INFRASOUND STATION AMBIENT NOISE ESTIMATES

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Science Applications International Corporation

Sponsored by Army Space and Missile Defense Command

Contract No. DASG60-03-C-0009

ABSTRACT

The main objective of this study was to characterize, for the first time, the noise environment of all existing infrasound stations using a standard methodology to enable meaningful comparisons among stations and to provide noise estimates for use in network detection simulations. Spectral amplitudes were measured for the central site of all 21 infrasound arrays for which data were available. Of these stations, 16 were part of the International Monitoring System (IMS) and 5 were research stations in North America. Power Spectral Densities (PSDs) were estimated for 21 consecutive 3-minute segments of data taken four times daily, beginning at 06:00, 12:00, 18:00, and 24:00 local time from January 2003 through January 2004. Three-minute windows were used to minimize smoothing of the amplitude distributions while permitting estimation of the longest periods of interest. For stations that had both high- and low-frequency sites, spectra were estimated separately, one site for each type. Spectra were corrected for instrument responses contained in the station database of the Space Missile Defense Command (SMDC) monitoring research program. More than 614,000 spectra were calculated and displayed in 16 plots per station (four times a day for four seasons) for frequencies from 0.03 to 7 Hz. This effort utilized the spinning disk mass-store archive of the SMDC monitoring research program, a unique resource providing researchers with almost instantaneous access to more than 12 terabytes of IMS and other waveform data.

The ambient noise at infrasound stations is highly variable by season, time of day, sensor type and station. For example, noise spectra for individual stations may vary by more than four orders of magnitude at any given frequency across the frequency band analyzed. At station I07AU (central Australia) the median noise PSDs for 6-7 AM below 1 Hz are similar for winter, spring and autumn, but are about an order of magnitude lower for summer. At I07AU the median PSDs for summer are about an order of magnitude higher at noon than at dawn, dusk or midnight. The microbarom peak is generally not observable above the level of other noise at I07AU, but at the quietest time of day (midnight) for the quietest season (summer), the microbarom peak is seen clearly. Ambient noise can vary significantly for the high- and low-frequency sites at I57US (Piñon Flat, California). Noise recorded by the two site types is almost identical between 0.1 and 1 Hz at midnight in January, but is a factor of three times higher on the low-frequency sites in July.

Drawing conclusions from comparisons among stations is difficult because of the variation with time of day, season and frequency. With that caveat, we compared the median PSDs of high-frequency sites during the winter months from 6 to 7 AM and from noon to 1 PM. Noise levels vary among stations by 1 to 2 orders of magnitude. Noise levels are less variable among stations in the 0.1 to 1 Hz band than they are at lower or higher frequencies. The quietest stations in the 0.1 to 1 Hz band appear to be DLIAR (New Mexico), I17CI (Ivory Coast) and TXIAR (Texas), whereas the noisiest stations appear to be I07AU (Australia), I26DE (Germany) and I33MG (Madagascar).

Inspection of noise PSDs uncovered anomalies with instrument responses for 9 of the 21 stations studied. Quantitative analysis of infrasound data relies on accurate knowledge and representation of station instrument response characteristics. This study demonstrates the utility of examining noise to help identify incorrect instrument response descriptions.

OBJECTIVE

The objective of this study was to characterize, for the first time, the noise environment of all existing infrasound stations using a standard methodology. The results allow meaningful comparisons among stations and provide noise estimates for use in network detection simulations.

RESEARCH ACCOMPLISHED

The ambient noise at infrasound stations is highly variable over time and among stations. Ambient infrasound noise is dominated by pressure fluctuations due to local winds and by long-range pressure fluctuations generated over the oceans (microbaroms). Station-dependent factors that contribute to the ambient noise include climate, station latitude and position relative to oceans, local topography, local noise sources, vegetation or snow cover at the sensor sites, and sensor and wind noise suppression filter configurations. In order to characterize the ambient noise, spectral amplitudes were measured at one site of 21 arrays (Figure 1) using an approach similar to that of Bahavar and North (2002). Data were analyzed from January 20, 2003 through January 31, 2004, from 21 consecutive 3-minute segments of data taken four times daily, beginning at 06:00, 12:00, 18:00, and 24:00 local time. Three-minute windows were used to minimize smoothing of the amplitude distributions, while permitting estimation of the longest periods of interest. Some stations have high- and low-frequency sub-arrays with different noise suppression filters at high- and low-frequency sites; for these stations spectra were estimated separately for one site of each type. Spectra were calculated using *geotool* (Coyne and Henson, 1995) and applying a Hanning taper to the outer 10% of each data window. Spectra were corrected for instrument responses contained in the station database of the SMDC monitoring research program.

