DETECTION OF REGIONAL AND DISTANT ATMOSPHERIC EXPLOSIONS AT IMS INFRASOUND STATIONS

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ABSTRACT

Work is proceeding rapidly on the establishment of the 60-station infrasound component of the International Monitoring System (IMS). This is a fairly sparse network. The average distance between stations is about 2500 km for stations located in continental land mass areas and up to about 4500 km for stations that monitor the vast open ocean areas of the Southern Hemisphere. A good understanding of the detection capability for small nuclear explosions located in the distance range from 1000 to 4500 km is clearly essential. At the present time, the properties of explosion-generated infrasonic signals observed in this distance range remain poorly understood. This is especially true for explosions with yields of a few kilotons or less due to a lack of well-documented digitally recorded events. It is worth noting that there have been surprisingly few observations in the last decade of infrasonic waves from surface mining explosions and other impulsive sources located at distances beyond 1500 km. This may indicate that currently used detection procedures do not reliably detect infrasound from surface explosions with yields of a few kilotons or less when the distance to the source is large. This initial investigation is therefore focussed on a study of the properties of regional and distant explosion-generated infrasonic waves observed at two neighbouring IMS infrasound monitoring stations, IS07 Warramunga and IS05 Hobart in Australia. The primary goal of this investigation is to delineate any possible problems that may reduce detection efficiency for regional and distant surface explosions and to determine procedures that will enhance the detection of explosions at distances in the range from 1000 to 4500 km.

A wide variety of infrasonic events has been detected at IS07 and IS05 ranging from impulsive short-lived signals generated by mining and volcanic explosions to continuous signals associated with storms over the open oceans around Australia, air flow over high mountains and auroral activity. The morphology and frequency content of observed infrasonic signals indicate that many of the detected short-lived signals are generated by local sources. The properties of continuous infrasonic signals and signals from local sources will not be described here. Instead, this study is concerned with the observed properties of relatively long-period infrasonic waves from regional and distant sources and the influence that these properties have on global detection capability for small nuclear explosions. In particular, this investigation is concerned with a study of the observed properties of signals from regional and distant mining explosions, distant bolides and distant volcanic explosions.

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OBJECTIVE

The main objective of this research in to identify potential problems with the detection of infrasound generated by distant atmospheric explosions and to determine procedures that will improve detection capability for explosions at distances that are comparable with the spatial separation of monitoring stations in the global IMS infrasound network. The vast open ocean areas of the Southern Hemisphere are particularly difficult to monitor since monitoring stations must be located at sites that are often separated by more than 3500 km. This research is therefore focused on a study of infrasound detection capability at typical IMS monitoring stations for infrasonic signals generated by explosions located at distances in the range from about 1000 to 4500 km.

RESEARCH ACCOMPLISHED

Introduction

The global IMS infrasound monitoring network is a 60-station network of array stations distributed as uniformly as possible over the surface of the globe. The average separation between stations located in continental land mass areas is about 2500 km. In contrast, the average spacing between stations that surround the vast open ocean areas of the Southern Hemisphere is greater than 3500 km. Since the minimum acceptable requirement of the IMS network for nuclear explosion monitoring is two-station detection capability for a 1 kiloton explosion located at any point on the globe, individual IMS infrasound stations need to be able to reliably detect 1-kiloton explosions at ranges of up to 3000 km or more. Upper atmospheric winds have a very beneficial influence on the propagation of infrasound when propagation is directed along the direction of the stratospheric winds. This means that detection capability for nuclear explosions will generally be very good at monitoring stations located downwind from the source in the direction of the stratospheric winds. Detection capability will be significantly reduced, however, when the monitoring station is located either upwind from the source or normal to the direction of the stratospheric winds. In this case, detection will usually be restricted to thermospheric arrivals. In this regard, we note that very few well-documented observations have been reported in recent years of infrasound from surface explosions at distances beyond 1500 km. The initial research summarized here is part of a more extensive program that is focused on a detailed investigation of the detection, location and discrimination of infrasonic signals under a wide range of conditions at IMS infrasound stations in the Southern Hemisphere.

Much of the work in recent years on the monitoring of small atmospheric nuclear explosions has been concerned with the detection of relatively high-frequency infrasonic waves in the passband from about 0.5 to 2 Hz. The emphasis on this particular passband has been motivated primarily by: a) problems with the construction of noise reducing systems that are effective at low frequencies, b) the recognition that infrasound from small nuclear explosions may be detectable in the 0.5 to 2 Hz passband, c) the problem of separating coherent explosion signals from a background of coherent microbarom signals in the passband from 0.1 to 0.5 Hz passband, and d) at higher frequency, concern with potential spatial aliasing and signal coherence problems. It is generally agreed (see, e.g., Blandford 1997, 2004) that detection of infrasound from small nuclear explosions at distances of up to at least 1000 km will usually be optimum in a passband around 1Hz. While it is clearly important to have good monitoring capability in the passband from 0.5 to 2.0 Hz, this passband may not be the best detection passband if the source is located at greater distances or if propagation is confined by the upper wind structure to a thermospheric waveguide. Indeed, the higher frequencies may be eroded away completely at larger distances with the result that it may not be possible to detect infrasound from a distant nuclear explosion at any frequency above 0.5 Hz. The problem of the loss of the higher frequency signal components from distant sources is particularly relevant to the problem of monitoring the vast open ocean areas of the Southern Hemisphere.

