# SURVEYING INFRASONIC NOISE ON OCEANIC ISLANDS

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## ABSTRACT

An essential step in the establishment of an International Monitoring System (IMS) infrasound station is the site survey. The survey seeks a location with relatively low infrasonic noise and the necessary logistical support. This paper reports results from our surveys of three of the oceanic sites in the IMS - the Azores, Cape Verde and Ascension island. Each survey sampled infrasonic noise, wind velocity, air temperature and humidity for ~ 3 weeks at 4 sites near the nominal IMS locations. The surveys were conducted on Sao Miguel (the main island in the Azores) and Maio (Cape Verde) as well as Ascension. Infrasonic noise was measured using the French MB2000 microbarometer.

During our 3 week experiment in January the trade winds at Cape Verde varied little from an azimuth of 60°. Because of the unvarying wind azimuth, the experiment gave us an opportunity to examine the effectiveness of a forest at reducing both wind speed and infrasonic noise. We find that the thick Acacia forest on Maio reduces wind speeds at a 2 m elevation by more than 50% but does not reduce infrasonic noise at frequencies below 0.25 Hz. This forest serves as a high-frequency filter and clearly does not reduce long period noise levels which are due to large-scale turbulence in the atmospheric boundary layer above the forest. This is consistent with our observations in the Azores and on Ascension island where the relationship between infrasonic noise and wind speed is more complex due to frequent changes in wind azimuth.

In Cape Verde, wind speed and infrasonic noise are relatively constant. The diurnal variations are clearly seen but the microbarom is only rarely sensed. In the Azores, during our 3 week experiment in November and December of 1998, wind speed and infrasonic noise change rapidly. At this location, daily noise level swings of 40 to 50 dB at 0.1 Hz are not uncommon in the early winter and are due to changes in wind speed and atmospheric turbulence. The effectiveness of an infrasound station in the Azores will be strongly dependent on time during the winter season.

Our surveys have identified locations on each of these island where noise levels are relatively low and there is enough flat terrain to deploy infrasound arrays ranging in aperture from 1 to 3 km. We recommend 2 km aperture arrays at each location. Due to high winds at each location we further recommend augmented arrays of 7 elements. We recommend that 3 of the 7 elements in each array be deployed in a micro-array spanning 300 meters at the center of the larger array.

**Key words:** Atmospheric turbulence, infrasonic noise, noise reduction

**OBJECTIVE**

Our objective is to record infrasonic noise, wind velocity and air temperature and humidity on 3 islands in the Atlantic to identify the location on each island which is subject to the lowest infrasonic noise levels and is most suitable as a site for a station in the IMS infrasound network. In addition we seek the array and noise filter designs that are most appropriate for each site.

**RESEARCH ACCOMPLISHED**

Overview

The island stations in the planned global IMS infrasound network are essential, as they provide much needed coverage in oceanic areas, but are not ideal in other respects. Stations located on islands will, in general, be subject to strong winds (Figure 1) and thus high infrasonic noise levels. Strong trade winds dominate in the tropics. In latitudes above 30°N and below 30°S the prevailing westerly winds dominate although local winds can be strongly influenced by local pressure cells. Some islands (e.g. Ascension) are small (relative to the size of a 2-3 km aperture infrasound array) and rugged . Some islands (e.g. Cape Verde archipelago) receive limited rainfall and are sparesely vegetated.

The Provisional Technical Secretariat (PTS) calls for an infrasonic noise survey of the vicinity of each nominal infrasound station to find the most suitable location for a standard infrasound station (an array of 4 sensors with an aperture of 1 to 3 km). The noise survey for each station is to be conducted simultaneously at 4 locations in the vicinity of each nominal station location. Infrasonic noise is to be collected with wind velocity and temperature. With these requirements in mind this project has 4 main elements: Site selection, data collection, analysis and final recommendations regarding the location and design of the infrasound array at each of the 3 IMS sites. Four temporary stations were established on each of the three islands. All sites on each island were occupied concurrently for 3 or more weeks.

At each site we deployed an infrasound sensor equipped with a 30 m aperture Daniels filter composedof porous hose. We have used the MB2000 infrasound sensor fabricated by the D partement Analyse et Surveillance de l Environnement (DASE). These sensors provide a filtered signal between 0.01 and 27 Hz. We used RefTek 6x24 bit digitizers and sampled the infrasound data at 20 Hz. The Atlantic site surveys were preceeded by calibration tests in the field at the Pinon Flat Observatory (PFO) in southern California, and in the laboratory at IGPP in La Jolla, California. The tests were conducted to ensure all field systems were robust and yielded equal digitized signals for equal input.