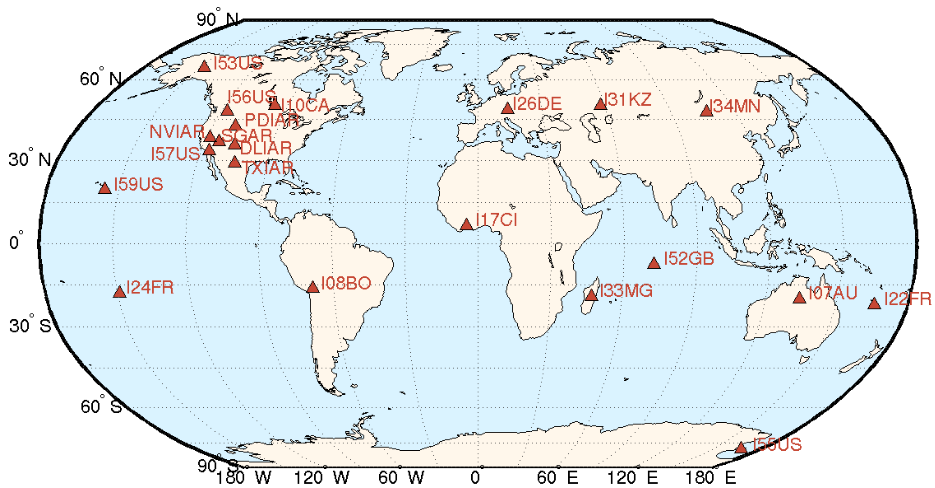

Figure 1. Infrasound stations for which noise was estimated.

Spectral Amplitudes of Noise

Plots of Power Spectral Density (PSD) for noise in four seasons and at four times of day are shown in Figure 2 for station I08BO in Bolivia. Southern hemisphere seasons are defined as summer: December 21-March 20; autumn: March 21-June 20; winter: June 21-September 20; and spring: September 21-December 20. Northern hemisphere seasons are reversed. All spectra calculated for each time and season interval are plotted as yellow lines, the median for each interval as a black line, and the 5^{th} and 95^{th} percentiles of the distribution as red lines. Green lines show the median of all spectra for all project stations, times and seasons (except those with anomalous instrument responses), and serve as a reference for comparison among time and season intervals and among stations. At all frequencies the amplitude varies among the I08BO spectra by 4 orders of magnitude. The median noise level is similar to the network median for some times, such as 6 PM in winter, but is almost 2 orders of magnitude higher than the median at others, such as noon in the spring. Plots similar to Figure 2 are provided for all 21 available stations in Bowman et al. (2004).

