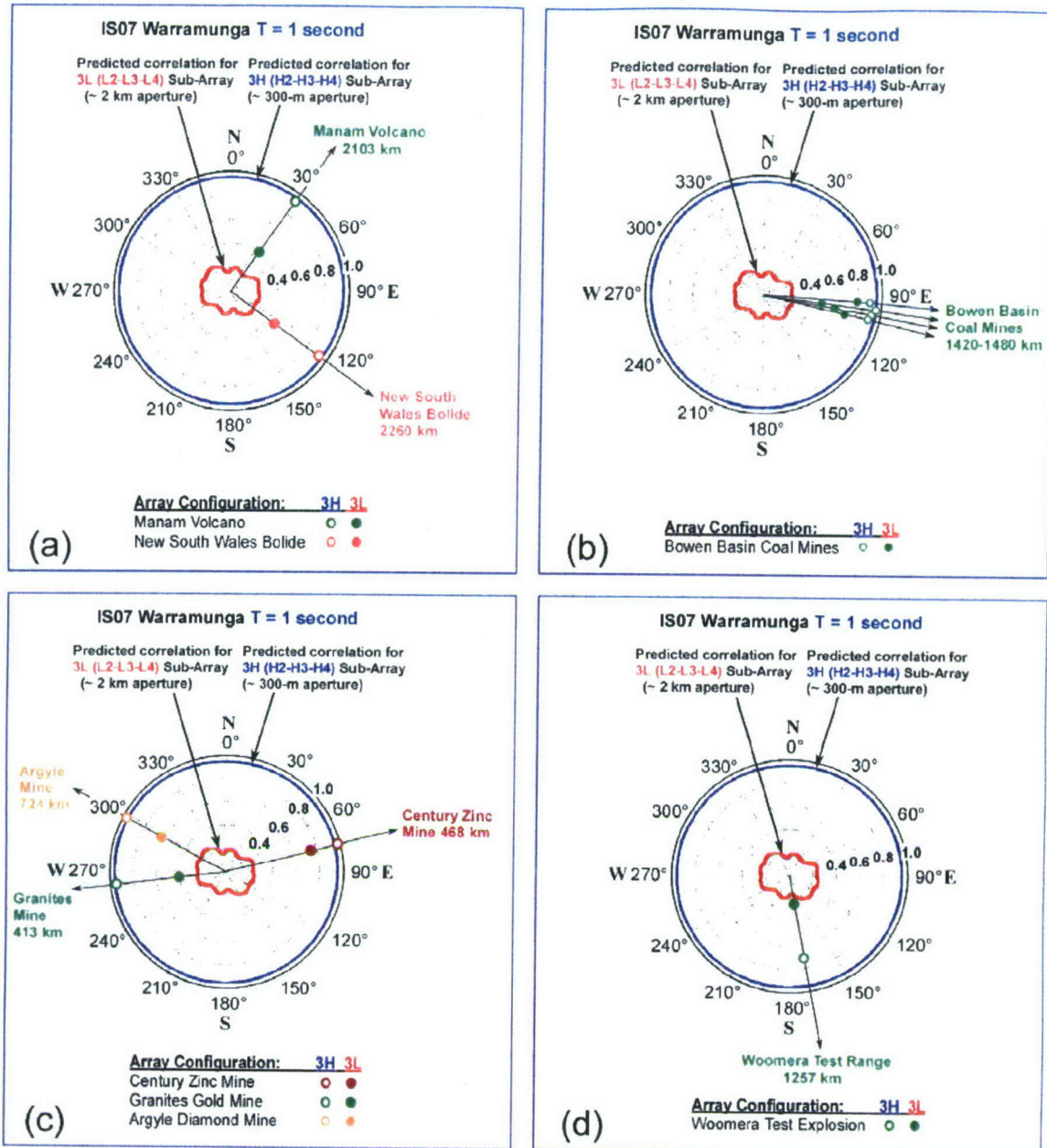


Figure 4. Array-averaged correlation coefficients observed at IS07 on large and small aperture arrays at a period of 1 second for explosion-generated signals compared with predictions based on the theory of Mack and Flinn (1971). The blue curve corresponds to the theoretical prediction for the 3-component small aperture sub-array H2, H3, and H4 (see Figure 2). The azimuthally anisotropic theoretical distribution specified by the red curve is computed for a larger aperture 3-component sub-array defined by L2, L3, and L4. $\Delta c = 15$ m/s and $\Delta \theta = 5^\circ$. (a) Results for two naturally occurring distant explosions: Manam Volcano on 27 January 2005 and the New South Wales bolide on 5 December 2004. (b) Results for distant coalmine explosions in the Bowen Basin. (c) Comparison of results for regional mining explosions. (d) Results for a chemical test explosion at the Woomera Test Range on 20 September 2002. Open circles are array-averaged correlation coefficients observed for signals detected on the small aperture 3H sub-array. Filled circles are observed array-averaged correlation coefficients for signals detected on the large aperture 3L sub-array.

