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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 two of the oceanic sites in the IMS – the Azores and Cape Verde. 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). 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 63°. 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 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 however 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.

The two surveys illustrate some of the difficulties inherent in the selection of sites for 1 to 3 km aperture arrays on oceanic islands. Due to elevated noise levels at these sites, 8 element, 2 km aperture arrays are strongly preferred.

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

1. Introduction

1.1. The CTBT and Infrasound

A natural consequence of any global nuclear-test ban treaty is the need for global monitoring. In the case of the recent Comprehensive Nuclear-Test-Ban-Treaty

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(CTBT), which bans nuclear explosions of any yield, four monitoring networks will be used – seismic, hydroacoustic, air acoustic (or infrasound) and radionuclide. This study is concerned with infrasound, the inaudible acoustic energy from 0.01 to 20 Hz. Although there are myriad infrasound sources (including natural ones such as atmospheric turbulence, bolides, aurora, earthquakes, volcanic eruptions, ocean waves, avalanches, convective storms; GEORGES and YOUNG, 1972; KULICHKOV, 1992; MUTSCHLECNER and WHITAKER, 1994; WILSON *et al.*, 1995; BONNER *et al.*, 1998; and man-made ones such as supersonic aircraft or rockets, industrial explosions; YAMAMOTO, 1956; FEHR, 1967; LISZKA, 1974; GOSSARD and HOOKE, 1975; KULICHKOV, 1972; BONNER *et al.*, 1998) the source of greatest interest, the kind that must be separated from the rest, are nuclear explosions. Since the era of atmospheric testing, it has been known that the shock front from a nuclear explosion will evolve into infrasonic energy that propagates efficiently through the lower atmosphere (LANDAU and LIFSHITZ, 1959; BERANEK, 1960). Buried nuclear tests cause a piston-like vertical ground motion which also produces infrasonic pressure waves (BLANC, 1985; CALAIS *et al.*, 1998). Much of the acoustic energy from an infrasound source is refracted back to the Earth's surface at the thermocline (at 100 to 150 km altitude) or at lower elevations due to wind shear (SIMONS, 1995). A Lamb surface wave exists principally below $\sim$30 km altitude (LAMB, 1932; FRANCIS, 1973) and will be sensed within 500 km of the source (BROCHE, 1977). The propagation of refracted and surface infrasonic energy through the atmosphere is dependent on the acoustic velocity and thus on wind, temperature, humidity and viscosity (e.g., STOKES, 1857; REYNOLDS, 1874; HAURWITZ, 1941; INGARD, 1953). Propagation of acoustic energy through the atmosphere thus depends strongly on time. The frequency content of infrasonic energy is strongly range-dependent due to attenuation (BLANC, 1984) and because of nonlinear stretching which favors the lower frequencies as propagation distance increases (SIMONS, 1995). Most signals of interest to the monitoring community lie between 0.02 and 4.0 Hz (CHRISTIE, personal communication).

On paper, any ideal monitoring network is perfectly uniform. On the earth's surface, the best possible global network will include a large number of stations on oceanic islands (Fig. 1). Of the 60 stations that will be in the IMS infrasound network, 23 will be on islands. Most of these island sites will be less than ideal in certain aspects considered important for a good station. For example, most sites will be subject to strong winds (Fig. 1). Wind is the most significant source of infrasonic noise between 0.01 and 1 Hz (MCDONALD *et al.*, 1971). Microbaroms are 5–8 second, intermittent, infrasonic waves that are produced at the air-sea interface by ocean swell (DONN and POSMENTIER, 1967). This noise is most evident on islands and at continental edges. Some islands will offer few suitable locations to deploy the standard infrasound station – a 1 to 3 km aperture triangular array of 4 to 8 sensors – a configuration that has been shown to be optimal (HAUBRICH, 1968). Most islands are rugged and thus there exists a significant potential for signal blockage and the generation of noise from turbulence due to wind flow over topography.

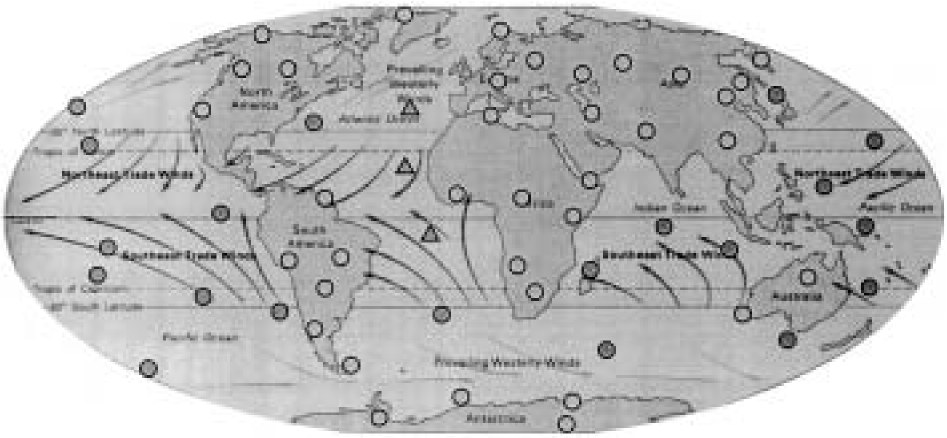

Figure 1
The planned global IMS infrasound network. Stations located on islands will, in general, be subject to strong winds and thus high infrasonic noise levels. Strong trade winds dominate in the tropics. In latitudes above 30°N and below 30°S the prevailing westerly winds dominate although local winds can be strongly influenced by local pressure cells. The three triangles in the Atlantic from north to south are the Azores, Cape Verde and Ascension. The background display of oceanic winds is adapted from the World Book Encyclopedia.

None of the oceanic or continental infrasound stations are to be selected without a site survey. The Provisional Technical Secretariat (PTS), which has issued a set of guidelines for site surveys, lists several factors as having distinct importance. A good site has low infrasonic noise between 0.02 to 4 Hz. The site is sheltered from winds by gentle topography and vegetation and has the necessary logistical support while being located as far as possible from cultural activity and other significant sources of noise – such as the ocean. Preference is given to sites located within 0.05° of the nominal station location and sites where a station from one of the other monitoring networks is located. In a standard site survey, infrasonic noise and meteorological data are collected at 4 favorable locations for a minimum of 2 weeks. A 2-week survey offers just a glimpse of the full range of meteorological phenomena that will occur through the year at an infrasound station, but should clearly indicate which site should be best.