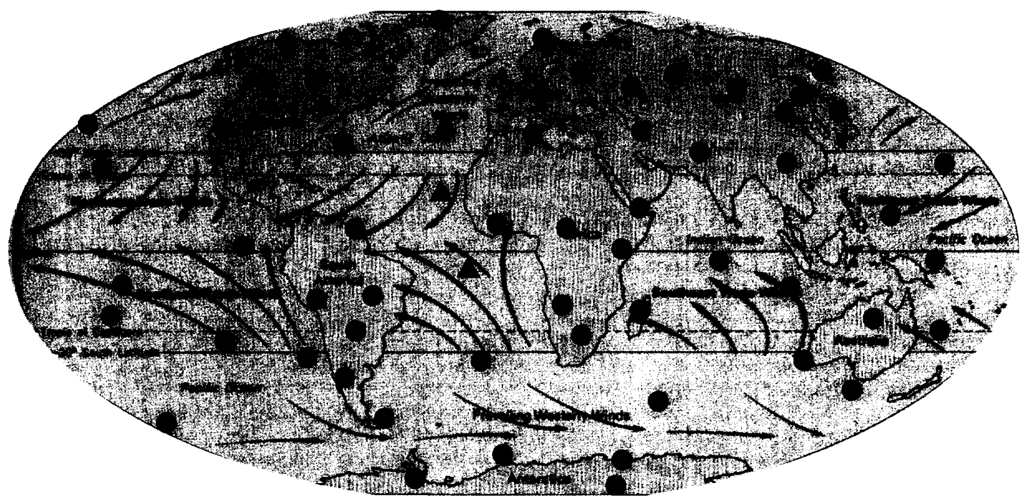

Figure 1. The planned IMS infrasound network. Stations located on islands will, in general, be subject to the strongest winds. The strong trade winds dominate in the tropics. In latitudes above 30°N and below 30°S the prevailing westerly winds dominate although local winds can be strongly influenced by local pressure cells. The 3 considered in this study are indicated by triangles. The Azores lie in the northern westerlies, Cape Verde and Ascension lie in the trades.

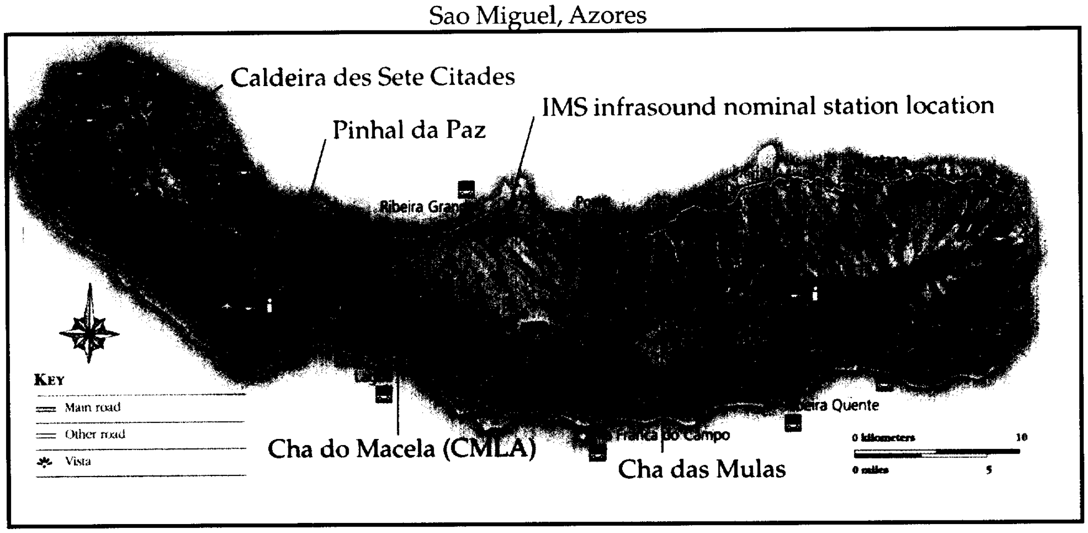


**FIGURE 2.** Sao Miguel, Azores and the 4 survey locations. The western site is located in a calderra. The two central sites are located in dense forests. Cha das Mulas is located on a plateau which has a rich low-level ground cover. Most of the original forest has been cleared. Most trees are in long rows and are used to decrease wind speed. The nominal station is located near the second largest city on the island, Ribeira Grande, in an active hydrothermal area. The recommended IMS infrasound array is at Cha das Mulas. One possible configuration is indicated by the triangle.

### Preliminary Site Selection

In the Azores, Cape Verde and on Ascension meteorological data have been collected for decades. These data together with ground cover, topography and infrastructure maps guided us in our selection of survey sites. In the Azores, meteorological data from the past 30 years indicates that winds on the main island, Sao Miguel, are relatively weak. We selected 4 sites on this island that sampled different means of reducing infrasonic noise. One site was located in a large calderra (Figure 2). Two sites (Pinhal da Paz and Cha da Macela) were located in thick forests. The fourth, eastern, site was located on a broad blateau between long rows of criptomeria trees.

The Cape Verde archipelago comprises 9 major islands. All but one are unsuitable for infrasound. The western islands are relatively young and rugged. The extreme example is Fogo, a 2829 m high active volcano. The eastern, relatively flat, islands have little vegetation and are subject to high trade winds from the northeast. The exception is Maio which is sparsely populated, has a substantial forest and a line of site to the largest island, Santiago, where telecommunications infrastructure is located. All 4 survey sites were located on this island in the forest in a 3 km aperture centered equilateral triangle (Figure 3). Forests reduce wind speeds and thus will attenuate atmospheric noise. The thickness of the forest on Maio is variable. We have chosen sites at which the forest comprises mature, closely spaced, Acacia trees (MAO2) and sites where the trees are either broadly spaced (MAO1 and MAO3) or very young (MAO4). There is essentially no ground cover at any of these sites. A comparison of measurements made at these dissimilar locations will allow us to gauge the utility of Acacia forests for reducing wind speeds and noise in the infrasonic band between 0.02 and 5 Hz.

