INITIAL ANALYSIS OF DATA FROM
THE NEW DIEGO GARCIA HYDROACOUSTIC STATION

Jeffrey A. Hanson

Science Applications International Corporation

ABSTRACT

The Prototype International Data Center (PIDC) began standard processing of data from the first of the new International Monitoring System's (IMS) hydrophone stations in November 2000. The station (designated HA08) is located off the Chagos Archipelago in the Indian Ocean (Lawrence et al, 2000). This is the first IMS hydroacoustic station that allows for coherent multi-sensor waveform processing. It provides better azimuthal arrival determination than was possible with the older IMS hydroacoustic stations. The station is not a classical hydrophone array, and standard array processing techniques may not produce the best results. Soon, two more stations, similar in design, will become operational in the Indian Ocean. It is important that we learn how these stations can best contribute to the Comprehensive Nuclear-Test-Ban Treaty's (CTBT's) hydroacoustic monitoring program.

The new station consists of six hydrophones arranged in two triads. The northern triad is 190 km northwest of the Diego Garcia atoll, and the southern triad is 30 km south of the atoll. The hydrophones are arranged in near equilateral triangles with sides approximately 2.5 km in length. The hydrophones are tethered to the sea floor and are suspended near the sound channel axis depth by subsurface buoys. The archipelago forms a large bathymetric obstruction between the two triads so signals observed at one triad are often completely or partially blocked at the other triad.

Each hydrophone produces on the order of 50 detections/day. The automatic system classifies the detections into three categories (N - noise, T - earthquake-generated signals, and H - signals that appear to be generated from an impulsive in-water event). The azimuth of arrival is determined for most detections. Because we lack ground truth, determining the accuracy of estimated azimuths is difficult. From earthquake locations, the southern triad's azimuth residuals have a standard deviation of approximately 2°. The northern triad detections have much greater residuals (often 50° or more), but most of the large outliers are from signals with partially blocked paths. Reflected acoustic waves appear to interfere with the direct signal. Establishing accurate error estimates for the azimuths as well as other signal features is a primary goal of this research.

KEY WORDS: hydroacoustics, prototype International Data Center, Diego Garcia, azimuth estimation

OBJECTIVE

This research attempts to establish a baseline of performance of the Diego Garcia hydrophone station. The new station has many advantages over previous IMS hydrophone stations such as those at Wake and Ascension Islands. The new hydrophones are well calibrated and use modern electronics to digitize and transmit the hydroacoustic data. In addition each triad has hydrophone spacing on the order of 2.5 km. Diego will soon be joined by two more stations in the Indian Ocean of similar design (Cape Leeuwin and Crozet). An accurate baseline will aid in determining where best to allocate resources to improve the monitoring capability of the new hydroacoustic stations the most.

There are several aspects to the stations that are new and require analysis. Although ocean acoustics is a mature field, the hydroacoustic global monitoring problem has only recently received attention and has gen-

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erally suffered from a lack of high-quality data. The new stations are in a different ocean basin than the previous stations used at the PIDC. Although the signals are similar, there are differences probably caused by the source region. The triads are not typical hydroacoustic arrays. The stations consist of a minimum number of elements (3) and the element spacing is greater than several wavelengths. The element spacing causes the array to be spatially aliased. However, this can be overcome because the phase velocity can be restricted, and the signals we are interested in have a large bandwidth. The signal coherency between sensors is not known, which makes error estimation difficult.