1.2. Wind and Infrasonic Noise

The turbulent flow of wind is the most significant source of infrasonic noise in the band from 0.01 to 1 Hz (McDonald *et al.*, 1971). The relationship between wind and infrasonic noise is given by Bernoulli's principle

$$p + (\rho v^2)/2 = C$$

where p is pressure, ρ is density, v is wind velocity and C is a constant. Differentiation of this formula shows that there is a simple linear scaling between variations in wind speed and pressure. Understanding the frequency dependence of infrasonic noise requires knowledge of the interaction of wind with topographic irregularities that cause the turbulence. In general terms, atmospheric turbulence is concentrated near the Earth's surface in the Atmospheric Boundary Layer (ABL; KAIMAL and FINNIGAN, 1994) – a region of high Reynolds-number flow. The upper extent of the ABL is limited by the capping inversion which is highest (at 1 to 2 km) during the day when the Earth's surface radiates heat and lowest (10's of meters) or nonexistent during the night (PANOFSKY and DUTTON, 1984; KAIMAL and FINNIGAN, 1994). The thickness of the boundary layer is also governed to some extent by topography as the turbulence of wind flow over the ground is increased by ground roughness. Large-scale atmospheric turbulence is maintained by thermal plumes and thus is most evident during the day. Wind shear introduces smaller eddies and "cascades" energy from the low to the higher frequencies (KAIMAL and FINNIGAN, 1994). There is no universal statistical characterization of atmospheric turbulence at large scales (WILSON *et al.*, 1999). The turbulence depends on the velocity and density profiles of the atmosphere as well as boundary effects such as topography and ground cover. The spatial structure of the atmospheric turbulence is dependent on the interaction of the wind with topography and can be modeled using one of a number of models including Gaussian, von Karman or Kolmogorov spectral models (WILSON *et al.*, 1999). Wind noise is known to be incoherent at spacing of 10's of meters (e.g., PRIESTLEY, 1966). There exists a direct scaling between the size of the wind eddies and the time-frequency of the noise they produce. At 0.25 Hz, the scale of the turbulence is $\sim$25 m (GROVER, 1971).

1.3. Overview of this Paper

Our group has conducted two of the oceanic surveys: The Azores, Portugal and Cape Verde, Western Africa. In this paper we discuss the relationship between wind and infrasonic noise and the utility of vegetation and topography for reducing noise across the frequency band of interest to the monitoring community. We conclude with an assessment of the utility of these sites for nuclear test monitoring.

2. Infrasonic Noise Surveys in the Azores and Cape Verde

2.1. Field Equipment

For our surveys we used the MB2000 aneroid microbarometer fabricated by the French Département Analyse et Surveillance de l'Environnement (DASE). These sensors provide a filtered signal between 0.01 and 27 Hz (cut back to 9 Hz by an anti-aliasing filter) with an adjustable sensitivity. We deployed the low sensitivity (20 mV/Pa) version. The electronic noise of the sensor is 2 mPa rms, between 0.02 and 4 Hz, which is well below natural background noise (DASE Technical Manual, 1998).

Each sensor was placed in an insulating case and equipped with a microporous "front end" filter (DANIELS, 1959; BURRIDGE, 1971) for suppression of noise due to wind turbulence (COOK and BEDARD, 1971). The filter senses air pressure through microporosity ports distributed over a small area. Uncorrelated pressure variations, such as those due to wind turbulence, sum incoherently and are attenuated. Although noise and the signal of interest might have the same time-frequency, the noise, which is most commonly due to wind turbulence, is incoherent over shorter length scales. For example, at 0.25 Hz, wind noise is incoherent at spacing of 10's of meters while acoustic waves at the same frequency can be coherent at >1 km (GROVER, 1971). Under windy conditions it has been demonstrated by numerous authors (incl. DANIELS, 1959; GROVER, 1971; BURRIDGE, 1971) that a spatial filter will suppress noise, however the suppression is highly dependent on frequency, hose configuration and wind speed (GROVER, 1971; NOEL and WHITAKER, 1991). For the surveys we deployed identical filters at all sites – a simple, 4 arm, 30-m aperture cross composed of microporous hose. Each sensor is deployed with ultrasonic wind velocity, air temperature and humidity sensors. The temperature and humidity sensors were located 1 m above the ground. The wind sensor was 2 m above the ground. The infrasound and meteorological signals were digitized at 20 and 1 sps respectively using a 24 bit Reftek 72A-08 data acquisition system. Each system was run on solar power.

The Atlantic site surveys were preceded 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.

2.2. Preliminary Site Selection

In the Azores and in Cape Verde, 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 (Fig. 2). In this region, winds are strongly influenced by local pressure cells. In the summer a high pressure cell normally lies over the northern islands (Pedro Mata, meteorologist at Portugal's Instituto de Meteorologia). Clockwise air circulation brings winds to Sao Miguel from the northeast. For the rest of the year, western winds dominate. The faintness of the winds at the station in Ponta Delgada on Sao Miguel is at least in part due to shielding this large island provides from these winds. Sao Miguel is a 70×10 km island that has a population of 125,000. Topography on the island is dominated by three active stratovolcanoes, each of which has erupted at least once in the last 700 years (Panduronga Dessai, personal communication). The highest point on the island is the Agua de Pau volcanic center at 947 m. Eroded and vegetated mounds of soft welded tuffs or pumice dominate much of the fine-scale