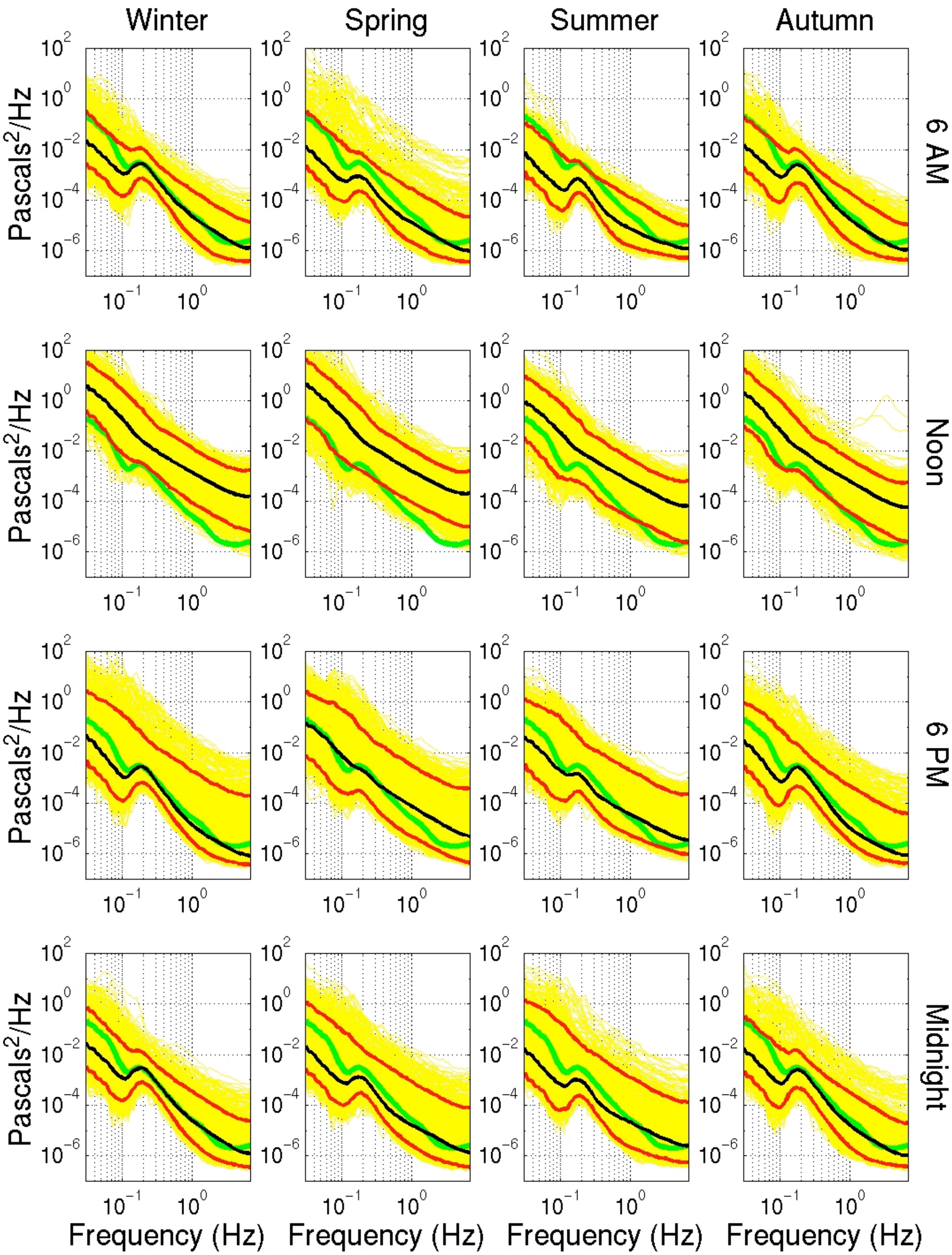

Figure 2. Power spectral density for I08BO, La Paz, Bolivia.

Plots are of power spectral density of individual time segments (yellow), the time and season specific station median (black) with 5th and 95th percentile confidence limits (red), and the all-time network median (green). The rows group plots by time intervals: 6 to 7 AM, 12 to 1 PM, 6 to 7 PM, and 12 to 1 AM local time. The columns group plots by seasons: winter, spring, summer, and autumn. Data were collected for I08BO from March 7, 2003 through January 31, 2004. Note that at any time, season and frequency the PSD varies by four orders of magnitude.

Several of the features seen in the noise spectra are highlighted here. Figure 3 shows the median power spectral densities recorded between 6 and 7 AM during each season at station I07AU in central Australia. The median PSDs vary seasonally by as much as an order of magnitude over most of the spectral range. The microbarom peak is only identifiable during summer, and then just barely, at this noisy station.

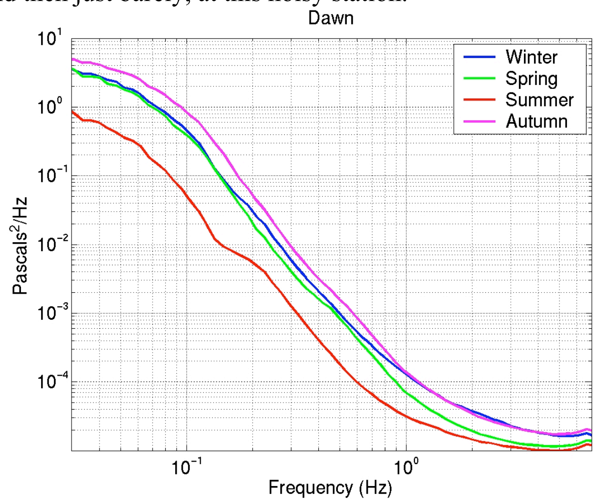

Figure 3. Median noise PSD from 6 to 7 AM during each season at I07AU, Warramunga, Australia. Noise levels are substantially lower in the summer than in the other seasons.

Figure 4 shows how the time of day can affect noise amplitudes at a single station. At I07AU the median power spectral density of noise at most frequencies is more than an order of magnitude larger around noon than at other times, although from 1 to 4 Hz, it drops dramatically to the quietest levels. The change in spectral slopes with time of day and frequency suggests that different processes may control the noise amplitudes at different frequencies, and those processes are most active at different times of day.

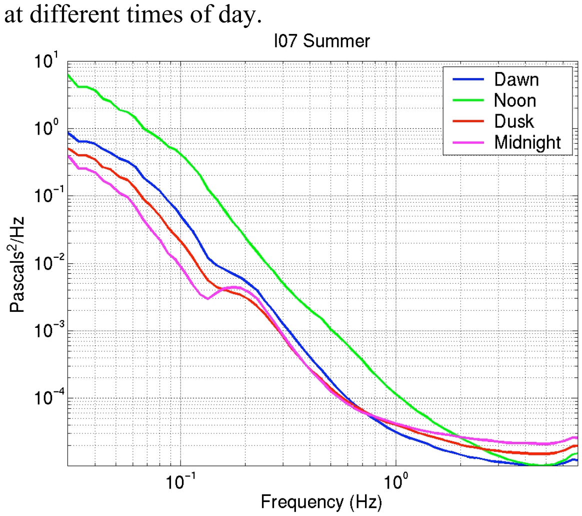

Figure 4: Median noise PSD during summer at four times of day at I07AU,Warramunga, Australia. Noise is substantially higher at noon than other times of day.

Figure 5 provides another example of seasonal variations in noise amplitudes and shows the effect of different spatial wind noise reduction filters on noise measurements at I57US, at Piñon Flat, California. It shows median pressure power spectral density recorded at midnight in January and July at nearby sites with high- (green) and low- (purple) frequency wind noise reduction filters. The filters are 18-m and 70-m pipe rosettes for the high- and low frequency sites, respectively (Hedlin et al., 2003) and were designed to suppress incoherent noise.