Our previous experience is primarily with the U.S. Air Force MILS (Missile Impact Locating System) type hydrophone stations in the Pacific and Atlantic Oceans (Hanson et al., 2001). These consist of 1 to 3 hydrophones generally separated by hundreds of kilometers. The data also suffered because the old instrumentation severely restricted the dynamic range of the signals. The distance between hydrophones in the old stations required incoherent array processing techniques in order to determine azimuth of arrival.
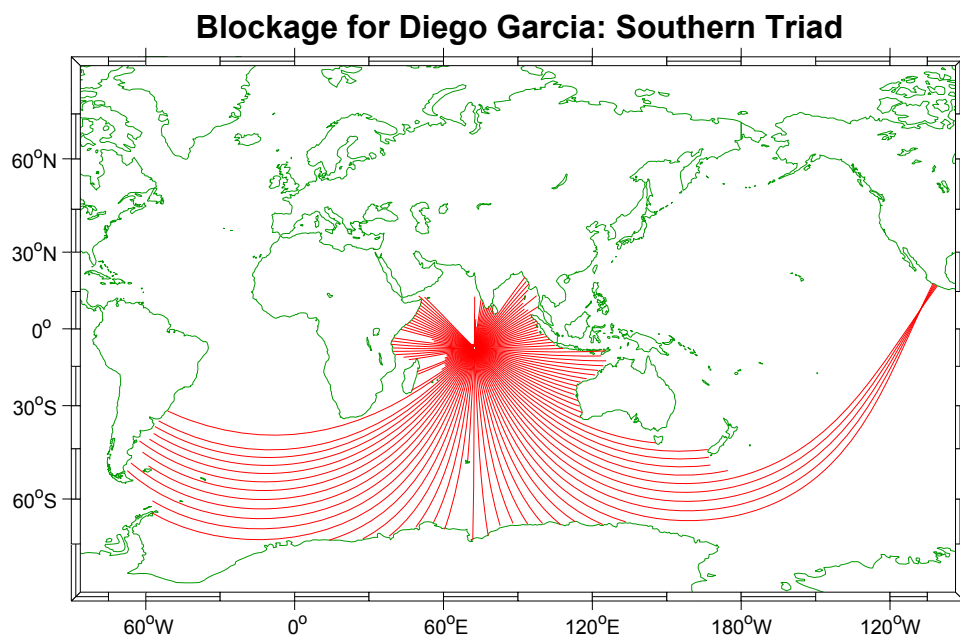

Figure 1. Example ray paths to Diego Garcia South. The northern triad has similar ray coverage but is not blocked to the northwest. Signal blockage maps are predicted from these ray paths (the actual blockage maps use a higher density of rays than shown here). The unblocked paths into the Pacific are real. In March of this year, T phases from earthquakes off Mexico's coast were recorded at Diego Garcia.

An additional objective of this research is to develop new algorithms that improve azimuth estimation with the new hydroacoustic array design. The small number of elements and the long baselines between elements (many wavelengths) cause problems with typical F-K analysis due to spatial aliasing and lack of data redundancy. Determining an unique direction of arrival relies on the signal's bandwidth and temporal duration. We have discovered weighting techniques that improve the estimated azimuths.

RESEARCH ACCOMPLISHED

Detection Processing

Automatic detection processing is handled by the PIDC's DFX application. DFX processes each hydrophone independently. Features are measured for each frequency band that reaches an established energy

13

threshold level. The frequency bands are the standard bands used for the other hydrophone stations (2-4, 3-6, 4-8, 6-12, 8-16, 26-32, 32-64, 2-80 Hz). A second process, StaPro, determines an initial phase identification. It currently uses a set of default rules that were developed for hydrophones in the pacific. It is anticipated that neural weights will be determined when enough data has been collected to form a training set.

Each hydrophone produces on the order of 50-100 detections/day (see Figure 2). The automatic system classifies the detections into three categories (N - noise, T - earthquake-generated signals, and H - signals that appear to be generated from an impulsive in-water event). The automatic system declares on average 20 T-phases/day for both the southern and northern triads. The southern triad records 1 to 3 H-phases/day. However, there are on the order of 10 H-phases/day at the northern triad. Most of these "H-phases" are believed to be signals from local earthquakes that have shorter duration and a greater frequency content than T-phases from distant sources. Reducing this clutter is an important objective for reducing false alarms that may overburden analysts. Additional tuning of the parameters used in classification may be enough to lower false alarms to an acceptable rate.
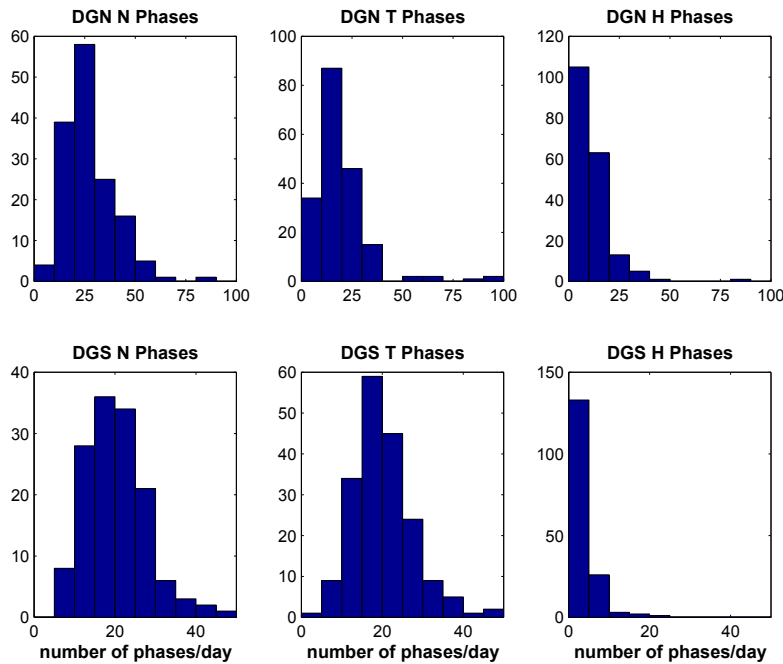