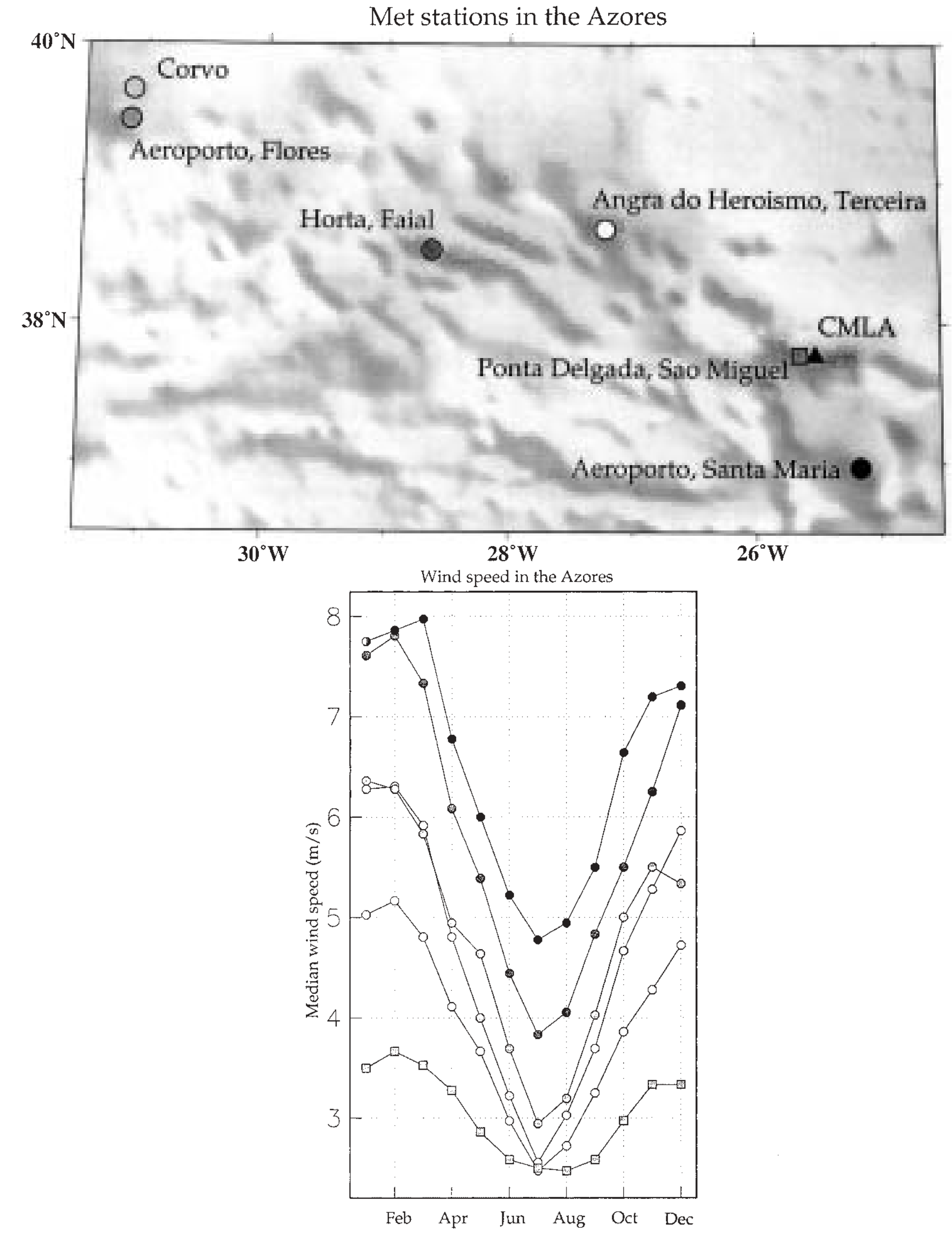

Figure 2

Meteorological data have been collected in the Azores for decades at the sites indicated above. As shown to the right, 30 year averaged wind speeds are strongly dependent on time and location. The square symbols represent wind speeds at Praia on Sao Miguel, the main island. The Met stations on the other islands are represented by the shaded circles. The shading is used to indicate the linkage between the curves on the right and the stations on the left. These data were collected between 1951 and 1980 and were published in "O Clima de Portugal", Instituto Nacional de Meteorologia e Geofisica, ISSN 0870-4767, 1991.

topography on this island. There are naturally occurring fumaroles in the east-central part of the island. The central, youngest, part of the island has no significant topography but is subject to relatively strong winds due to funneling around significant topography on both sides. All the islands in the Azores were once densely forested however they were settled in the 15th century and most of the trees have been cleared for agricultural or cultural use. Most of the flat areas on the island are a patchwork of stone walled pastures. Some dense forests exist in the more rugged areas. Most flat areas are a patchwork of pastures separated either by trees or rock fences.

The four survey points were selected to sample diverse means of reducing wind noise. A large, 5-km diameter, calderra exists at the west end of the island (Fig. 3). An eruption last occurred there in 1287 AD (Booth *et al.*, 1978). The small population within the calderra is concentrated in Sete Cidades. The calderra was chosen as a survey point as it is large enough to accommodate an infrasound array. The walls of the calderra reach 275 m high. With the survey we planned to quantify the noise reduction, if any, that results from shielding provided by the walls. Two other sites, Pinhal da Paz and Cha do Macela, were located in thick Criptomeria forests in rolling topography. The latter site was co-located with the GSN station CMLA and lies closest to the nominal infrasound station location. The exact nominal location was not surveyed as this area is densely populated (Fig. 3) and is the site of considerable hydrothermal activity. The fourth site, Cha das Mulas, was

Figure 3
Sao Miguel, Azores and the four 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.

situated on a broad plateau near the east end of the island. The plateau is ~580 m above sea level and has large pastures separated by rows of Criptomeria trees.

The Cape Verde archipelago comprises 9 major islands (Fig. 4). All but one is 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 four survey sites were located on this island in the forest in a 3-km aperture centered equilateral triangle (Fig. 5).

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.

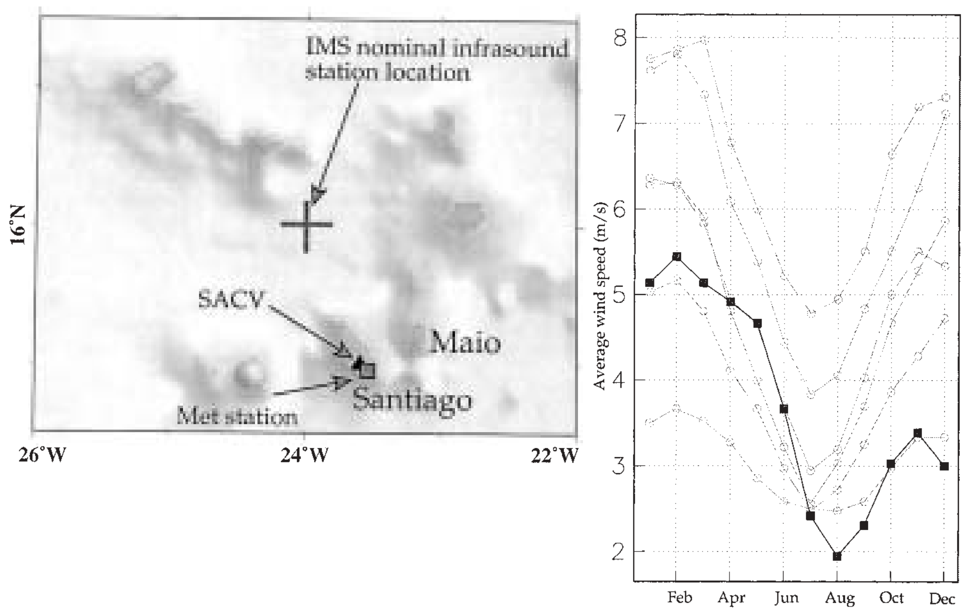

Figure 4
Meteorological observations have been made at Praia for decades. Seasonal trends in Cape Verde are similar to those in the Azores (right) however the wind in Cape Verde is dominated by the NE trades. Our survey occurred in January, a time of relatively strong winds. Meteorological data were taken from a 30 year study (O Clima de Portugal, 1931–1960).

Figure 5
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 four times the size of Ascension Island, the site of another nominal IMS infrasound station. The four survey points are in a forest of Acacia trees.