Ascension island (Figure 4) offers few options for siting infrasound sensors. In this survey, all sensors were located near the center of the island in an equilateral triangle. None of the sites are located in a well developed forest. The central site has a low ground cover. The site near the GSN station has mature, broadly spaced, pine trees.

### Preliminary results from the surveys

The 4 survey points on Sao Miguel, Azores were occupied in November, 1998. After 19 days of simultaneous recording at all sites, the equipment was moved to Cape Verde (Figures 1 & 4) for an additional 3 weeks of recording in January, 1999. The Ascension survey occurred in April to June, 1999.

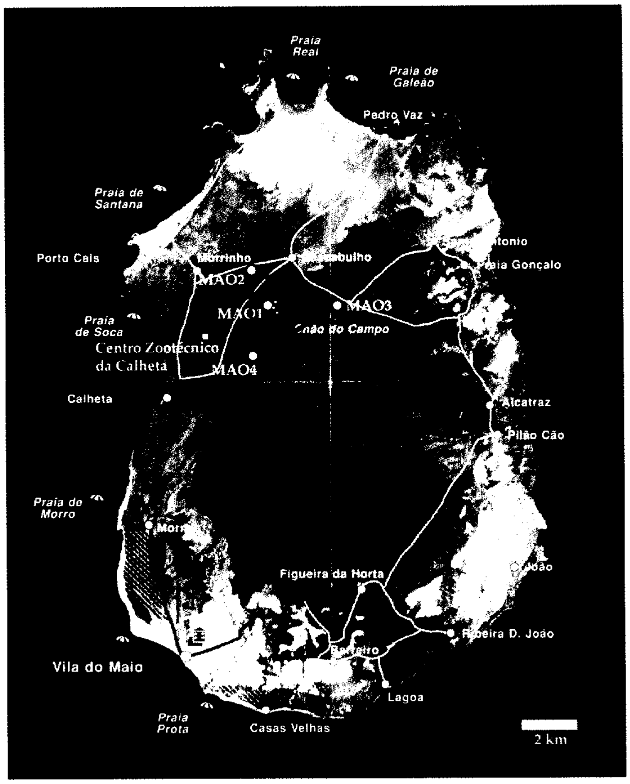


**FIGURE 3.** The island of Maio, Cape Verde has little vegetation except in an Acacia tree forest in the north. The island covers ~ 310 square km - roughly 4 times the size of Ascension island, the site of another nominal IMS infrasound station. The 4 survey points are in a forest of Acacia trees.

Fifteen minutes of pressure and meteorological data from the Azores experiment are shown in Figure 5. The unfiltered pressure timeseries from the station at Cha das Mulas exhibits 30 s period fluctuations superimposed on substantially longer period energy. The shorter period variations dominate the filtered record (second panel). In this time period, minor wind velocity fluctuations are constant. The temperature and humidity vary relatively slowly. The detailed structure of the filtered pressure record results from the superposed contributions of myriad atmospheric phenomena. Our study is concerned primarily with the dependence of the noise on frequency and the exact location of the sensor and thus we will focus on the spectral properties of the noise.

To examine the spectral content of the filtered data we used Welch s method (Welch, 1967) which yields a single power spectral estimate from an average of several taken at regular intervals in the time range of interest. The spectral estimates we have used in this study were derived from an average of 4 estimates, each taken from consecutive 204.8 s intervals. The power spectral density taken from the filtered record (Figure 6) shows a decay in power levels from the peak at 30 s to the corner of the anti-aliasing filter at 9 Hz. A strong microbarom peak is centered at 0.2 Hz. The overall spectral shape is due to a well known phenomena in the atmosphere which receives a major input of energy at ~ 0.1 to 1 mHz. Energy from large scale eddies cascades into smaller eddies, and thus into higher frequencies, as the large eddies are broken up (Kaimal and Finnigan, 1994).

From the full 3 weeks of recording at all 4 sites we calculated power spectral denstiy at 454 time intervals. Each interval began at the turning of the hour and spanned 15 minutes. Tenth, 50th and 90 percentile noise levels at all frequencies from 0.005 Hz to 10.0 Hz are shown in Figure 6. At times of relatively low noise the microbarom peak is obvious at Cha das Mulas. This figure shows that the interval displayed in Figure 5 was a time of relative quiescence. From this figure it is evident that the longer periods depend more strongly on time. For example, the spread between the 10th and 90th percentiles is 50 dB at 0.1 Hz and just 20 dB at 1.0 Hz.

The same spectral character is seen at all four sites (Figure 7). Median noise levels between 0.03 and 0.1 Hz are 5 to 10 dB lower in the calderra and in the forest at Pinhal da Paz than on the plateau at Cha das Mulas and at Cha do Macela. A other frequencies the noise levels are comparable. The noise spikes at 3.5 and 7.0 Hz at Pinhal da Paz are likely due to infrequent industrial activity. That survey point is near several quarries.

At Cape Verde, the wind azimuth is relatively constant and there exists a simple dependence of infrasonic noise levels on wind speed (Figure 8). As wind speeds at Cape Verde are relatively constant, the most significant source of variability in infrasonic noise levels is the diurnal effect which is predominantly due to day-night variations in the speed of the trade winds. Infrasonic noise levels are highly correlated with this effect and thus at any time of day, noise levels are quite easily predicted.

During our experiment in the early winter, wind speed and noise levels in the Azores varied strongly with time(Figure 9). The experiment in Nov. and Dec. occurred at a time of advancing inclement weather. Toward the end of the experiment wind speed at Cha das Mulas could increase from 1 to 6 m/s in a few hours.