The potential difficulties in detecting infrasound from distant explosions will be illustrated here by observations recorded at two IMS infrasound stations in Australia. The main detected events that we use to illustrate this problem have been chosen because they are located a distances beyond 1000 km and because they include an example of signal detection along a propagation path that is perpendicular to the stratospheric winds.

Infrasound monitoring stations in Australia

Australia is host to a total of four IMS infrasound monitoring stations on Australian territory and an additional station (IS03 Davis Base) located in Antarctica. Two of these stations, IS05 Hobart in Tasmania and IS07 Warramunga in the Northern Territory, are in operation and certified. The construction of a third station, IS04

Shannon, located in the southwestern corner of Australia, is nearly finished and this station should be in operation and certified by October 2005. This station is expected to play an important role in the monitoring of the South Indian and Southern Oceans. The forth station in this regional network, IS06 Cocos Islands, will be installed in 2006 and the station at Davis Base will be established in the following year.

The location of the infrasound monitoring stations in Australian, the source location of two of the analyzed events and the location of the main open-cut mining areas in Australia are shown on the map in Figure 1. The average distance between the three infrasound monitoring stations located on the Australian mainland is about 2730 km. All of the observations used in this study were recorded at IS05 and IS07.

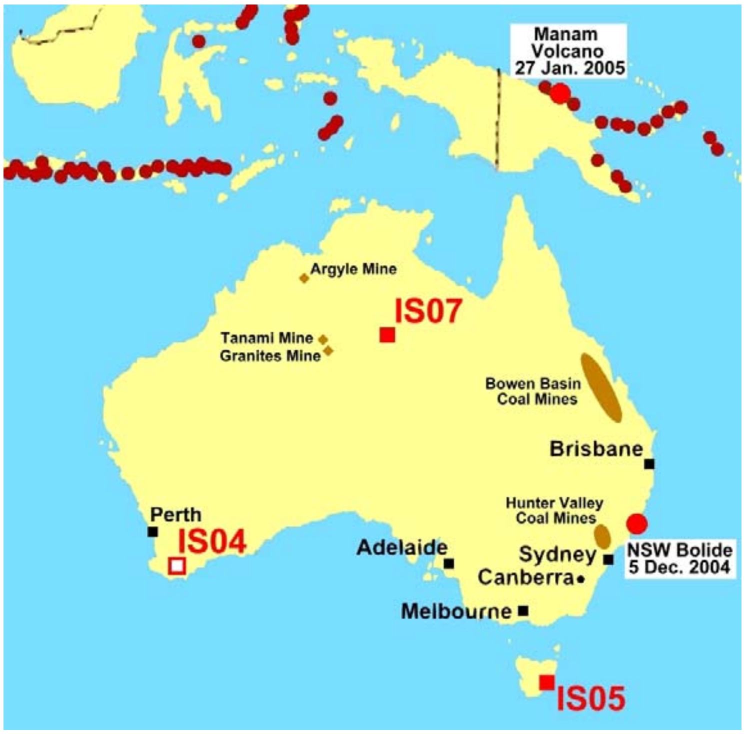


Figure 1. Map of the Australian region showing the locations of infrasound monitoring stations IS04, IS05 and IS06, the locations of the main open-cut mines, the locations of the nearest active volcanoes (dark red circles) in the area to the north of Australia, the location of the explosive eruption of Manam Volcano in Papua New Guinea on 27 January 2005, and the location of the New South Wales (NSW) bolide on 5 December 2004.