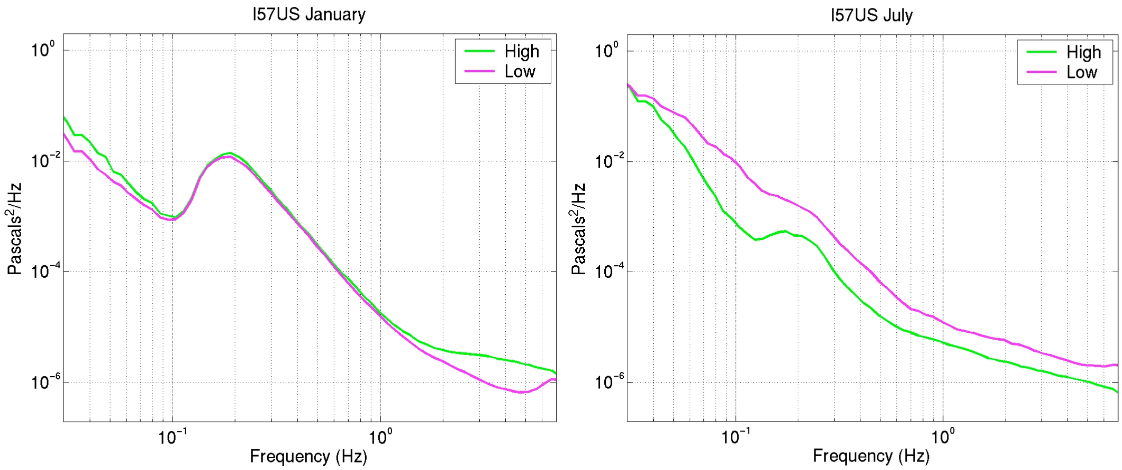

Figure 5. Median noise PSD at high- and low-frequency sites at I57US, Piñon Flat, California. Plots show noise from midnight to 1 AM during January (left) and July (right). Noise observed by the two nearby sensors with different spatial filters is almost identical between 0.1 and 1 Hz in January, but the noise observed at the site with the low-frequency filter is about a factor of 3 higher than the high in July.

Noise levels at the high- and low-frequency sites of I57US are similar in some passbands and seasons, and different in others. The left panel of Figure 5 shows noise for January. Microbaroms, centered at 0.2 Hz, are prominent at I57US during this winter month, because of the station's proximity to the ocean and its lower overall noise level compared to I07AU (Figure 3). Microbarom levels are nearly identical on the high- and low-frequency sites from 0.1 to 1.0 Hz, suggesting that they span both the high- and low-frequency sites. Microbaroms are acoustic waves, distinct from the pressure variations advecting past the sensors that are the likely sources of noise at other frequencies. We expect the high-frequency site's spatial noise filtering to perform worse at low frequencies, where noise may be coherent across all or most inlets, and this prediction appears to hold below 0.1 Hz in January. Noise amplitudes at the high-frequency site above 1.0 Hz are also higher than those at the low-frequency site, showing that the 70-m pipe rosette more completely suppresses uncorrelated noise.

The right panel of Figure 5 shows noise for July. The noise level above 0.03 Hz at the high-frequency site is much lower than that at the low-frequency site. The high-frequency site (I57H1) is surrounded by Piñon pine trees (Hedlin et al., 2003), which may reduce the wind velocity and therefore the noise compared to the low-frequency site (I57L1).

These observations provide an important reminder that the response of the noise reduction filters is not being taken into account, so the measurements recorded are not of pressure at the ground, but of pressure sampled at the many filter inlets and convolved with the filter response. The different responses of the noise reduction filters used at each installation may be responsible in part for the apparent differences in noise amplitudes and the falloff of noise with frequency.

The variability in noise levels at different stations and at different times of day is illustrated in Figure 6, which shows the median amplitude spectra of high-frequency sites at each station during the winter months, from 6 to 7 AM. PSDs are shown for 18 stations and are partitioned alphabetically. (Insufficient winter data were available for the other three stations.) A number of interesting observations can be made from these plots. One is that microbaroms, with a peak at 0.2 Hz, define a lower bound on the noise level at most stations and times of day. For stations where the microbaroms do not stand out, other sources of noise may be dominant. Second, although resonance within the pipe arrays typically peaks around 8 Hz, a broad pipe resonance may affect the background noise at lower frequencies for which we would like to detect signals of interest. For example, the noise level stops decaying at a rate of 1/f somewhere around 1 Hz at station I10CA in Canada and I26DE in Germany and by 4 Hz starts increasing towards the pipe resonance peak. In addition, the PDIAR station in Wyoming appears to have a reverberation peak at about 3 Hz.

At some stations, the noise level varies little with time of day, for example at I26DE and PDIAR. At others it varies considerably. For example, I24FR (Tahiti) is an order of magnitude noisier at noon than at dawn over all frequencies. It appears that diurnal wind noise intensity at many stations repeats from day to day. In contrast, noise levels at I55US (Windless Bight, Antarctica) do not exhibit diurnal variation, because of the station's extreme southern latitude.