Figure 2. Automatic detections at the northern (top) and southern (bottom) triads. The noise phase (N) and T phase detection rates are comparable between triads. However the northern triad has many more H phase detections than the southern triad. These signals are generally due to local seismicity which are more impulsive and have higher frequency content than the typical T phase. These characteristics make classification more difficult at Diego than was the case for Wake or Ascension.

Average noise levels at the two triads are within normal bounds (Figure 3). The southern triad's ambient noise is somewhat higher than the northern triad. This is not surprising since the southern hydrophones are in a shallower environment and closer to shore. The noise level fluctuates on a daily and seasonal time scale (Figure 4).
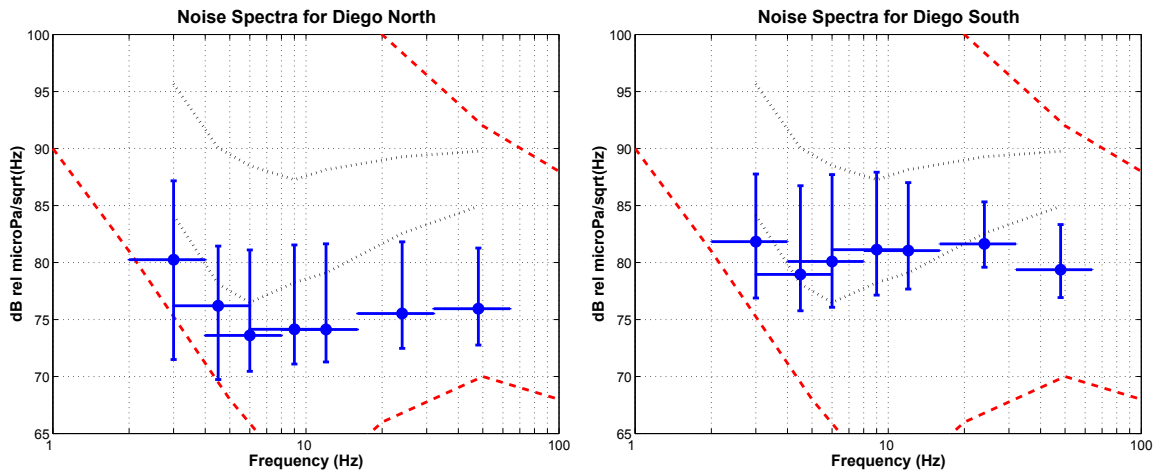
14

Noise Spectra for Diego North

Noise Spectra for Diego South

Figure 3. Average noise level (solid dots) at the two triads. The vertical error bars represent the range of noise levels observed over a half year's worth of data (about 9,000 measurements in each). The horizontal error bars indicate the bandwidth each measurement covers (although the measurement covers the whole band, the values are normalized so that the units are Power/Hz). The dashed line represents high and low noise values for a deep ocean environment (from Wenz, 1962). The dotted lines are similar high and low values observed at WK30 (the Wake Island hydrophone station).
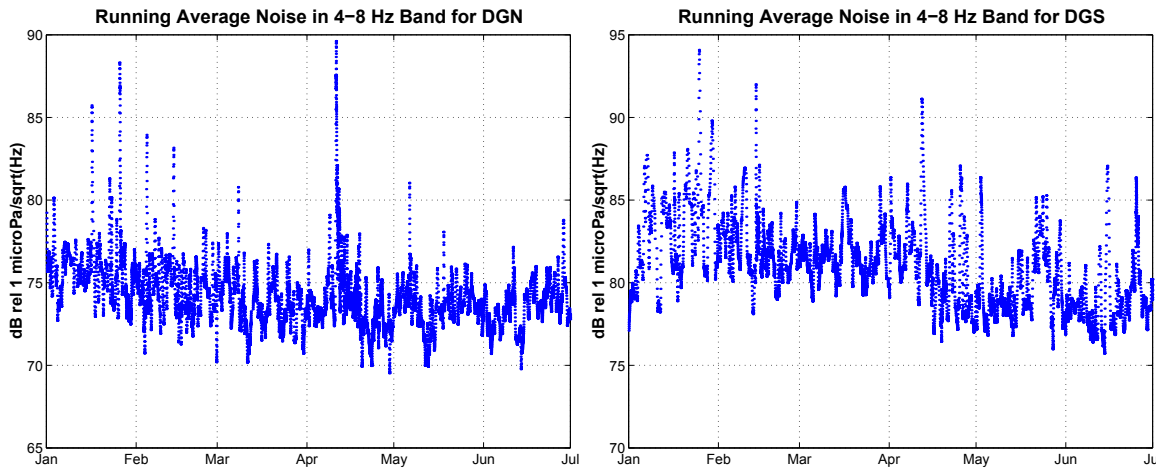
Running Average Noise in 4–8 Hz Band for DGN