The characteristics of IS05 Hobart and IS07 Warramunga differ significantly. IS05 is located on the southeastern side of Tasmania at latitude 42.5 ºS in a fairly sparse eucalyptus forest, about 20 km from the coast of the South Pacific Ocean. The station is partially sheltered from the ambient winds by the surrounding forest, but noise levels over the array tend to vary widely from site to site at all times of day. The station is also subject to infrasonic noise generated by surf activity along the eastern margin of Tasmania and to high levels of microbarom noise associated with intense storms over the Southern Ocean. IS07 is located at latitude 19.9 ºS in the arid interior of Australia. Long grass and a few small trees and bushes provide some shelter from the ambient winds, but wind noise levels tend to be fairly high during the daytime and much lower at night when the upper winds are decoupled from the surface by an intense nocturnal radiation inversion. Thermal mixing due to convection is extreme at Warramunga and the well-mixed daytime boundary layer can extend to a height of two km or more. In contrast with IS05 Hobart, IS07 Warramunga is subject to highly nonlinear gravity wave disturbances in the form of large amplitude solitary waves and internal bore waves (see e.g., Christie, 1989; Brown and Christie, 1998). These mesoscale disturbances are significant because they generate turbulence and local wind squalls that increase background noise levels at IS07. Highly nonlinear gravity waves propagate over great distances in Northern Australia on the deep nocturnal boundary layer inversion. They are a commonly occurring feature at Warramunga, but they seldom, if ever, occur at IS05 Hobart.

As can be seen in Figure 2, the array configuration at IS07 differs substantially from the array configuration at IS05. The array response for each of these stations is fairly good, but not ideal. The overall apertures of the two arrays are comparable and each array contains a smaller aperture sub-array (H1, H2, H3 and H4 at IS07 and H6, H7 and H8 at IS05), which significantly improves the array response and helps to minimize the influence of spatial aliasing (Kennett et al., 2003).

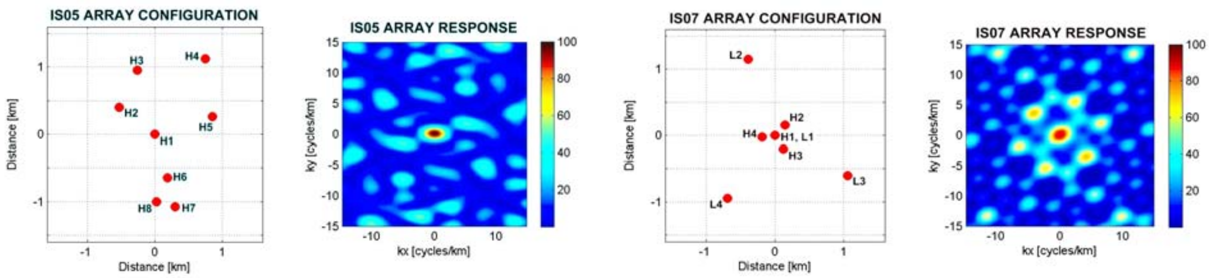


Figure 2. Array configuration and response of IS05 Hobart (left) and IS07 Warramunga (right).

Detection of distant explosions

Numerous studies have been reported in recent years (see, e.g., Sorrells et al., 1997; Stump et al., 2002; Sarker and Kim, 2002) of the use of seismic and infrasound data recorded simultaneously at the same site as a means to improve discrimination and location estimates for surface mining explosions. This has proven to be an effective procedure when mining explosions are located at regional distances. These investigations are, however, usually limited to source distances of less than 800 km. A survey of the detection of small mining blasts in the Western United States at infrasonic arrays operated by the Los Alamos National Laboratory at ranges of up to 880.5 km is described as part of a discrimination study in ReVelle et al. (2004). There appear to be very few reports of the detection of infrasound from large mining explosions at distances beyond 1000 km. A brief description of the detection at IS07 Warramunga of infrasonic waves generated by a large open-cut coal mining explosion in the Bowen Basin (see Figure 1) at a distance of 1520 km is given in Christie (2004). In this regard, we note that the Australian IMS stations are almost ideally located for long-range studies of infrasound generated routinely by large open-cut mines located on the Australian mainland and in other areas to the north of Australia.

Very well documented observations of infrasound signals generated by the Watusi surface explosion experiment on 28 Sept. 2003 at the Nevada Test Site have been reported by Bhattacharyya et al. (2003) and Whitaker et al. (2003). Infrasonic signals from this relatively small test explosion (0.019 kT of TNT equivalent) were clearly detected at a number of stations in the Western United States at distance of up to 883 km and also at IS10 Lac du Bonnet in Canada at a range of 2165 km. All observations appear to be consistent with a thermospheric propagation path. No signals were detected at IS57 (390 km) and TXIAR (1440 km), both located to the south of the explosion. Brown et al. (2003) have also described infrasound signals from small test explosions (5000 and 27000 kg) at the Woomera facility in South Australia. Signals from both explosions were clearly recorded at two stations located at distances of 467 and 476 km to the east and north of the source. Clear signals (probably thermospheric) were also recorded from the larger explosion at IS07 Warramunga, 1257 km to the north. Norris and Gibson present a detailed comparison of wave propagation modeling results with observations of infrasound at a range of 1579 km at IS31 Aktyubinsk in Kazakstan from a large train car explosion in Newyshabur in Iran on 18 Feb. 2004. The observations were made in a passband extending from 0.5 to 3 Hz. The observed signals probably correspond to propagation in a thermospheric waveguide, but stratospheric or mixed stratospheric /thermospheric propagation cannot be ruled out. These authors also note that this event was observed at a range of 4078 km at IS34 in Mongolia, but no details are given.