2.3. Preliminary Results from the Surveys

The four 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 (Figs. 1 and 4) for an additional three weeks of recording in January, 1999. Fifteen minutes of pressure and meteorological data from the Azores experiment are shown in Figure 6. The unfiltered pressure time series from the station at Cha das Mulas exhibits 30 s period fluctuations superimposed on

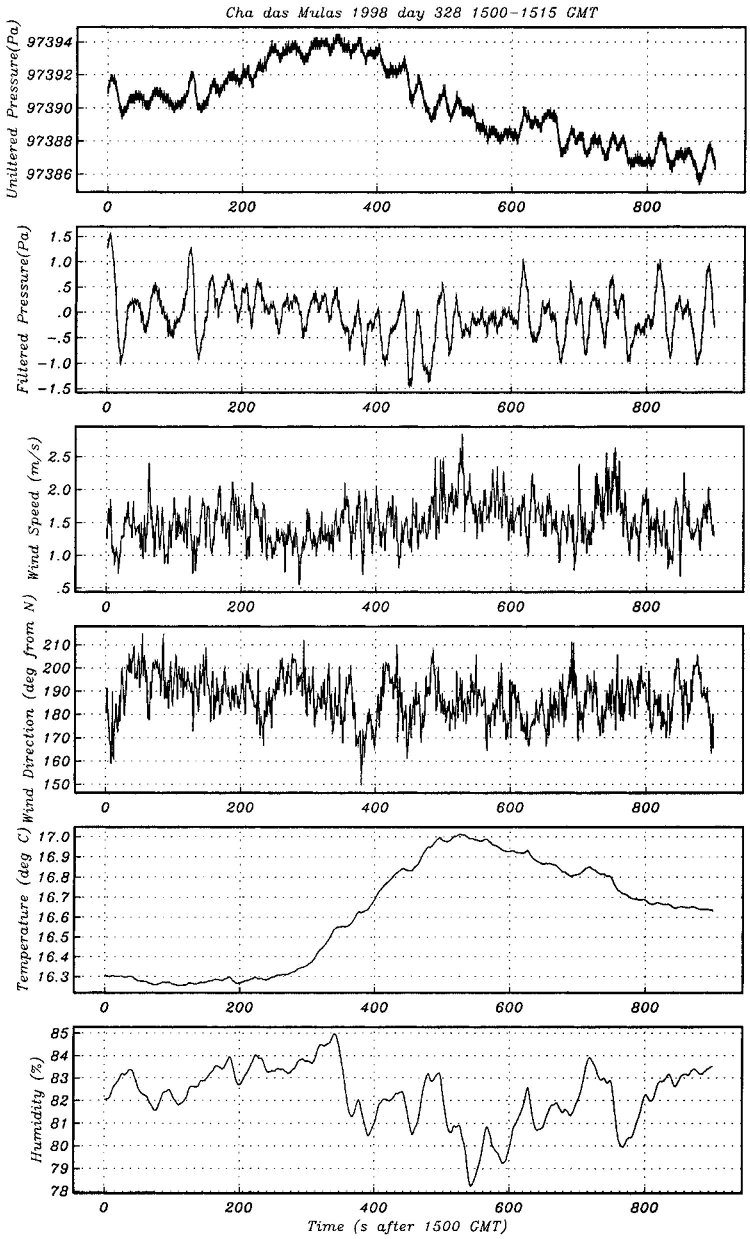

Figure 6
Atmospheric pressure and meteorological data from a 15-min interval starting at 15:00 GMT at Cha das Mulas. Raw and filtered pressure data are shown in the upper two panels. Wind speed, direction, temperature and humidity are shown below. As shown in the next figure, this is a time of relatively low infrasonic noise.

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. This detail is impossible to fully understand or predict. 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 four estimates, each taken from consecutive 204.8 s intervals. The power spectral density taken from the filtered record (Fig. 7) shows 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 peak at 30 s is somewhat misleading as it does not reflect an intrinsic lack of noise

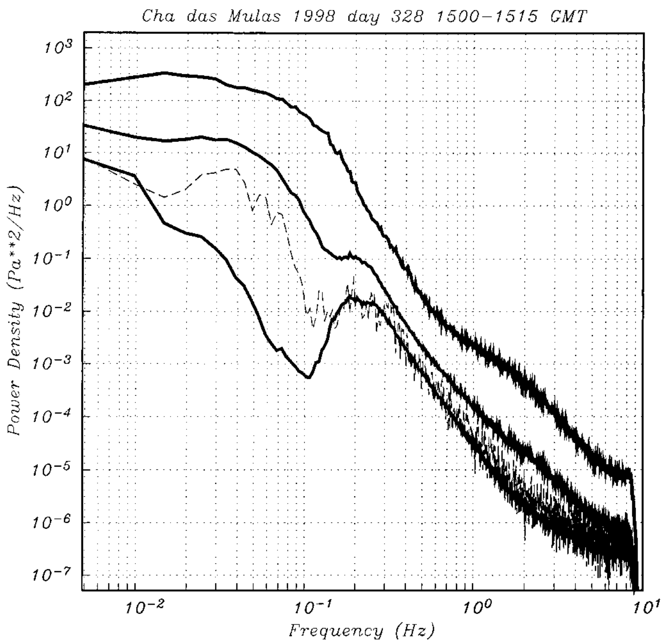

Figure 7

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 6. The thick 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.

power in the atmosphere at longer periods but is what remains after the sensor filter which bandpasses the raw signal to exclude energy below 0.01 Hz. The overall spectral shape is due to a well-known phenomena in the atmosphere which receives a significant 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 fragmented (KAIMAL and FINNIGAN, 1994).

From the full three weeks of recording at all four sites we calculated power spectral density at 454 time intervals. Each interval began at the turn of the hour and lasted 15 minutes. Tenth, 50th and 90 percentile noise levels at all frequencies from 0.005 Hz to 10.0 Hz are shown in Figure 7. At times of relatively low noise the microbarom peak is obvious at Cha das Mulas. This figure shows that the interval displayed in Figure 6 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 (Fig. 8). Median noise levels between 0.03 and 0.1 Hz are 5 to 10 dB lower in the calderra (thick dashed curve)

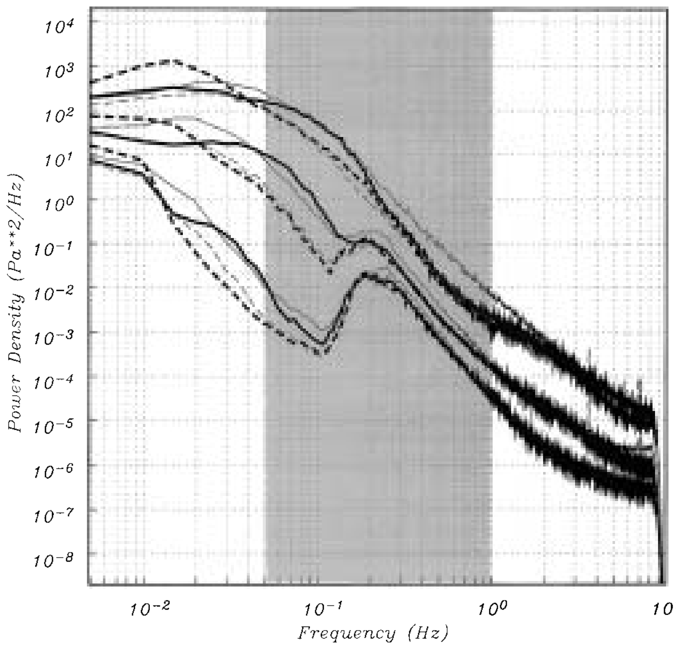

Figure 8
Tenth, 50th and 90th percentile noise curves at the four sites surveyed in the Azores. Noise levels in the calderra, at Pinhal da Paz, Cha da Macela and Cha das Mulas are represented by the thick dashed, thin dashed, thin solid and thick solid curves respectively. Between 0.02 and 0.2 Hz, noise at Cha das Mulas and Cha do Macela is 5 to 10 dB higher than in the calderra and in the forest at Pinhal da Paz. At higher frequencies, median noise levels are comparable at all sites. Most signals of interest to the monitoring community lie in the shaded region.

and in the forest at Pinhal da Paz (thin dashed curve) than on the plateau at Cha das Mulas (thick solid curve) and at Cha do Macela (thin solid curve). At 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.