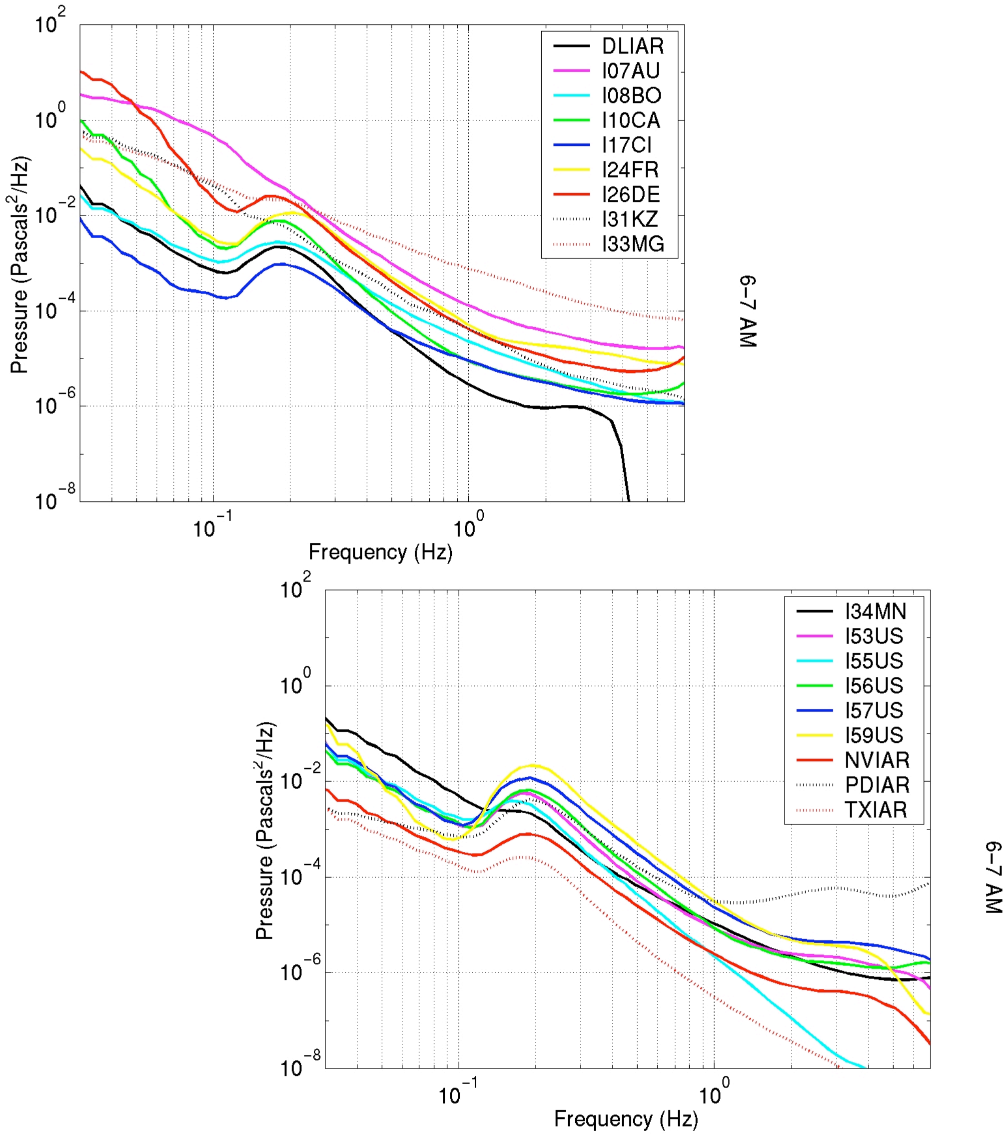

Figure 6. Comparison of wintertime power spectral density from 6 to 7 AM for project infrasound stations. Curves are median power spectral densities of noise between 6 and 7 AM during winter at high-frequency sites. Stations are divided alphabetically among the upper and lower plots for easier identification. The microbarom peak is clearly seen near 0.2 Hz at all stations except I33MG and I07AU. No winter data were available at I22FR, I52US, or SGAR.

From 6 to 7 AM, the noise level at I55US is in the middle of the range of spectral amplitudes at the microbarom frequencies and below, but falls off dramatically at high frequencies. The sharp drop may be due to generally low winds, the spatial filters, or the effect of snow cover that would filter wind noise when the snow is deep. Typically, the spatial filters must be extracted from under approximately 1.5 m of snow every year.

Instrument responses and electronic filters are also not consistent among stations. Some may be in error. The non-IMS stations SGAR (Utah) and PDIAR appear to be high-pass filtered, with much of the noise filtered out below 0.1 Hz. The high corner at the non-IMS station DLIAR seems to be at 3 Hz. Many of the stations appear to use low-pass, presumably anti-aliasing, filters with different high-frequency corners that are not properly represented in the station database. Furthermore, no correction has been made for spatial wind noise reduction filters, which may affect details of frequency response as well as the calibration value at the calibration period.