Running Average Noise in 4–8 Hz Band for DGS

Figure 4. Noise in the 4- to 8-Hz band for the first half of 2001. The values have been smoothed using a 20-point low-pass filter window. There is a 3- to -dB decrease from January to July, which appears to be correlated between triads. Increased noise levels due to ships, marine seismic experiments, and storms have been observed.

The azimuth of arrival is determined for most detections. Because we lack ground truth, determining the accuracy of estimated azimuths is difficult. From earthquake locations, the southern triad's azimuth residuals have a standard deviation of approximately 2° (Figure 5). The northern triad detections have much

15

greater residuals (often 50° or more), but most of the large outliers are from signals with partially blocked paths. Reflected acoustic waves appear to interfere with the direct signal.
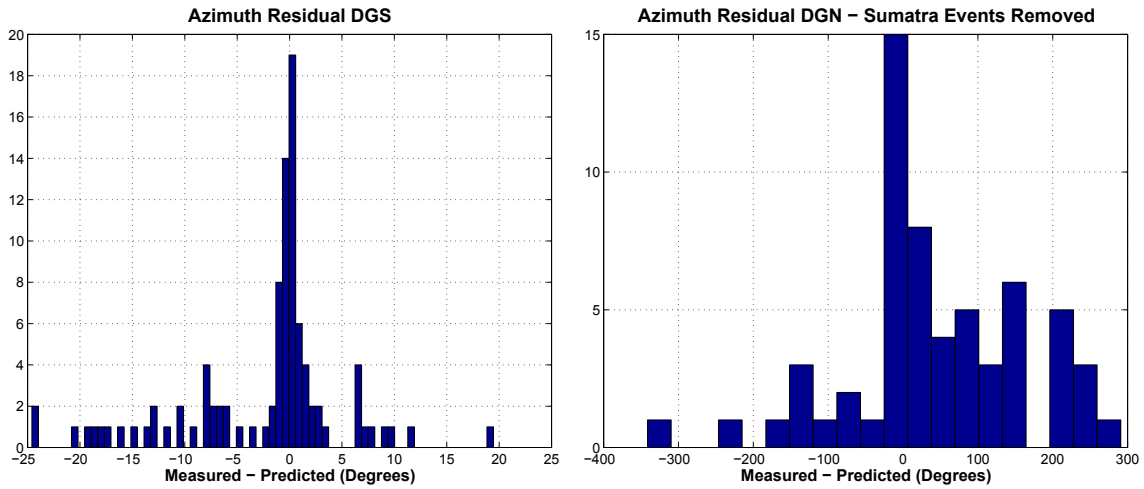

Figure 4. Residuals between measured and predicted azimuths. The predictions are from earthquake locations. The associations in this case were made strictly on time of arrival so some of the large errors may be due to incorrect associations. However, the incorrect association rate does not appear to be greater for the northern triad and does not explain the large residuals.