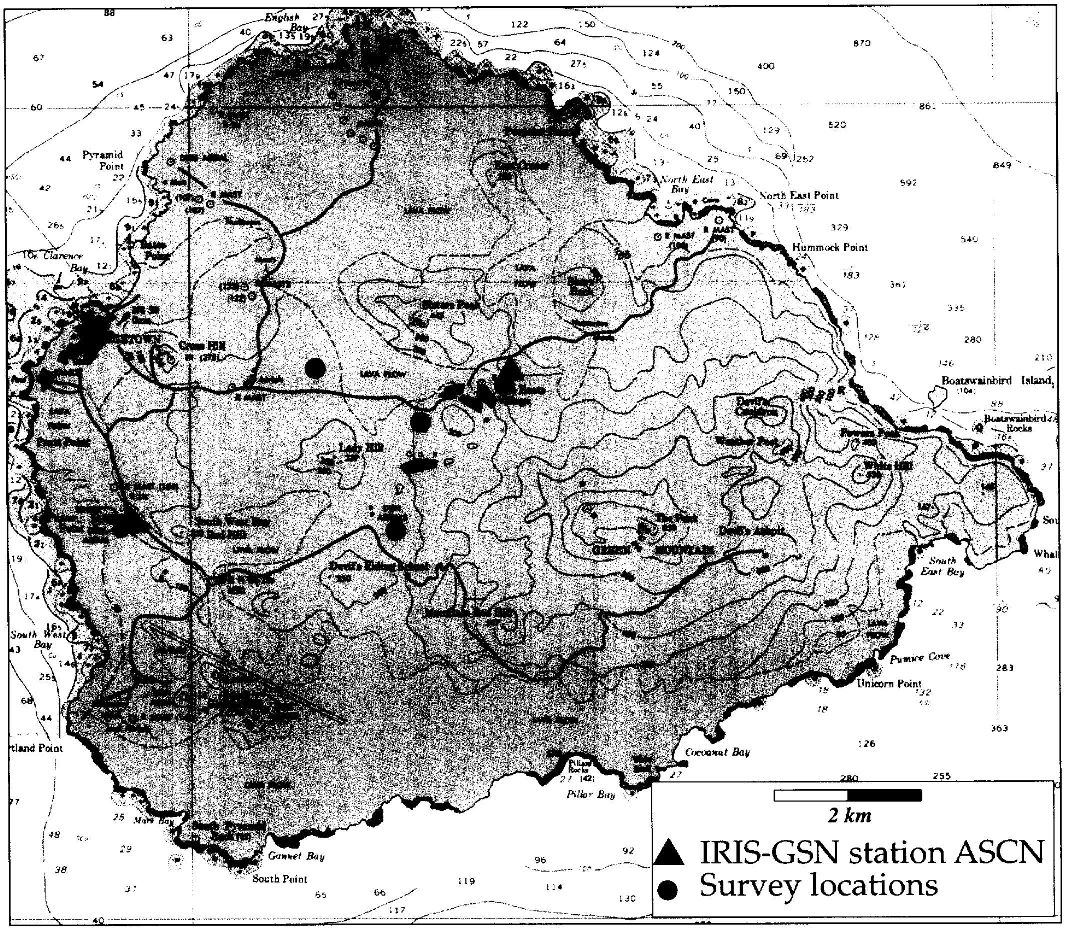


Figure 4. Ascension island topography and the GSN station (ASCN) and the 4 infrasound survey sites we occupied in early 1999.

## CONCLUSIONS AND RECOMMENDATIONS

### Forests and Infrasonic Noise Reduction

Cape Verde is perhaps the ideal place to study the generation and suppression of infrasonic noise. The archipelago is located at 16°N where northeast trade winds are dominant. During the 3-week experiment in January, the mean wind azimuth was 63° with a standard deviation of 9.6°. The wind-topography interaction is relatively time invariant when the wind azimuth remains constant. These wind tunnel conditions produce a simple scaling between wind speed and wind noise at all frequencies from 0.02 to 5 Hz (Figure 8).

With azimuthal considerations effectively nullified it is possible to address the issue of the effectiveness of a forest for reducing infrasonic noise in the frequency band between 0.02 and 5 Hz. The Acacia forest on Maio is thickest at MAO2. At this location the trees were planted in the 1950 s and are ~10 to 15 m high. The forest is less mature, the trees are smaller (5 to 10 m) and more broadly spaced, at MAO1 and MAO3. MAO4 was located in a grid of recently planted ~ 5 m tall Acacia trees. As we see in Figure 8, wind speeds (at an elevation of 2 m) at MAO2 are reduced sharply. The maximum wind speed at this location is ~ 1.4 m/s wheras at MAO1 and MAO4 the wind speed reached 2.7 m/s and 2.5 m/s respectively and at MAO3 the wind speed reached 3.1 m/s. As we see in Figure 8, at frequencies below