The seasonal variability of amplitudes at a single station, and the variation among stations, can be seen in Table 1, which lists the median amplitudes at 6 to 7 AM local time, for each season, at 0.2 and 1.0 Hz, for all high-frequency stations. The last row shows the ratio between the highest and lowest noise levels for stations in this season and passband. Dashes indicate times with no data or when gains were in doubt. Amplitudes at 0.2 Hz reflect the effect of microbaroms. The seasonal effect is generally stronger at 0.2 Hz than at 1 Hz. For example, at DLIAR the median amplitude at 0.2 Hz increases by a factor of 3 from summer to winter, while the 1 Hz noise is unchanged. PDIAR has by far the greatest change in 1 Hz median amplitude, dropping by a factor of 5.7 from autumn to winter, possibly due to snow cover. The corresponding drop at 0.2 Hz is by a factor of 3.5.

Table 1. Noise Amplitudes in Millipascals/Hz$^{1/2}$ by Season for High-Frequency Sites

Station	Spring		Summer		Autumn		Winter	
	0.2 Hz	1.0 Hz	0.2 Hz	1.0 Hz	0.2 Hz	1.0 Hz	0.2 Hz	1.0 Hz
DLIAR	–	–	15.5	1.7	37.9	1.8	44.6	1.7
I07AU	145.6	8.4	76.4	5.7	228.6	11.8	192.0	12.4
I08BO	27.5	3.7	24.2	2.7	48.8	4.4	48.7	4.8
I10CA	28.9	2.2	20.2	2.2	47.9	3.0	82.5	3.0
I17CI	21.4	1.8	30.2	3.0	20.3	1.3	15.5	1.3
I22FR	68.8	4.8	111.9	6.2	–	–	–	–
I24FR	80.4	6.5	102.6	5.7	121.4	6.5	109.2	8.8
I26DE	26.7	3.2	19.7	2.5	88.1	5.9	139.6	6.5
I31KZ	–	–	16.7	2.4	41.6	5.2	69.3	6.4
I33MG	71.6	14.0	89.8	11.6	100.6	14.5	130.3	26.5
I34MN	40.0	7.3	50.3	8.6	46.4	5.2	43.5	3.3
I52GB	–	–	–	–	43.6	4.4	–	–
I53US	22.5	1.5	15.4	1.5	61.2	3.0	69.7	3.0
I55US	33.4	0.8	36.8	0.8	67.0	1.6	49.9	1.3
I56US	18.8	1.8	15.0	1.4	50.4	3.0	79.6	3.0
I57US	–	–	25.6	2.5	109.5	5.3	104.8	4.9
I59US	48.0	2.9	30.0	2.9	94.8	4.4	145.3	5.7
NVIAR	16.2	2.3	8.8	1.2	23.7	1.6	27.4	1.6
TXIAR	13.2	1.2	11.9	1.1	16.3	0.7	15.3	0.6
PDIAR	120.1	24.5	123.0	31.7	217.7	31.7	63.0	5.6
SGAR	65.4	12.0	–	–	–	–	54.6	4.5
Ratio max/min	11.3	30.6	14.0	39.6	14.0	45.3	12.5	44.2

The maximum noise variations among stations range from 11 to 14 at 0.2 Hz and 30 to 45 at 1 Hz, depending on the season. The noise is generally higher in winter than summer by an average factor of 3 at 0.2 Hz and 2 at 1 Hz, although at I17CI, 134MN and PDIAR, the noise is higher in the summer at both frequencies.

In the course of this investigation, inspection of noise spectra uncovered a number of problems with instrument responses and gains, summarized in Table 2. This demonstrates the utility of examining noise to confirm proper operation of stations and to help to verify instrument response descriptions.

Table 2. Calibration Problems Identified at Network Stations

Station	Anomaly Identified	Resolution
DLIAR	Anomalous amplitudes for April 7 – June 3, 2003.	Excluded data from anomalous period from analysis.
I10CA	Unusual increase in noise spectral amplitude above 0.7 Hz.	Identified error in instrument response received from the International Data Centre (IDC) in 2001. Updated instrument response file with information from IDC database current in January 2004 and recalculated spectra.
I26DE	Same as for I10CA.	Same as for I10CA.
I52GB	Spectral amplitudes higher than observed by station operator.	Acquired new instrument response from station operator and recalculated spectra.
I57US	Anomalously high amplitudes by 10^4 for January -April 2003.	Excluded data from anomalous period from noise analysis. Identified and fixed problem with calibration value for anomalous period.
NVIAR	Spectral amplitudes are 6 orders of magnitude larger than other stations.	Acquired new calibration value from station operator and replotted spectra. Excluded station from network median noise.
PDIAR	Spectral falloff with frequency much flatter than other stations.	Made inquiries to station operator.
SGAR	Same as for PDIAR.	Same as for PDIAR.
TXIAR	Same as for NVIAR	Same as for NVIAR.