It is now recognized that infrasound generated by high altitude bolide explosions in an elevated waveguide will leak to the surface by scattering from large scale inhomogeneities and may be detectable at monitoring stations located at great distances from the source. The first outstanding example of the long-range detection at IMS stations of infrasound from a high altitude bolide was the unexpected observation of signals at a distance of 10800 km at IS26 Freyung in Germany from a large bolide explosion (~ 10 kT) over the Pacific Ocean between California and Hawaii at a height of 28.5 km on 23 April 2001 (see, e.g., Brown and Gault, 2001; Garces et al., 2004). There have been several other reports of the long-range detection of infrasound from high-altitude bolides since this initial observation in 2001. McCormack (2004) has recently described and interpreted observations from a particularly interesting bolide explosion that occurred on 3 Sept. 2004 over the Atlantic Ocean side of the Antarctic ice shelf. This relatively large event (estimated yield is 33 ± 17 kT) was detected at IS27 Neumayer, Antarctica (1090 km), IS55 Windless Bight, Antarctica (3720 km), IS35 Tsumeb, Namibia (5400 km), IS17 Dimbokro, Ivory Coast (7000 km), and IS26 Freyung, Germany (13000 km). Weak signals from this event were also recorded at IS05, Hobart (7055 km) (Brown, 2005, private communication). However, failure to detect signals from this event at many other IMS infrasound monitoring stations, including IS07 Warramunga (8990 km), suggests that the propagation of energy away from this rapidly moving source was highly anisotropic. It is also worth noting that all observed signals from this event were detected only in the long-period passband from 0.03 to 0.1 Hz.

Observations

We now consider the results of a study of infrasound observations at IS05 Hobart and IS07 Warramunga from two significant explosive events located at large distances from each monitoring station. The first event is a series of explosions generated by the sudden eruption of Manam Volcano on the northern side of Papua New Guinea on 27 January 2005. The second event corresponds to a bolide explosion on 5 December 2004, over the east coast of New South Wales in southeastern Australia. Both events were clearly detected at IS05 and IS07, but the characteristics of the signals recorded at each station differ considerably. Details relating to the detection of each of these events are given in the following table.

Table 1. Station and source parameters for the detection of infrasound from Manam Volcano and the New South Wales bolide.

	Manam Volcano	New South Wales Bolide
Source location	4.10 ºS, 145.06 ºE	31.7 ºS, 152.6 ºE
Source time	~ 14:00 27 Jan. 2005 UT (00:00 28 Jan. 2005 LT)	18:15 5 Dec. 2004 UT (04:15 6 Dec. 2004 LT)
Distance to IS05	4261 km	1270 km
Back azimuth from IS05	355.8 º	22.5 º
Distance to IS07	2103 km	2260 km
Back azimuth from IS07	35.0 º	126.0 º

The sudden eruption of Manam Volcano started at around 14:00 UT (midnight local time) on 27 January 2005 and continued as a series of violent explosions for a period of about two hours. Signals from this large event were detected at the two operating IMS stations in Australia (IS05 and IS07) and also at IS55 Windless Bight in Antarctica at a distance of 8303 km and IS53 Fairbanks, Alaska at a distance of 9358 km (Wilson and Olson, 2005). The signals detected at IS55 and IS53 were long-period signals with maximum power in the passband from 0.03 to 0.10 Hz. The observations at IS05 show that the higher frequency components above 0.1 Hz have also vanished completely at a range of 4261 km. In contrast, higher frequency components were detected up to a frequency of at least 3 Hz at IS07 at a range of 2103 km. The signals detected at IS07 and IS05 are illustrated in Figures 3 and 4 for frequency passbands spanning the range from 0.01 to 9 Hz. No signals were detected at IS05 at frequencies above 0.1 Hz. The passband from 0.1 to 0.5 Hz at IS05 was completely dominated by coherent microbarom signals from severe storms in the Southern Ocean. In contrast to the observations at IS05, higher frequency components were observed at IS07 at frequencies above 0.1 Hz, but the best signal-to-noise ratio occurs in the longer period passband from about 0.03 to 0.07 Hz. It is also interesting to note that signals from the eruption of Manam Volcano were clearly detected in a background of microbarom signals in the passband from 0.1 to 0.5 Hz. Hobart is located almost due south of Manam Volcano. In the case of IS05, the absence of higher frequency signals can be attributed to the greater distance to the source and also to the rapid attenuation of higher frequencies in a thermospheric waveguide.