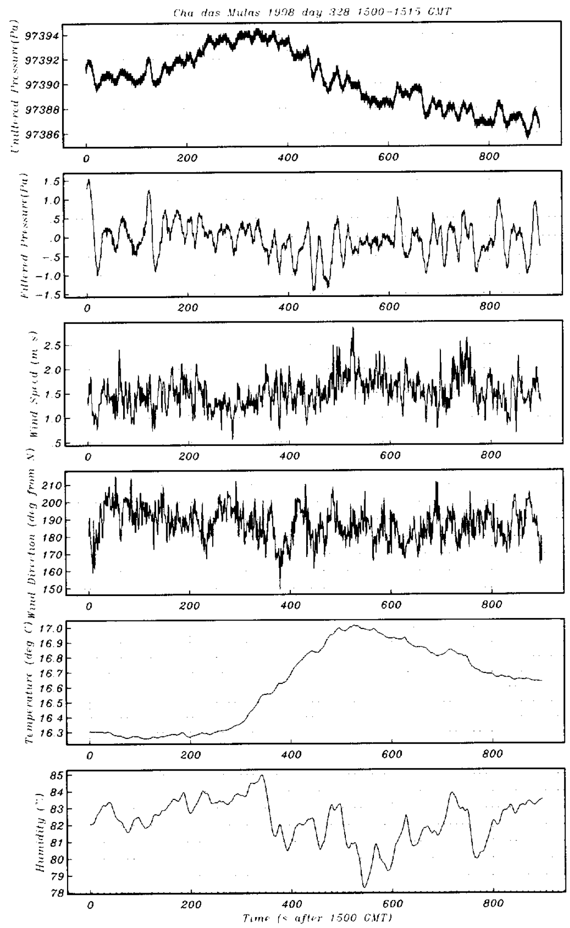


**FIGURE 5.** Atmospheric pressure and meteorological data from a 15 minute interval starting at 15:00 GMT at Cha das Mulas. Raw and filtered pressure data are shown in the upper two panels. Wind speed, direction, temperature and humidity are shown below. As shown in the next figure, this is a time of relatively low infrasonic noise.

0.25 Hz there is no reduction in noise levels. For example, at all locations infrasonic noise at a period of 20 s ranges from .01 $Pa^2/Hz$ when there is no wind to 50 $Pa^2/Hz$ when wind speeds are highest. It is apparent that infrasonic noise at frequencies below 0.25 Hz is not dependent on wind speed at 2 m elevation within the forest. Noise at these long periods depends on turbulence that is common to all sites - that which exists in the boundary layer above the trees. The thick forest at MAO2 is clearly reducing noise levels at frequencies between 0.25 and 5.0 Hz. The noise estimates at MAO2 become progressively lower than at the other sites as the wind speeds increase. At times when the wind speed is near the maximum, noise levels in this frequency band at this site are 5 to 10 dB lower than at the other sites. Although the forest is reducing high-frequency infrasonic noise levels, the reduction is not complete. A comparison of noise levels at the maximum speed of 1.4 m/s at MAO2 with noise levels at the other sites at the same wind speed indicate that at frequencies at and above1 Hz, noise levels in the thick frorest are 5 to 15 dB higher than elsewhere. When wind speeds are low, the noise suppression within the thick forest extends to 0.1 Hz (Figures 8).

## Noise levels within a calderra

Wind flow over a two-dimensional ridge is laminar upwind of the ridge crest and becomes turbulent on the lee side (Kaimal and Finnigan, 1994). The turbulence results when the wind flow, which is compressed and accelerated at the ridge crest, decompresses on the lee side. A separation bubble forms at the location where some air flows in the opposite direction, back to the ridge, and is followed by a turbulent wake. The site in the calderra on Sao Miguel island was chosen for our survey to determine if this turbulence would contribute noise in the band between 0.05 and 1.0 Hz or if, overall, the walls of the calderra would deflect the wind away from the site and reduce noise levels. Figure 7 indicates that noise levels are clearly increased at .02 Hz and suggests the presence of unusually energetic large-scale turbulence in this area. It is difficult to make definitive conclusions about noise levels at higher frequencies because of the scatter in the noise estimates. However it is apparent that although the calderra is effectively reducing wind speeds, noise levels at 0.05 Hz and above are not clearly reduced when wind speeds are high. When the wind is near-average, the calderra noise levels between 0.05 and ~ 0.15 Hz are comparable to those in the forest at Pinhal da Paz and 5 to 10 dB lower than at the other two sites (Figure 7). As discussed in the previous section, at times of elevated winds, the calderra walls reduce wind speed but no notable reduction in infrasonic noise levels results.

**The best site in the Azores**

The primary objective of our field program is to identify the location on each island that is most suitable for a permanent IMS infrasound array. The paramount factor is infrasonic noise however our selection must be guided by practical considerations. A site that offers low infrasonic noise but gives few options for siting a permanent array might