As expected, the noise power in the band between 0.005 Hz and 10 Hz is highly dependent on wind speed. In Figure 9 we display the power spectral density at several frequencies between 0.02 and 5 Hz as a function of wind speed. The wind speeds depend strongly on the site. In the calderra, the winds at an elevation of 2 m reach ~2.5 m/s. The winds are strongest in the forest at Cha da Macela where they reach 6.8 m/s. The winds are slightly weaker on the plateau at Cha das Mulas (max.

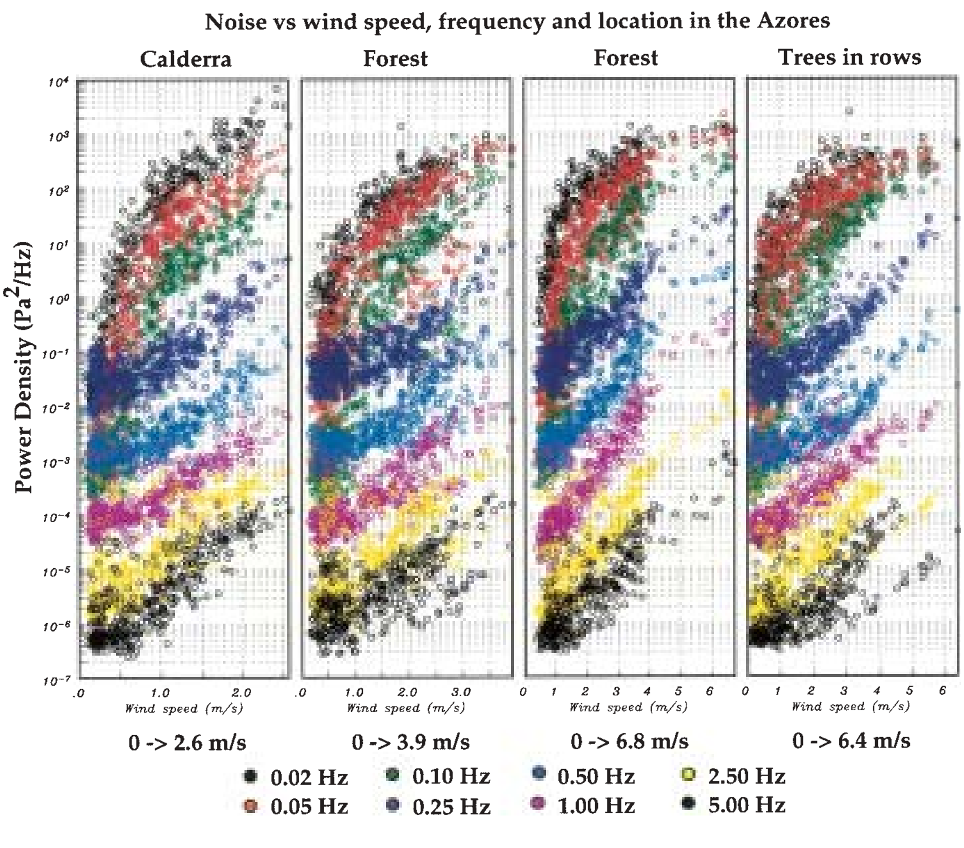

Figure 9

The four panels above show the strong dependence of infrasonic noise on wind speed and frequency at the four sites in the Azores. 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). The wind speeds are relatively slight in the calderra however this doesn't appear to have yielded much of a noise reduction. Long-period noise levels are elevated at this location.

6.4 m/s) and are somewhat weaker in the forest at Pinhal da Paz where they reach a maximum of 3.9 m/s. Winds in the calderra are sharply reduced by the walls of the calderra which are 200 to 300 m above the central floor. The forest at Cha da Macela is thick however this location is adjacent to the topographically low, central, part of the islands where winds appear to be relatively strong. Figure 9 shows that the infrasonic noise at all frequencies between 0.02 and 5 Hz depends strongly on wind speed however the dependence is complicated by the highly variable wind azimuth (Fig. 10; left panels). In the Azores, mobile pressure cells dominantly influence local wind and thus the wind direction is highly variable. This variability is strongly dependent on receiver location. As a result, at each site there is a time-variant interaction of wind flow and local topographic features and thus the more complex scaling of wind power with wind speed (Fig. 9). The winds are weakest in the calderra, however at this location the noise power at long periods increases most rapidly with wind speed. The noise power increases relatively slowly at Cha das Mulas. This is likely because of the remoteness of this site from any rugged topography.

In Cape Verde the spectral character of the infrasonic noise is markedly different. The noise percentiles, taken from 400-hourly segments of data, are shown in Figure 11. In Cape Verde the noise levels are comparable to those in the Azores however the microbarom is not often sensed . It is not seen at any of the stations on the tenth percentile curves or above. This difference is unlikely due to proximity to the surf zone. The stations on Maio were between 3 and 6 km from the coast whereas the sites on Sao Miguel were located 4 to 8 km from the coast. The loss of the microbarom is due to the winds at Cape Verde which rarely fall below 1 m/s. As shown in Figure 11, at the times of lowest winds the microbarom is seen clearly. Considering all four sites together, this occurred less than 2% of the time and only when the 15 min average wind speed dropped below 0.3 to 0.4 m/s. The winds reached this level most often ($\sim$3% of the time) at MAO2 in the thickest part of the forest.