The large amplitude infrasound signals generated by the New South Wales bolide on 5 December 2004 and signals from the explosive eruption of Manam volcano on 27 January 2005 are very easily detected on the small aperture 3H sub-array at IS07 with high array-averaged correlation coefficients (see Figure 4a) comparable to those predicted by the theoretical model. Observed correlation coefficients for the large aperture 3L sub-array are much smaller and detection is limited to a few time intervals with correlation coefficients close to the detection threshold. As noted above the predicted correlation coefficients for the large aperture array are substantially below the detection threshold. This low degree of correlation may be an artifact of the simple constant amplitude model used in the wavenumber domain. Alternatively, the results may indicate that the attenuation of the degree of spatial correlation predicted by the model is too high. In any case, the observed degree of correlation between array elements in the large aperture array is significantly attenuated and signal detection is marginal. These comments apply to all other results shown in Figure 4. In most cases, the array-averaged correlation coefficient observed on the large aperture array for infrasonic signals at 1 Hz is generally very close to the detection threshold. Some infrasonic signals observed on the large aperture array from distant coal mining explosions in the Bowen Basin have higher than expected correlation coefficients which suggests that the parameters used in Mack and Flinn predictions may give results that are slightly too restrictive. On the other hand, we note that the degree of correlation over the large amplitude array for signals from the Woomera test explosion is too small to allow any automatic detections. The essential conclusion is that regional and distant explosions will not be reliably detected using standard automatic data processing algorithms based on correlation techniques at a frequency of 1.0 Hz or higher at infrasonic array stations which have a small number of array elements and array element spacings of about 1.5 km or more.

Development of New Noise-Reducing Techniques

As noted above, high levels of wind-generated background noise continue to be the primary limiting factor on the performance of many infrasound stations. Traditionally, noise reduction has been achieved by using pipe arrays constructed either from porous hoses or from a series of pipes with discrete inlet ports. Both methods are in use at infrasound stations in the IMS. However, it seems unlikely that significant noise-reduction improvements can be achieved by simply refining existing pipe array designs since the size and number of inlet ports in these designs has reached practical limits. It has been proposed that substantial improvements might be achieved by replacing the noise-reducing pipe system at each monitoring array element with a compact array of individual sensors (Talmadge et al., 2001; Bass and Shields, 2004; Shields, 2005). The digital output from all sensors in each of these compact arrays would then be analyzed adaptively to discriminate against wind-generated noise and thus provide improved noise reduction. It seems very likely that this technique could indeed be used to achieve better signal-to-noise ratios, but the number of sensors and digitizers required at each array element is likely to be quite large and the cost for an installation of this type could be fairly high. Noise reduction in the monitoring passband can also be achieved by using techniques to attenuate the ambient winds and/or transform noise-producing eddies into smaller scale eddies that generate micropressure fluctuations at frequencies that lie well outside the monitoring passband. Significant noise reduction has been achieved at higher frequencies (> 1 Hz) using this technique in the form of relatively small-scale porous wind fence structures. We emphasize that the results to date from the present research project suggest that the optimum passband for the detection of infrasound from regional and distant explosions is centered at frequencies below 1.0 Hz. We have therefore decided to focus on techniques that can potentially enhance existing noise-reducing techniques at frequencies below 1 Hz. Our preliminary attempts in this regard are based on the results of a limited series of experiments described briefly by Christie (2000). In this report it was shown experimentally that noise levels obtained using a single inlet port mounted close to the surface can be significantly reduced at higher frequencies by effectively lifting the turbulent boundary layer over the port by covering the port with a fine 80-cm diameter screen carefully positioned to ensure that the screen does not interfere with the ambient flow. Noise levels in this single port experiment were reduced by nearly an order of magnitude at 5 Hz, but there was only a small improvement at a frequency of 1 Hz as could be expected, considering the small diameter of the surface screen. However, it seems likely that this noise-reducing technique can be extended to lower frequencies by increasing the diameter of the surface screen. A larger scale experiment has therefore been carried out and the results appear to be promising.

We emphasize that in the present technique we attempt to place the inlet port (or an array of ports) in a stagnant turbulence-free layer at the surface created by lifting the turbulent boundary layer over the inlets without disturbing the flow. This procedure should minimize dynamic pressure contributions to background noise. It is important to avoid any perturbation to the surface flow, since any obstacle will potentially generate further unwanted turbulence.