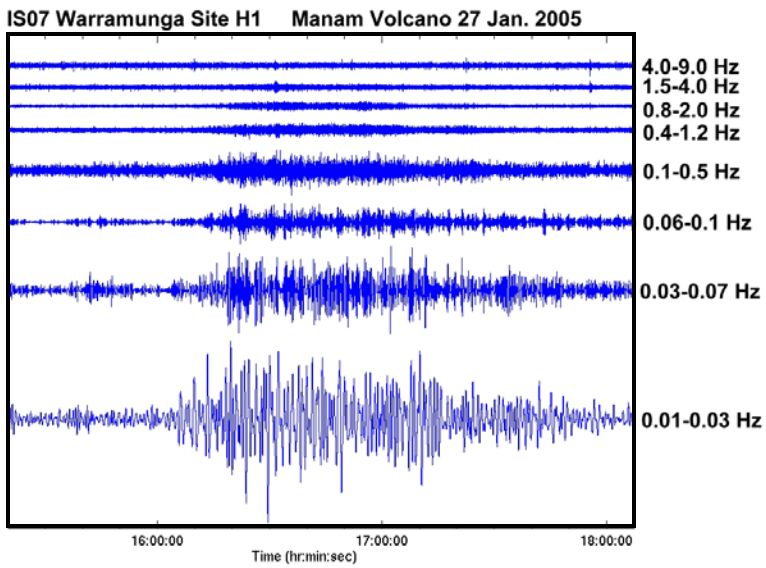


Figure 3. Bandpass filtered signals recorded at IS07 Warramunga from the explosive eruption of Manam Volcano on the north side of Papua New Guinea on 27 Jan. 2005.

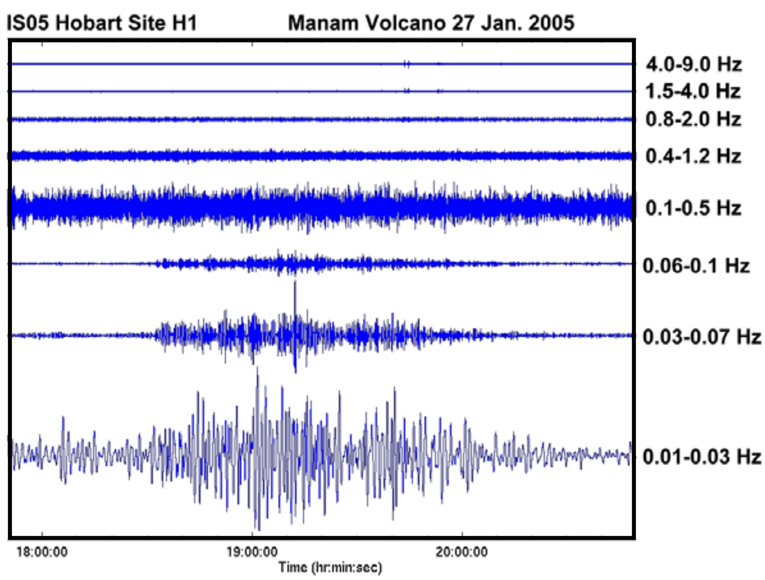
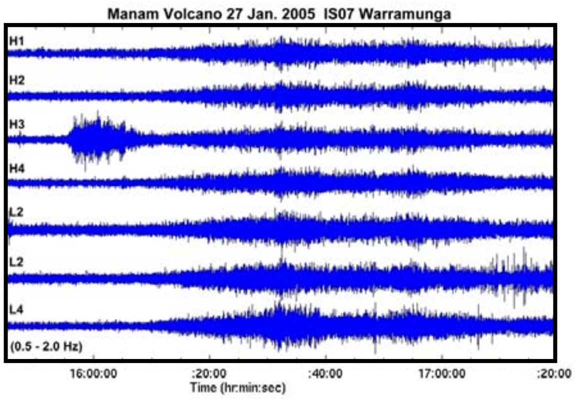


Figure 4. Bandpass filtered signals recorded at IS05 Hobart from the explosive eruption of Manam Volcano on 27 Jan. 2005.

A comparison of the high- and low-frequency signals from the eruption of Manam observed at IS07 Warramunga and the longer period signals observed at IS05 Hobart is given in Figures 5 and 6. As can be seen from these examples, large signal-to-noise ratios were observed at both IS05 and IS07 for longer period signals. The signal-to noise ratio observed in the 1 Hz passband (0.5 –2.0 Hz) at IS07 is also quite large. It might appear, at first glance, from the high frequency results presented in Figure 5, that high-frequency signals from Manam Volcano observed at a distance of 2103 km would be easily detected in the routine automatic processing of data at IS07. However, an examination of the high frequency data shows that the degree of correlation of the higher frequency signals from Manam is very small between the array elements in the large aperture main array (L array). The spatial coherence of the higher frequency Manam signals is much higher between array elements in the small aperture sub-array (H-array) and this partial degree of coherence between elements in the small array does in fact allow these higher frequency signals to be detected by the routine data processing algorithms. However, the average Fisher F-statistic found in the high-frequency analysis is much smaller than the average F-statistic found in the analysis of long-period data. The significance of these results is discussed below.