Transformation of Spectra to Probability Density Functions

A quantitative knowledge of the noise field at a given station is also essential for estimating that station's signal detection capability. However, infrasound detection is performed against time-domain measures, so the PSD is not the most useful form of noise information for that purpose. The ability of any time-domain detector to detect target signals is ultimately linked to the signal-to-noise ratio (SNR) so that the detection capability of a station is largely determined by the fraction of time that the SNR exceeds some detection threshold. The SNR is substantially controlled by the amplitude of the noise at any moment. Thus, we have converted the PSDs into time-domain noise amplitude Probability Density Functions (PDFs) at each station within each of several typical frequency bands used in infrasound detection processing, 0.1 to 0.5 Hz, 0.5 to 1.0 Hz, 1.0 to 1.5 Hz, 1.5 to 2.0 Hz, and 2.0 to 2.5 Hz. The conversion to root-mean-square time domain amplitude from the PSDs is straightforward. However, our infrasound detectors is based on mean-absolute amplitude, so we estimated a conversions between the two by evaluating both measures on random noise with a 1/f amplitude spectrum (an accurate first-order approximation in which noise is generated by shearing of eddies into ever smaller eddies) filtered to match each of the detection filter bands. PDFs were estimated for all 21 stations, the four seasons and four times of day, as for the PSDs, and can be found in Bowman et al. (2004).

The shapes and amplitudes of the noise PDFs at any given station vary substantially with time of day, seasons, and passband. Figure 7 illustrates some of this variation at I07AU. Noise amplitude histograms for the 0.5 to 1 Hz passband are displayed for January and February (summer) in the upper row for July and August (winter) in the lower row, at the four canonical times of day. Noon is the noisiest time of day in both seasons; dawn is also noisy in the winter. Dusk, especially in winter, and midnights during summer are the quietest times of day. At this station, the histograms have similar shape in all passbands, although the absolute amplitude decreases with frequency.

A noteworthy property of these histograms is their extreme skew to the right and heavy tails. In the past, noise amplitude has been approximated as log-normal in many estimations of station detection capability, but such extreme features may invalidate such approximations or at least complicate their application. Generally, we observe that the noise amplitude becomes more heavy-tailed than log-normal as the frequency increases. At I07AU the Kolmogorov-Smirnov test (e.g., Hogg and Tanis, 2000) indicates that the 0.1 to 0.5 Hz PDF has a probability of 0.61 of having been drawn from a log-normal distribution, and the 0.5 to 1 Hz PDD, a probability of 0.48. In the higher bands, that probability drops precipitously to 6.7×10^{-3}, 3×10^{-5}, and 4.2×10^{-7}, respectively. Even when diurnal and seasonal trends are accounted for, infrasound noise distributions cannot generally be described as log-normal.

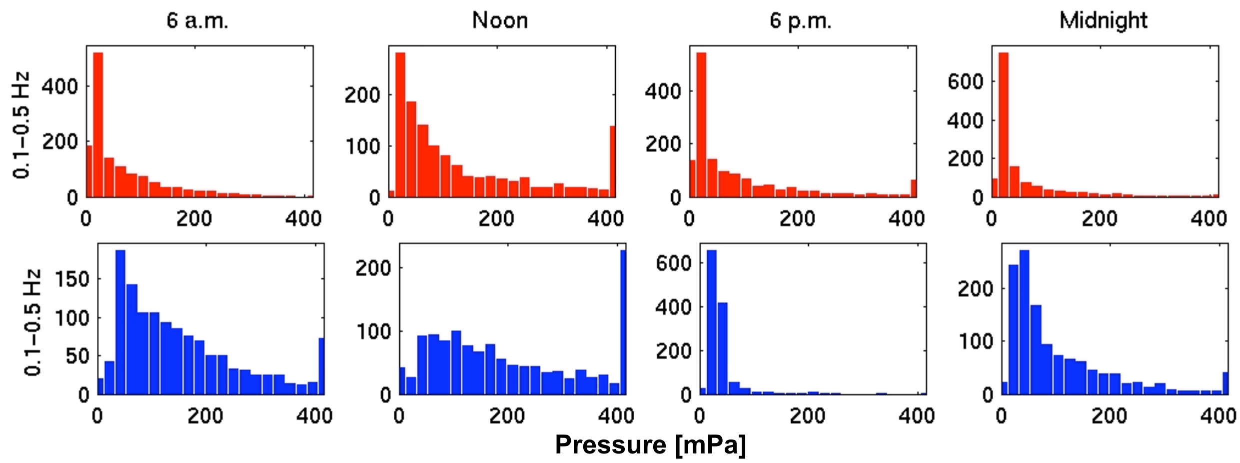

Figure 7. Noise amplitude histograms at I07AU, Australia.
Noise amplitude histograms for four different times of day during January and February (top row) compared with July and August (bottom row). Horizontal axis is noise amplitude in mPa. Maximum pressure plotted for each passband is that which includes 95% of the data for all times and months (the last 5% are included in the rightmost bins of the histograms for that passband). Bin widths are chosen to permit 20 bins.

Figure 8 shows empirical noise amplitude PDFs for station I59US, at Kona, Hawaii. I59US has generally lower noise levels than I07AU and, in contrast, the PDFs are quite different between summer and winter. Winter noise (January and February, bottom row) is higher and has heavier tails. Also unlike the I07AU observations, there is little difference due to time of day in either season. Again, the distributions are similar in different passbands for the same time of day and month.