Array Processing

As previously mentioned, the triads are spatially aliased arrays. This is caused by the 2.5-km spacing between hydrophones while the wavelengths of interest range from 750 meters to as short as 15 meters. However, in hydroacoustic processing we have the advantage that the phase velocity is essentially known (~1.5 km/s). This reduces the spatial aliasing problem, but does not eliminate it (Figure 6).
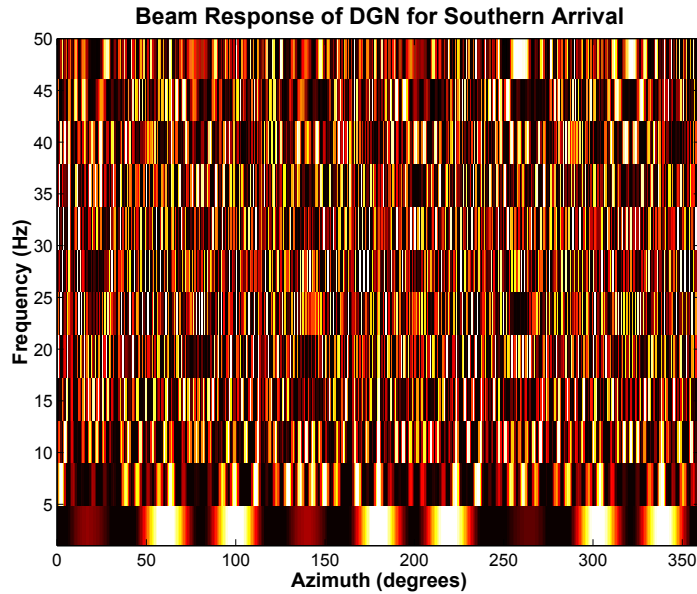
16

Beam Response of DGN for Southern Arrival

Figure 5. The beam response of the of the northern triad for a plane wave arriving from 180° azimuth. The phase velocity is fixed at 1.5km/s. The strong spatial aliasing is evident especially at an azimuth of 100°. Summing the response over a range of frequencies removes most of the aliasing.

The response pattern shown in Figure 6 demonstrates that the aliasing problem can be overcome by summing over frequency. This is because the array response varies with frequency except at the actual arrival bearing. A broadband signal should not have side lobes with the same amplitude as the main lobe. However, there are side lobes whose frequency dependence is weak (for example, at 100° in Figure 6). Therefore, it is important to take advantage of as much frequency content as possible.
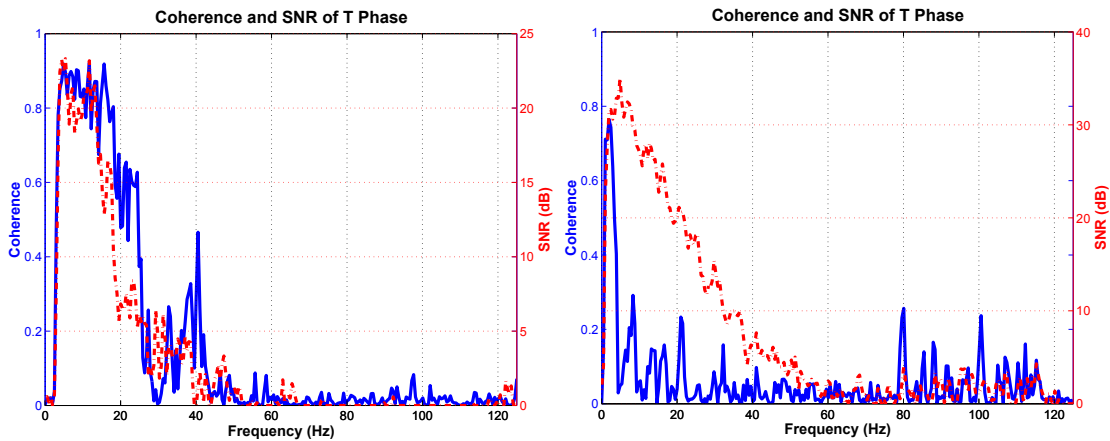
Figure 6. Coherence between two sensors for two T phases. The left vertical axis corresponds to the solid blue line (coherence), and the right vertical axis corresponds to the dashed red line (SNR). The SNR of the two signals are similar, but the T phase on the right loses coherence above 5 Hz while the coherence of the left T phase appears to be controlled by its SNR. Considering many other observations, the amount of coherent energy in a T phase appears to be azimuthally dependent. However, this may be more a function of source area than interference at the receiver. The signal on the right is from a trench earthquake, and the left signal is from a shallow mid-ocean ridge earthquake.
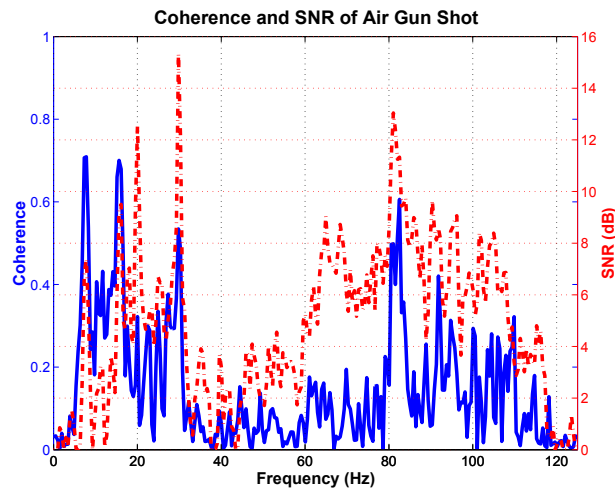
17