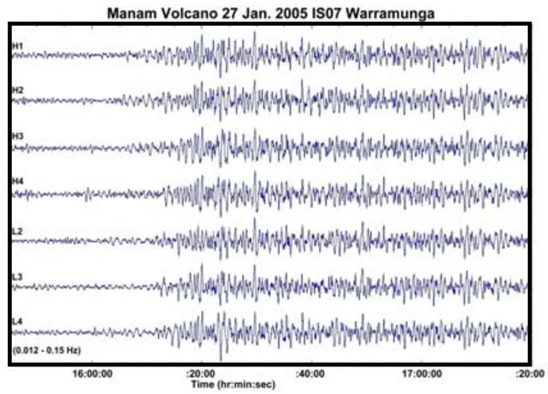


Figure 5. High-frequency (left) and low-frequency (right) infrasonic signals observed at IS07 Warramunga from the explosive eruption of Manam Volcano on 27 January 2005.

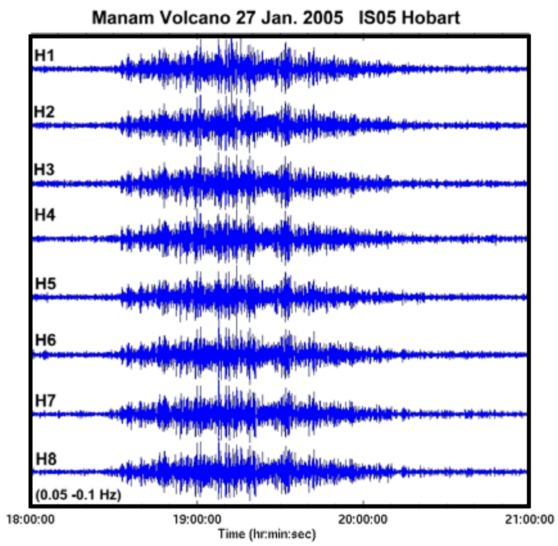


Figure 6. Low-frequency 0.05 to 0.1 Hz passband filtered infrasonic signals observed at IS05 Hobart from the explosive eruption of Manam Volcano on 27 January 2005.

A second example of the long-range detection of infrasonic waves at both IS05 Hobart and IS07 Warramunga is presented in Figures 7 to 9. In this case, the observed signals were generated by an early morning bolide explosion over the east coast of New South Wales at about 18:15 on 5 Dec. 2004 UT (04:15 AM on Dec. 6 local time). This event was widely reported in the media. From the media reports, it appears that this event was accompanied by a number of separate explosions and this appears to be supported by the observed infrasonic signatures at IS05 and IS07. Again, infrasound was detected at both IS05 and IS07 over a wide range of frequencies. This is illustrated in Figures 7 and 8 for data filtered in a number of passbands between 0.03 and 9.0 Hz. As in the case of infrasound detections from Manam, the high level of noise due to coherent microbarom waves precluded any detection of the bolide signals at IS05 in the passband from 0.1 to 0.5 Hz. Signals from the bolide were, however, easily detected in the 0.1 to 0.5 Hz passband during the automatic processing of data from IS07 Warramunga. The observations at IS05 and IS07 also differ in that signals were detected at IS05 at longer periods in the low-frequency passband from 0.05 to 0.1 Hz. There is no trace of any longer period energy below 0.1 Hz in the observations at IS07. Finally, we note that the signal-to-noise ratio in all passbands (including the very high frequency passband from 4 to 9 Hz) is significantly larger for observations recorded at IS05 than it is at IS07. These results are somewhat puzzling since both stations are located at roughly the same distance from the source (2103 km for IS07 and 2260 km for IS05). Furthermore, the stratospheric wind component along the propagation path is higher for the path to IS07 than it is to IS05. Failure to detect any signals in the 0.1 to 0.5 passband at IS05 can be attributed to the high levels of coherent microbarom signals in this passband.

The main result of interest here is similar to that found for the detection of signals from Manam Volcano. The degree of signal coherence between array elements in the larger aperture sub-array at each station is found to be significantly smaller than the degree of coherence between array elements in the small aperture sub-array. This means that automatic detection in the higher frequency passbands is almost entirely the result of the partial coherence between array elements in the smaller aperture sub-array. It should be emphasized, however, that signal-to-noise ratios and the degree of signal coherence decrease fairly rapidly for frequencies above 1Hz.