At Cape Verde the wind azimuth is relatively constant (Fig. 10; right panels) and there exists a simple dependence of infrasonic noise levels on wind speed (Fig. 12). As wind speeds at Cape Verde are relatively constant, the most significant source of variability in infrasonic noise levels is the diurnal effect (Fig. 13; right panel) 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. Our survey indicates that significant wind speed and noise level variations are common in the Azores in the early winter. The experiment in November and December 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. Commensurate noise power increases of 40 to 50 dB occurred. Noise levels vary far more strongly with time than location. Periodically, any infrasound station on Sao Miguel will be "deafened" by wind noise. At times of high wind, the microbarom noise is obscured. Rapid changes in wind speed and noise

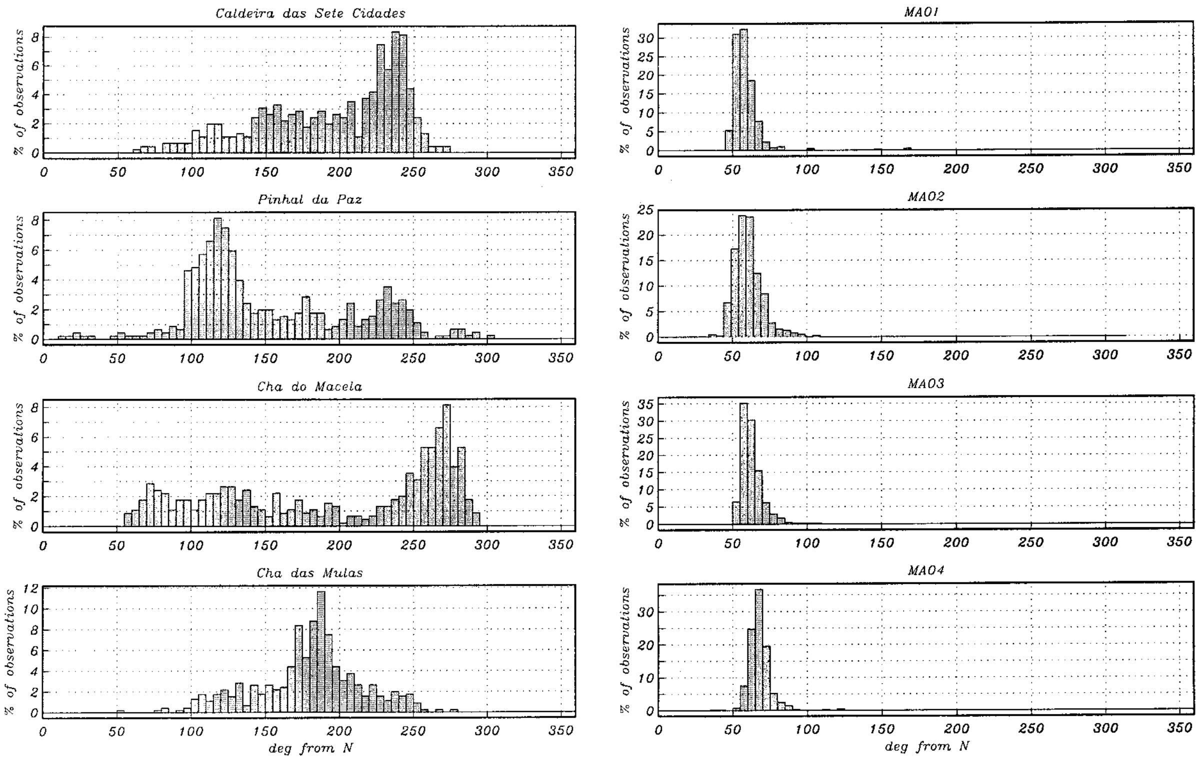

Figure 10
Wind direction at the 8 sites in the Azores and Cape Verde. In Cape Verde, the northeast trade winds dominate whereas in the Azores, wind is influenced by moving pressure cells.

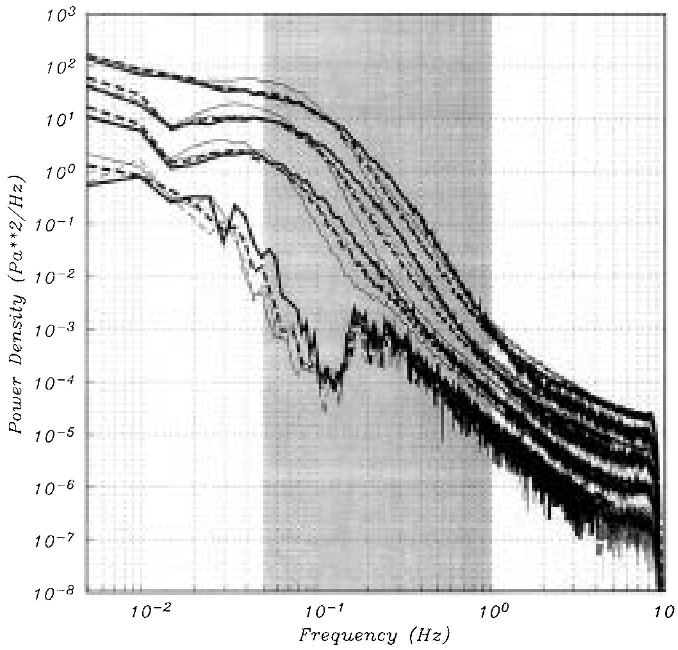

Figure 11
Minimum, 10th, 50th and 90th percentile noise curves from the Cape Verde experiment. The noise levels at MAO1, MAO2, MAO3 and MAO4 are indicated by the thick dashed, thin solid, thick solid and thin dashed curves, respectively. The four sites were located within 3 km of each other. MAO2 was located in the thickest part of the forest. MAO3 was located closest to the coast (Fig. 5) however MAO2 was just slightly further inland. The microbarom is seen just at times of minimal noise. Most signals of interest to the monitoring community lie in the shaded region.

levels, and thus in the effectiveness of any infrasonic station to sense signals from distant events, are not uncommon, at least in the winter in the Azores.

3. Discussion

3.1. Forests and Infrasonic Noise Reduction

Cape Verde is an excellent, natural, laboratory for the study of 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° (Fig. 10). The wind-topography interaction is relatively time invariant when the wind azimuth remains constant. As we see in Figure 12, these "wind tunnel" conditions produce a simple scaling between wind speed and wind noise at all frequencies from 0.02 to 5 Hz. Infrasonic noise levels are easily predicted (Figs. 12 and 13).