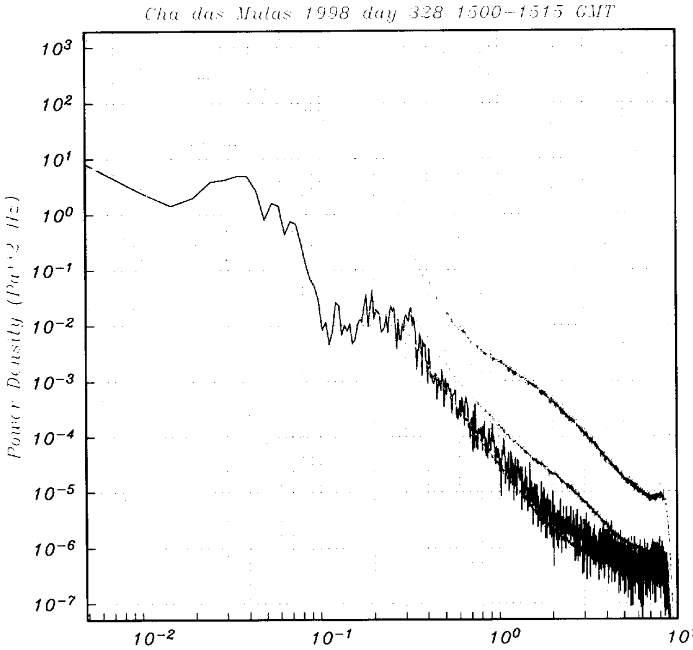


**Figure 6.** Noise power density at Cha das Mulas. In black is shown a single power density estimate taken from the filtered pressure data displayed in figure 5. The colored curves are the 10th, 50th and 90th percentile noise levels from the entire experiment. These curves are based on 454 noise level estimates taken at 1 hour intervals. Each estimate is taken from 15 minutes of data. The 5 second microbarom is not observed at times of high noise.

not be optimal. The ideal site is large enough to allow any array configuration from 1 to 3 km aperture to be considered. On Sao Miguel, the Cha das Mulas site is the only one that could accommodate *any* IMS array design. From every perspective other than the most important one, noise, the plateau is clearly the best site and it will serve as the standard against which all other sites in the Azores will be judged. In addition to plenty of space to deploy array elements at the same elevation, there are unobstructed views to the horizon from most points. There is little cultural activity and the site is relatively far from the ocean. Most of the plateau is covered by a lush grass. Long rows of trees interrupt the flow of wind.

Median noise levels in the calderra on Sao Miguel are comparable to those at Cha das Mulas at all frequencies except between .03 and .1 Hz where the median noise levels in the calderra are 5 to 10 dB lower (Figure 7). Most signals of interest lie between 0.05 and 1.0 Hz (PTS summary) and so this discrepancy could be important. Because of short duration of the survey (~ 3 weeks) it is not clear if this noise spread is significant and indicates relative noise levels throughout the year. The calderra is large enough to accommodate an IMS infrasound array and could be an excellent site however it offers few options for array configurations. Two large lakes and a village lie within the calderra. Just one array configuration is possible - 4 elements in an isosceles triangle 2 1/2 km tall and 1 1/2 km at the base. As shown in Figure 7, noise levels at long periods are elevated - probably due to wind flow across the rim of the calderra. For these reasons, and because of the potential for signal blockage at some azimuths due to the walls of the calderra, this location is not preferred over Cha das Mulas.

The second site, Pinhal da Paz, lies in a dense Criptomeria forest on the axis of the island. This site is near several quarries but has median noise levels that are on par with those in the calderra (Figure 7). This site lies in rolling hills and, like the calderra, offers few options for array design. Elements in any array deployed at this location would be separated vertically by ~ 50 m. If full-scale (70 m aperture) Daniel s filters are required, it would be difficult to keep all ports at the same elevation. This site is also not preferred over Cha das Mulas for these reasons and because there is more cultural activity in this area. The third site, Cha da Macela, also lies in a dense forest but is subject to high winds directed through the central, low, part of the island (Figure 2). Although median noise levels are comparable to those at Cha das Mulas, 90th percentile noise levels are high. Despite the proximity to the GSN station CMLA and the nominal infrasound coordinate (Figure 2) this site is also not preferred.

Our survey indicates that the best site in the Azores is at Cha das Mulas. This broad plateau is large enough to accommodate any array configuration. Our brief survey indicates that this area is subject to substantial noise level swings (Figure 9) however comparable noise swings occurred at all sites on Sao Miguel (and presumably at all other islands in the Azores). Any infrasound monitoring station located in the Azores will offer a highly variable performance - particularly during the winter when storms are not uncommon.

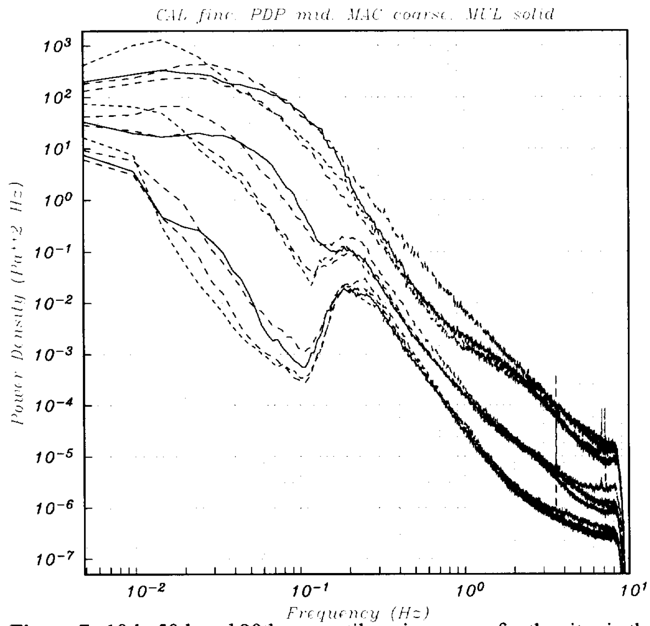


**Figure 7.** 10th, 50th and 90th percentile noise curves for the sites in the Azores. Cha das Mulas noise is represented by the solid curves. The other sites are identified at the top of the figure.