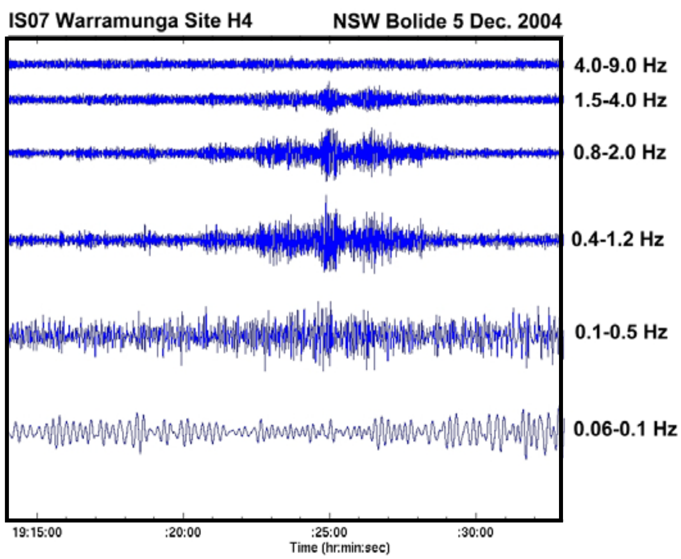


Figure 7. Bandpass filtered signals recorded at IS07 Warramunga from the New South Wales Bolide on 5 Dec. 2005. No detectable signals were found at frequencies below 0.1 Hz.

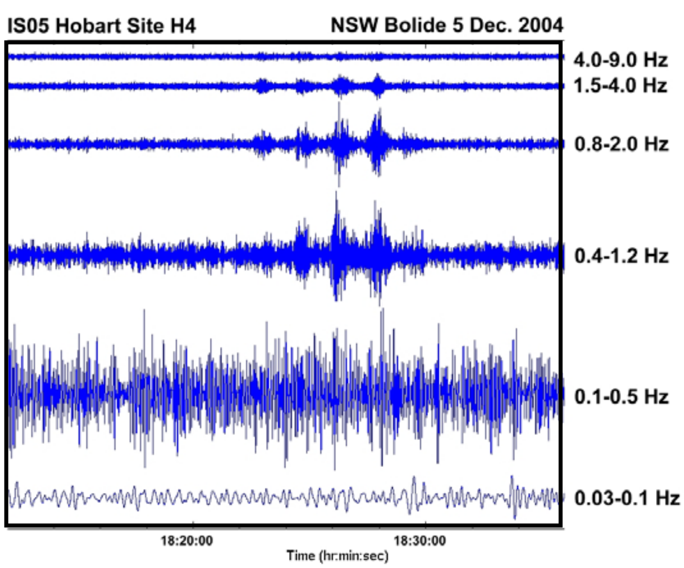


Figure 8. Bandpass filtered signals recorded at IS05 Hobart from the New South Wales Bolide on 5 Dec. 2005. Signals were detected above and below the microbarom passband (0.1 to 0.5 Hz).

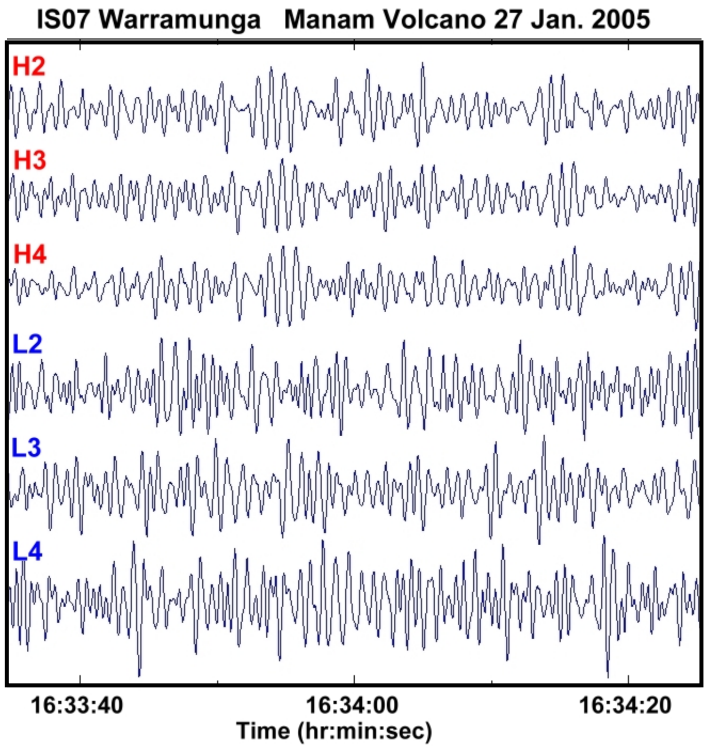


Figure 9. Detailed comparison of signals from the Manam eruption recorded at IS07 in the 0.8 to 2.0 Hz passband. H2, H3 and H4 are separated by about 380 m. L2, L3 and L4 are separated by about 2 km.