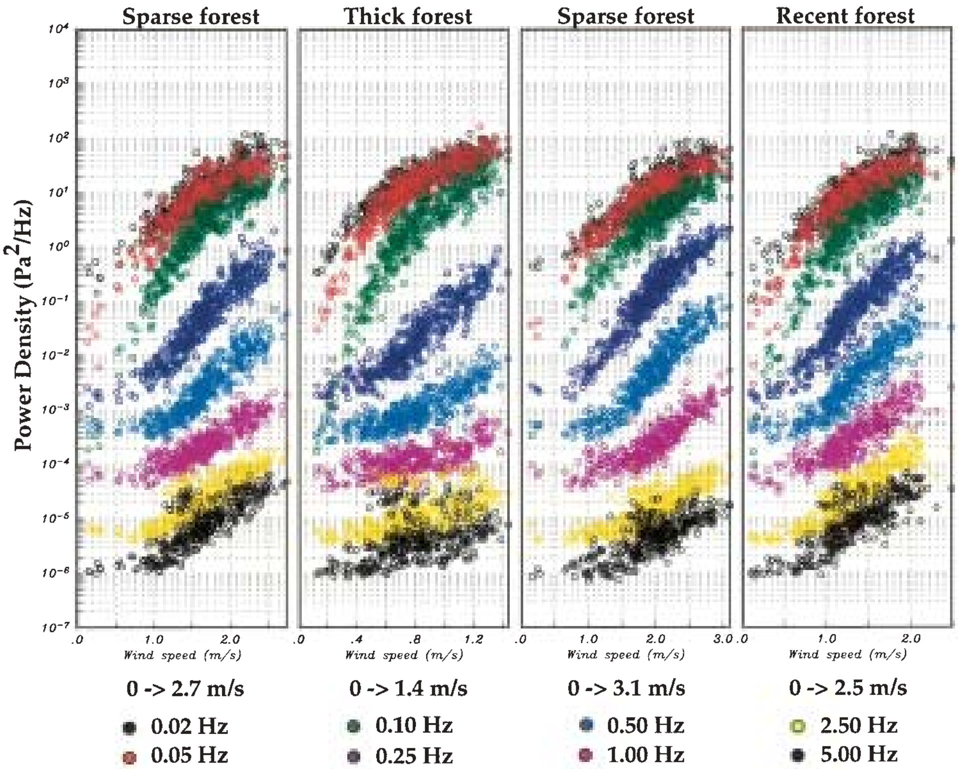

Figure 12
Noise power as a function of wind speed and frequency at the four locations on Maio. Wind speeds in the thickest forest on Maio, which at MAO2 are lower than elsewhere, however noise power is not reduced at frequencies lower than 0.25 Hz. Winds are weakest in the thickest part of the forest at MAO2. Noise power has a relatively simple dependence on wind speed.

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 1950s 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 12, wind speeds (at an elevation of 2 m) at MAO2 are sharply reduced. The maximum wind speed at this location is ~1.4 m/s whereas 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 12, at frequencies below 0.25 Hz there is no concomitant reduction in noise levels. For example, at all locations infrasonic noise at a period of 20 s ranges from 0.01 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

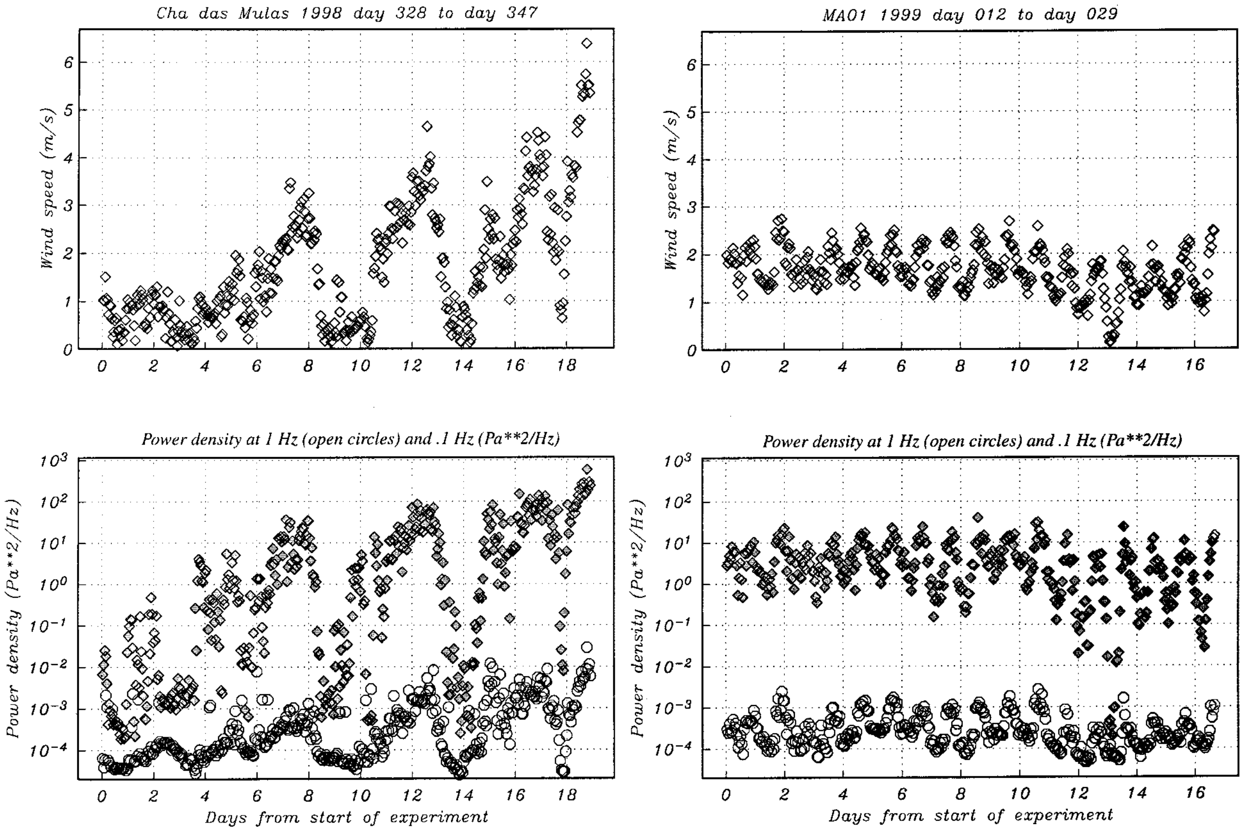

Figure 13

Noise power and wind speed as a function of time at one station in the Azores (left) and in Cape Verde. In the Azores, wind noise at 0.1 Hz (upper sequence of points in the lower panel) and at 1.0 Hz track closely the wind speed. Severe winds during a storm near the conclusion of the Azores experiment lead to wild swings in the noise level. At times, any infrasound station on the island will be deafened by the wind. In Cape Verde, diurnal variations are relatively slight.

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 clearly reduces 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 indicates that at frequencies at and above 1 Hz, noise levels in the thick forest 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 (Figs. 11 and 12).

The "wind tunnel" experiment in Cape Verde indicates that wind near the ground is not the cause of infrasonic noise at periods greater than 4 s. The most likely source of this noise is turbulence in the atmospheric boundary layer above the forest.

In the Azores, the dependence of infrasonic noise on wind speed is complicated by the azimuthal variations of the wind (Fig. 10). As shown in Figure 9 there is more scatter of noise estimates about a general trend to increased power at higher wind speeds. It is clear, however, that wind noise scales with wind speed as it does in Cape Verde. In the thickest forest at Pinhal da Paz, the wind speeds at an elevation of 2 m are reduced sharply (relative to Cha do Macela and Cha das Mulas) however the infrasonic noise levels at frequencies below 0.1 Hz are not also sharply reduced. Figures 8 and 9 indicate that the thick Criptomeria forest at Pinhal da Paz reduces noise levels between 0.05 and ~0.1 Hz by 5 to 10 dB when winds are above average. Most trees at this location are mature and reach ~25 m.