The PDFs at I59US are closer to log-normally distributed than are those at I07AU, although all of the distributions still fail a Kolmogorov-Smirnov normality test. Specifically, they fail because they are heavier tailed than a Gaussian distribution. The deviation from log-normality of PDFs for I59US does not change systematically with passband.

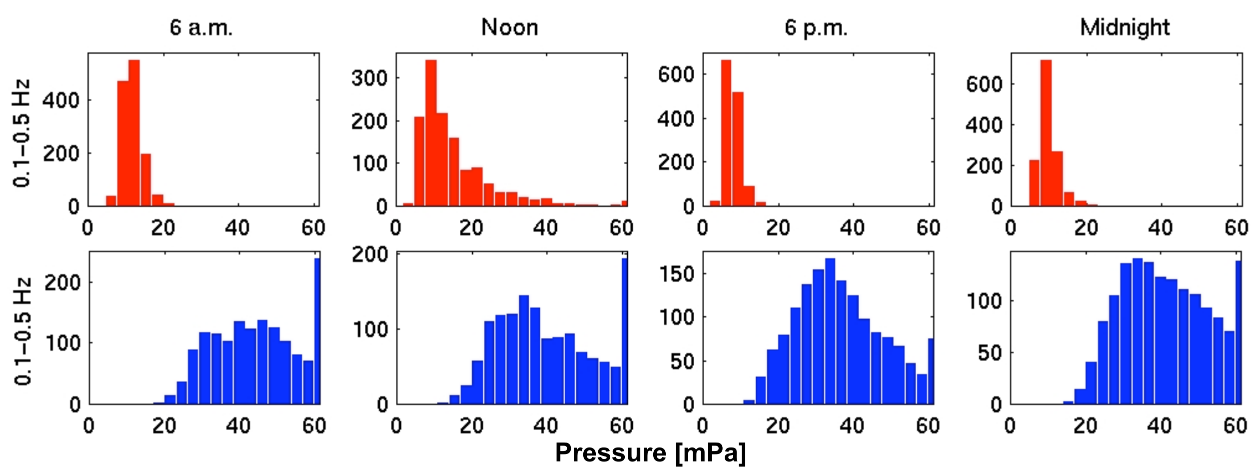

Figure 8. Noise amplitude histograms at I59US, Hawaii.
Details of the figure are the same as for Figure 7. Unlike the I07AU observations, there is little difference due to time of day in either season.

CONCLUSIONS AND RECOMMENDATIONS

Products and Accomplishments

- Summary statistics (power spectral densities and amplitude histograms) of infrasound background noise were tabulated versus season, time-of-day, and frequency at 21 existing infrasound stations.
- Instrument response or gain anomalies were uncovered during the noise survey and corrected for six stations (I10CA, I26DE I52GB, I57US, NVIAR and TXIAR) and documented for three others (DLIAR, PDIAR and SGAR).

Conclusions

- The median noise amplitude varies among the stations characterized by a factor of about 10 at 0.2 Hz and about 40 at 1 Hz.
- The median noise amplitude at a given station may vary by 2 orders of magnitude depending on time-of-day or season.
- The median noise amplitude at a given station is on average a factor of 2.5 higher during local winter than local summer.
- The frequency specific noise PDFs estimated for each station are not well approximated by a log-normal distribution as assumed in the past and, specifically, have longer than log-normal tails.

Recommendations

- Extend estimates of ambient noise to a full year for all current stations to fully quantify seasonal variations.
- Estimate ambient noise for new infrasound stations as they become available.
- Estimate the correlation between ambient noise and surface meteorological conditions for all infrasound stations.
- Estimate noise statistics at all station elements to capture site-to-site variations due to sensors, local topography, vegetation, etc.

ACKNOWLEDGMENTS

We thank Paul Piraino for calculating noise spectra, Bob North for identifying and helping to unravel errors in instrument responses, Dan Osborne for comments on an early draft, and Paul Golden for providing updated calibration values for two stations.

REFERENCES

Bahavar, M. and R. North, Estimation of background noise for International Monitoring System seismic stations, *Pure Applied Geophysics*, 159, 911-944, 2002.

Bowman, R., M. O'Brien, D. Adams, M. Bahavar, E. Baker, J. Bhattacharyya, D. Drob, M. Garces, C. Hetzer, H. Israelsson, D. Norris, C. Reasoner, G. Shields and J. Stevens, Methods for monitoring nuclear explosions using infrasound, SAIC technical report SAIC-04/3000, 2004.

Coyne, J. and I. Henson, Geotool Sourcebook: User's Manual, Teledyne Brown Engineering, Scientific report. no. 1, 01 Sep 1995.

Hedlin, M. A. H., B. Alcoverro, G. D'Spain, Evaluation of rosette infrasonic noise -reducing spatial filters, *J. Acoust. Soc. Amer*., 114, 1807-1820, 2003.

Hogg, R.V. and E.A. Tanis, Probability and Statistical Inference (6th Edition), Prentice Hall, 704 pp., 2000.