Discussion

A good understanding of the spatial coherence of infrasonic signals as a function of frequency and source distance is clearly important to the design of reliable infrasound monitoring stations. Mack and Flinn (1971) developed a model for spatial coherence as a function of source distance and frequency from observations of relatively long-period signals from very large explosions at a large aperture array. Blandford (1997, 2000, 2004) has carried out a sophisticated design study based on an extrapolation of the Mack and Flinn model to determine an optimal design for IMS type infrasound monitoring arrays. The optimal design depends on the accuracy of the extrapolation to much higher frequencies and smaller aperture arrays. There have been several attempts in recent years (see e.g., Blandford, 1997, 2000 and 2004; Armstrong, 1998; McCormack, 2002) to accurately measure the spatial correlation of infrasonic waves from smaller explosions at higher frequencies and sensor separation distances that are of interest to the detection of smaller nuclear explosions. There seems to be a tendency for the observed coherences to be somewhat higher than those predicted by an extrapolation from the results of Mack and Flinn, but accurate measurements have proven to be quite difficult and the errors on the reported results are significant. Further work needs to be undertaken in this area.

The observations presented above show that the higher frequency components in explosion-generated infrasonic signals decay fairly rapidly with distance from the source and may not be detectable at frequencies above 0.5 Hz at distances that are comparable with distances between array elements in the global IMS infrasound monitoring network. These results also indicate that detection of signals from distant explosions may be limited at higher frequencies due to a decrease in the degree of spatial coherence between array elements in the monitoring array. The loss in signal coherence in the 0.8-2.0 Hz detection passband between widely separated array elements can be seen in the comparison shown in Figure 9 for data recorded at array elements H2, H3 and H4 with an average sensor separation of about 380 m with the data recorded at array elements L2, L3 and L4 with an average sensor separation of about 2.06 km. As can be seen from Figure 9, the observed signals have a fairly high degree of coherence between elements in the H-array and a much smaller degree of coherence between elements in the L-array. The addition of the central element H1 in the small aperture array significantly improves detection capability in the 0.8 to

2.0 Hz passband. The potentially serious limitations imposed on signal detection by the reduction in spatial coherence of higher frequency signals can be summarized by the detection parameters presented in the following table for signals from Manam Volcano recorded on large and small aperture sub-arrays at IS07. Signal detection fails completely on the large array at all frequencies above 0.8 Hz and is only marginal for frequencies in the 0.4-1.5 Hz band. Signal detection is also marginal on the small aperture array in the highest frequency passband 1.5-4.0. The analysis of signals from the New South Wales bolide and signals from other distant sources gives essentially the same results.

Table 2. Detection parameters for infrasound signals from Manam Volcano recorded at IS07 on a small aperture triangular sub-array (H1, H2 and H3 with an average separation of 380 m) and a large aperture triangular sub-array (L1, L2 and L3 with an average separation of 2.06 km).

Frequency Band	Sub-Array	Maximum F-statistic	Average F-statistic	Comment
1.5-4.0 Hz	H1, H2, H3	19.0	~ 7	Marginal detection
	L1, L2, L3	-	~ 2.5	Not detected
0.8-2.0 Hz	H1, H2, H3	44.3	~ 15	Good detection
	L1, L2, L3	-	~ 2.5	Not detected
0.4-1.5 Hz	H1, H2, H3	31.7	~ 15	Good detection
	L1, L2, L3	10.1	~ 3.5	Marginal detection
0.1-0.5 Hz	H1, H2, H3	45.1	~ 22	Good detection
	L1, L2, L3	24.6	~ 14	Good detection
0.03-0.1 Hz	H1, H2, H3	70.4	~ 40	Good detection
	L1, L2, L3	136.3	~ 60	Good detection

CONCLUSIONS AND RECOMMENDATIONS

It is clear, from the results presented here, that the loss of signal coherence may seriously reduce detection capability at higher frequencies for infrasound signals from sources that lie at distances beyond 1000 km. This result has particular relevance for IMS monitoring stations that have only four widely separated array elements. Attenuation of higher frequency signals over long propagation paths may also rule out any possibility of signal detection in the higher frequency passbands when the distance to the source is large. This is an especially important factor when propagation is confined to a thermospheric waveguide. The essential conclusions are as follows:

a) Infrasound monitoring stations should have both large and small aperture sub-arrays in order to eliminate spatial aliasing and signal coherence problems at higher frequency 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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