The forest is effective at reducing wind speeds. For example, at Pinhal da Paz, the maximum wind speed was 3.9 m/s and at Cha das Mulas the maximum wind speed was 6.4 m/s. At the peak wind speed, noise levels at Pinhal da Paz between 0.05 and 0.25 Hz were ~5 dB lower than at Cha das Mulas. However it is clear that the forests are not dissipating all the energy at these frequencies. The noise power in this band at Cha das Mulas when wind speeds were ~3.9 m/s was 5 to 15 dB lower than the peak.

3.2. 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 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 9 indicates that noise levels are clearly increased at 0.02 Hz and suggests the presence of unusually energetic large-scale turbulence in this area. Figure 8 displays essentially the same result as it indicates that this noise enhancement at ~0.02 Hz is most pronounced on the 50th and 90th percentiles, i.e., when noise and wind speeds are elevated. 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 effectively reduces 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 (Fig. 8). As discussed in the previous section, at times of elevated winds, the calderra walls reduce wind speed although no notable reduction in infrasonic noise levels results (Fig. 9).

3.3. Final Site Selection

Choosing a site for a 1 to 3 km aperture infrasound array on an oceanic island is far from trivial. Infrasonic noise levels can vary sharply across a topographically rugged island. Aside from purely technical considerations, there are a number of practical issues such as land availability. Each array element is to be equipped with a noise reduction system that might span an area as much as 70 m across. Some nearby infrastructure (such as power lines, airports, etc.) should be in the vicinity of the array but not too close so as to influence noise levels. The two site surveys in this paper perhaps shed light on some of the difficulties inherent in the selection process.

3.3a Azores

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 ample space to deploy array elements at the same elevation, there are unobstructed views to the horizon from most points. There is minor cultural activity and the site is relatively far from the ocean. A lush grass covers most of the plateau. Long rows of trees interrupt wind flow.

Median noise levels in the calderra on Sao Miguel are comparable to those at Cha das Mulas at all frequencies except between 0.03 and 0.1 Hz where the median noise levels in the calderra are 5 to 10 dB lower (Fig. 8). Most signals of interest lie between 0.05 and 1.0 Hz (PTS summary) and therefore this discrepancy could be important. Because of the 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 12, 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 (Fig. 8). 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 (Figs. 3 and 9). 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 (Fig. 3) 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 (Fig. 13) 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 winter when storms are not uncommon.

3.3b Cape Verde

Due to limited options, the Cape Verde survey points were all located together on Maio. Because of topography, 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 that thick forest reduces wind speed, however just as in the calderra in the Azores, the wind noise was not substantially reduced at long periods (Fig. 11). The best site for an infrasound array on this island is in the oldest, thickest, part of the Acacia forest near the site MAO2.

3.4. Recommended Arrays for these Oceanic Sites

There is an ongoing discussion regarding optimal designs for an IMS infrasound array. Given the constraint which will hold at most sites that no more than four elements are to be used, it is generally accepted that the best array is an equilateral triangle with one element at the center. At locations where infrasonic noise levels are high, the constraint on the number of elements will likely be loosened and as many as 8 will be allowed with the extra 4 sensors placed with the fourth at the center in a micro-array 200–300 m across. The aperture of the array is still an open issue. The PTS site survey summary (CHRISTIE, 1998) puts bounds on the acceptable array aperture at 1 and 3 km. Larger arrays will permit more accurate estimates of the source azimuth but only if the signal is coherent between the stations. At some sites where signals of interest will typically lie above noise and if the peak signal amplitudes lie at periods significantly longer than 1 s, a 3-km aperture might be optimal. It is expected that due to the frequency of the signals of interest and because of high-noise levels, infrasound arrays at most sites will have to be smaller than 3 km. A lower limit on the aperture of an effective infrasound array exists because of the loss of resolution at the lower apertures and owing to the microbaroms. An analysis of coherence (MACK and FLINN, 1971; BLANDFORD, 1997) indicates a 1-km aperture array gives the best overall balance between signal and microbarom coherence. In areas where the coherence drop-off of energetic microbaroms is slow, a 2-km array will be preferred. At sites where land is scarce (e.g., oceanic islands) nontechnical issues, such as land usage permits and topography, might render the scientific debate pointless.

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 sites in a microarray at the center.

3.5. The Utility of Infrasound Site Surveys

Because of limited resources and manpower, the standard infrasound site survey lasts just 2 to 3 weeks. This provides 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 surveyor 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, climatic 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 turbulence 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 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 and Cape Verde surveys appear to be in line with long-term observations. Both surveys occurred at times of elevated winds, nonetheless these winds were as expected from historical data. There is no reason to believe that these winter surveys are misleading.

Another argument in favor of brief surveys, other than cost, is that a survey is not used to decide whether or not to locate a station near the nominal coordinates but simply to decide where. It is not necessary to survey for an entire year to be able to judge overall performance of the location, just relative performance of candidate sites.

3.6. 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 – only a subset are of interest to us. Other sources such as earthquakes, rocket launches, volcanoes are easily identified using other means and are infrequent. 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 although 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 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 spatial 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 four 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; COLLINS *et al.*, 1995; NORRIS and GIBSON, 1999) should lead to improvements in estimating global monitoring thresholds as a function of time.

4. Conclusions

A three-week noise survey gives just a glimpse of the full range of meteorological conditions that will occur in a typical year. The survey should, however, reveal any serious discrepancy in noise levels that will render one site inferior to all others. Our survey found no significant noise level discrepancies between any site in the Azores and in Cape Verde.

In the Azores, at least in the early winter when our survey was conducted, noise level swings of 40 to 50 dB at 0.1 Hz are not uncommon. Any permanent infrasound array in this region will be periodically rendered ineffective at all frequencies of interest to the monitoring community. In Cape Verde, noise levels are relatively constant to the dominance of the NE trade winds over local air pressure systems. The most significant factor causing change in infrasonic noise levels is diurnal.

In the Azores, the preferred site is Cha das Mulas, the site that offers the most options for siting array elements. If array modifications are necessary, this area presents no limitations to what could be considered. The preferred location in Cape Verde, on the island of Maio, offers a similar degree of flexibility. In both the Azores and Cape Verde, it is clear that winds will be higher, on average, than at most continental sites. For this reason, it is also clear that these locations will require more array elements. For this reason 2-km aperture, 8-element arrays are recommended for both locations.

One goal of these site surveys was to quantify the infrasonic noise reduction possible in forests and in a large calderra. Our surveys provided evidence that topography and ground cover will reduce wind speed but will not affect noise levels at long periods (above 4 to 10 s). Noise at longer periods clearly stems from air flow at an elevation beyond the reach of the topography and forests we have considered in our surveys. Noise reduction at these periods might be beyond the reach of any practical noise suppression scheme.

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