This is achieved by using very low profile surface screens. The results described here are of an essentially exploratory nature since the scale used in these preliminary experiments is small in comparison to the effective wavelengths of turbulent eddies associated with longer period micropressure fluctuations and small in comparison to the scale of currently used pipe arrays. We have decided to use a distributed porous hose in these experiments, since any improvement in noise-reducing performance will indicate the potential for improvement over conventional pipe array systems when the scale of the system is increased to the scale of current pipe arrays.

A diagram illustrating the dimensions of the relatively small-scale low-profile screened noise-reducing system used in this preliminary experiment is given in Figure 5. A section of porous hose was arranged in a 3-m diameter circle and connected by a short section of impervious hose to the microbarometer. Two low-profile screens constructed from 3.6 m² sheets of 60% porous shade cloth were then carefully fastened in place over the circular section of porous hose and background noise measurements were carried out over a period of several days. For comparison, measurements were also made simultaneously on an identical conventional unscreened 3-m diameter porous hose system located about 5 m away from the screened porous hose system. The results are also shown in Figure 5 for an average wind speed of about 3.5 m/s. As can be seen, the surface boundary layer screen used in this small-scale experiment does provide improved noise reduction capability over that obtained with a conventional noise reducing system at all frequencies above about 0.3 Hz. Rather unexpectedly, we found that the addition of the second low-profile surface screen layer did not lead to any improvement. We note that noise suppression has been extended to lower frequencies by the use of a larger diameter screen. These preliminary measurements appear to indicate that large-scale low-profile boundary layer surface screens may prove to be an effective means for enhancing noise-reducing capability at infrasonic stations located in high wind environments.

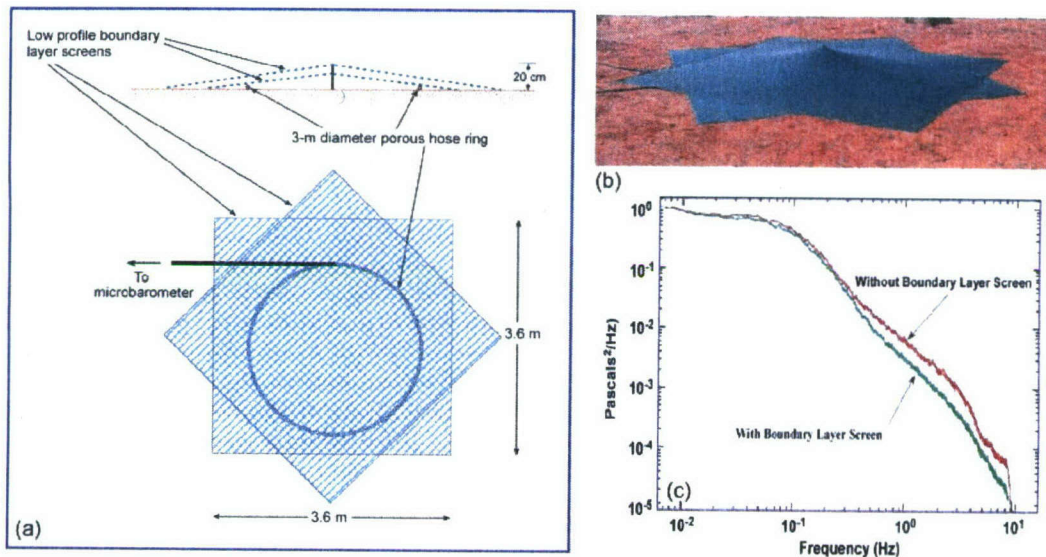


Figure 5. (a) Schematic diagram illustrating the layout and construction of the boundary layer screens used in the preliminary noise-reducing experiments. (b) Photograph of boundary layer screens in place over a 3-m diameter porous hose noise-reducing system. (c) Comparison of power spectral density of micropressure noise data recorded simultaneously from the screened porous hose system and an identical conventional unscreened porous hose system. The average wind speed is about 3.5 m/s.

CONCLUSIONS AND RECOMMENDATIONS

It is clear, from the results presented here, that detection capability for regional and distant explosions at some existing larger-aperture 4-element infrasound monitoring stations in the global infrasound monitoring network will be severely limited by the low degree of signal coherence between array elements. The results from the on-going investigation of signal coherence are proving to be surprisingly complex. This can probably be attributed in part to source characteristics, but variations in waveguide properties will also contribute to the observed variation in the degree of observed signal coherence. It seems likely at this point that observed spatial coherence will not prove to be a reliable discriminant. The main conclusions are as follows:

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- a) Infrasound monitoring stations should have at least eight array elements configured in both large and small aperture sub-arrays designed to eliminate spatial aliasing and signal coherence problems at higher frequency. The overall aperture of the array should be at least 1 km in order and to ensure accurate azimuthal measurements.
- b) Automatic data processing should be carried out in passbands that span both high and low frequencies.

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