## The best site in Cape Verde

Due to limited options, the Cape Verde survey points were all located together on the same island - Maio. Because of topograpy, cultural activity or a lack of ground cover the other islands are clearly unsuitable for an effective infrasound deployment. This micro deployment was in the configuration of a standard IMS array (a 3 km aperture centered equilateral triangle) in the event that all sites were shown to be adequate and all could be chosen to be sites for the permanent installation. All sites appear to be adequate however this configuration lies at the upper limit of the allowable range for IMS infrasound arrays and might not be appropriate for this rather windy site. Our survey revealed thick forest reduces wind speed however, just as in the the calderra in the Azores, the wind noise was not reduced substantially at long periods. We recommend that the IMS array be deployed in the oldest, thickest, part of the Acacia forest near the site MAO2.

## Recommended arrays in the Azores, Cape Verde and Ascension Island

On the Azores and in Cape Verde the array designs are still not finalized. Due to the strength of the microbarom and the presence of high noise due to winds the best array designs will likely have an aperture of ~ 2 km with extra 3 sensors in a microarray at the center. The location in Cape Verde is in a state park and there are no logistical limitations on array design. At some locations the forest is not mature and additional high-frequency noise suppression might be advisable. Some locations might require additional ground cover and trees. In the Azores, the final array design is pending as not all local landowners have been contacted.

Both array locations are near small hills which have existing road access and could serve as central processing stations. In Cape Verde, telecommunications infrastructure is located on Monte Babosa on Santiago island. This facility is ~ 52 km from Monte Vermhelo and will be used to transmit data from the GSN station, SACV, located just west of the capital, Praia. In the Azores, telecommunications facilities are situated on Pico de Barrosa - the 947 m high peak located 15 km west of Cha das Mulas.

The Ascension array design is still pending as the data have just recently been retrieved from the field.

## The utility of infrasound site surveys

Because of limited resources and manpower, the standard infrasound site survey lasts just 2 to 3 weeks. This gives just a glimpse of the full range of meteorological conditions that will occur in a typical year. Is it fair to assume that the brief period sampled is representative of the entire year and the survey will lead the surveyer to recommend the best site or is a 2 to 3 week survey too brief to be useful? For a brief survey to be ineffective, climactic conditions at the time of the survey would have to be out of the ordinary and tilt the balance of infrasonic noise so that the relative noise levels at the sites are not representative of the yearly average. Intuitively, this seems rather unlikely and easy to check. The chief source of infrasonic noise is turbulence due to wind flow over topography. If wind direction changes in such a way that the wind-topography interaction at the time of the survey is unusual and, as a result, anomalously little turbulance is generated at certain sites, or excessive turbulence is generated at others, the brief survey taken at that time would be misleading. It should be possible to rule out this scenario by comparing wind velocity measurements made during the

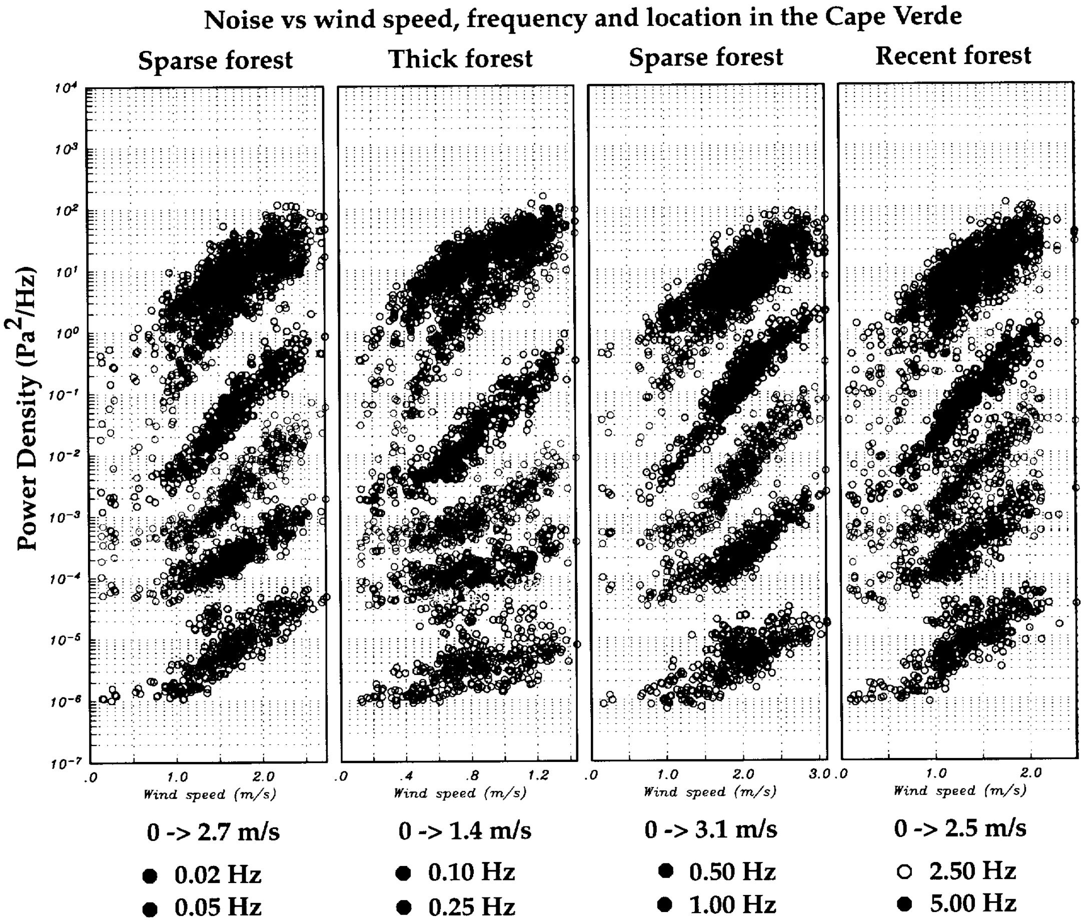


**Figure 8.** The four panels above show the strong dependence of infrasonic noise on wind speed and frequency at the four sites in Cape Verde. From top to bottom in each panel is noise power at 0.02 Hz (black); 0.05 Hz (red); 0.1 Hz (green); 0.25 Hz (dark blue); 0.5 Hz (light blue); 1.0 Hz (pink); 2.5 Hz (yellow); and 5.0 Hz (black). Wind speeds in the thickest forest on Maio, which at MAO2, are lower than elsewhere however noise power is not reduced at frequencies lower than 0.25 Hz. Winds are weakest in the thickest part of the forest at MAO2. Noise power has a relatively simple dependence on wind speed.

survey with those from long-term meteorological observations. A significant discrepancy in wind speed or direction combined with azimuthally dependent topography would be cause for concern. The winds observed during the Azores, Cape Verde and Ascension surveys appear to be in line with long term observations. These surveys occurred at times of elevated winds, but these winds were as expected from historical data. There is no reason to believe that these winter surveys are misleading.

The utility of oceanic sites.

There are numerous requirements for a good infrasound station (Christie, 1998). The exceptional island might meet all of them. Noise is the most important consideration. There are a plethora of noise sources - wind noise is the paramount concern. As we have seen, wind in the Azores, in the early winter at least, is capricious. This is not a trait of just oceanic sites but it is reasonable to expect such conditions to be more common on islands. Changes in wind speed of 5 to 6 m/s in a few hours appear to be common in the early winter in the Azores. No infrasound station deployed in

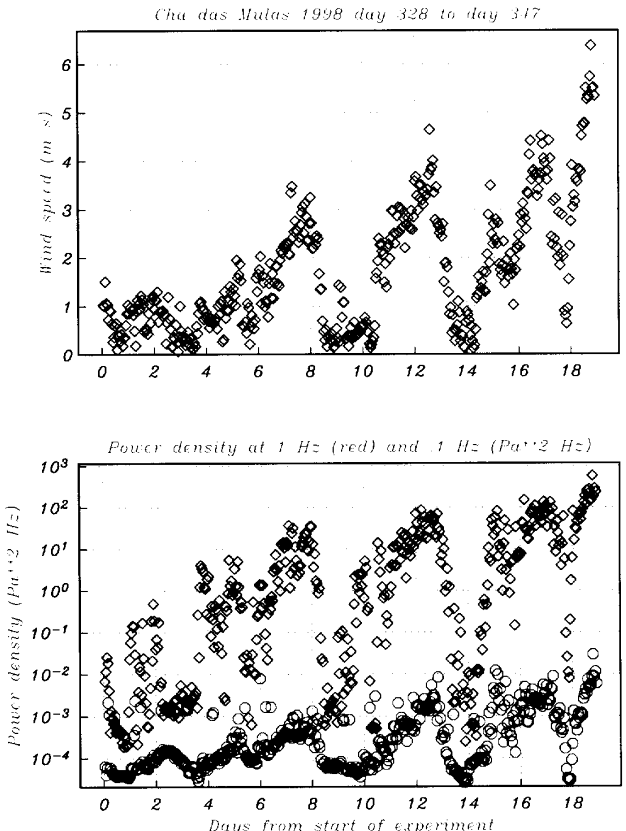


**Figure 9.** Noise power and wind speed as a function of time at Cha das Mulas in the Azores. In the Azores, wind noise at 0.1 Hz (upper sequence of points in the lower panel) and at 1.0 Hz closely track the wind speed. Severe winds during a storm near the conclusion of the Azores experiment lead to substantial swings in the noise level.

such a setting can be expected to deliver invariant performance through the year. At times of high wind, such a station will be rendered ineffective for sensing all but the most energetic signals. There are several options for improving signal to noise levels. It is well known that Daniels filters reduce noise and the effectiveness of these filters is strongly dependent on the design. It might be necessary to design the filters to suit local needs at each of the windy sites. The standard IMS infrasound array has 4 elements. Additional elements, located in a microarray at the center, will improve the performance of the overall array. In some areas flat ground will be unavailable and the best noise suppression scheme, beyond vegetation, will likely be spatially limited wind fences (e.g. ReVelle and Whitaker, 1999).

The oceanic sites will make an important contribution to global monitoring but it is clear that the effectiveness of a typical oceanic, or continental, site will be highly dependent on local meteorological conditions. Global detection thresholds will be strongly dependent on time at all locations (Trost, 1997). Recent research by Clauter and Blandford (1997) indicates that detection 90% confidence level two station detection levels will be between 0.1 kt and 0.3 kt over most continental areas and between 0.3 and 0.7 kt over most oceanic regions. Advances in empirical atmospheric wind models (e.g. Drob, 1999) and improvements in modeling the propagation of acoustic waves through a non-stationary medium (e.g. Collins, 1993; Norris and Gibson, 1999) should lead to improved estimates of global monitoring thresholds as a function of time.

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