Figure 7. The coherence between two sensors for a series of signals from air gun shots. The left vertical axis corresponds to the solid blue line (coherence), and the right vertical axis corresponds to the dashed red line (SNR). The signals arrive from the northeast. The distance to the ship is not known. There is coherent energy from 5 to 30 Hz and from 90 to 110+ Hz, even though the SNR is relatively low. This suggests that the lack of coherence in some of the T phase signals may be source effects rather than interference from local reflections.

The useful frequency content of a signal for azimuth estimation is obviously dependent on the signal-to-noise ratio, but the energy must also be coherent between sensors. We have examined the coherence of waveforms between sensors within a triad. Most of our signals are earthquake-generated T phases whose characteristics may not be similar to explosion-generated signals. For a given signal, the coherence is generally equivalent for any given pair of sensors within the triad. However, the coherence of one signal can greatly differ from another (Figure 7). T phases from one azimuth may be coherent over their entire band width, but T phases from another azimuth may have very little coherent energy. It remains to be seen if this is a source or receiver end effect.

On the receiver end there could be near-sensor reflectors that are more efficient for waves propagating from one direction than the other. The reflections could interfere with the direct arrival breaking up the signal's coherence. But for the earthquake-generated T phases, the azimuth is directly related to the region that the signal was generated. The incoherent signals seem to come from trench events off of Sumatra while the coherent arrivals seem to be generated from shallow mid-ocean ridge seismicity. The T phases from trench events may emanate from multiple regions (de Groot-Hedlin et al., 1998) creating interfering signals at the receiver end.

There are few examples of in-water sources recorded at Diego Garcia. However, the signals that are recorded appear to be coherent between sensors over the entire bandwidth of the signal (Figure 8). This suggests that the coherence is related to the source, and one needs to be careful when using earthquake-generated T phases as a proxy to explosion data. However, this is based on only a few examples, and therefore we cannot rule out coherence loss due to effects at the receiver end of the path.

Optimizing Azimuth Estimates

The accuracy of azimuth estimation for the hydroacoustic network is especially important because of the network's sparse design. Given good coverage, travel-time estimates will generally constrain an event location much better than azimuth estimates. This is because a small uncertainty in azimuth can become a very large spatial uncertainty as you back project from the hydroacoustic station to the event. But because of the sparse network, there may not always be adequate coverage for event location based on travel times alone. With the earlier IMS hydroacoustic stations (like Wake and Ascension), the accuracy in azimuths was not

18

sufficient to be of much use in location estimation. However, the triads appear to produce much more accurate azimuths.

Because there are only three elements in a triad which are widely spaced, there may be better ways to process the data than standard array techniques. The geometry of the northern triad is shown in Figure 9. It is essentially an equilateral triangle. Cross-correlating signals is usually not done for arrays with many elements. However, because a 3-element array only has 3 pairs of sensor to cross-correlate, it is quite feasible in this case. In our algorithm, we estimate the F-statistic from an average of the cross-correlations (Katz, 2001). This can be shown to be equivalent to estimating the F-statistic from the beam.

The sensitivity of the cross-correlation function for a given pair of sensors can be easily calculated as a function of azimuth. We do not have to calculate the sensitivity in the slowness direction because we know the phase velocity. The sensitivity can be used to weight the cross-correlations when averaging. Intuitively one can see that the cross-correlation will be particularly insensitive for azimuths that are near parallel to the baseline between the sensors. These sensitivities provide a sophisticated method for weighted data that is not directly possible in beam formation. The effect of this weighting is to narrow the main lobe (improve the resolution). However in doing so, we increase leakage and side lobes in the 'FK' spectrum. This is probably not a significant problem for the type of signals we are interested in. In Figure 9 we demonstrate that modest gains in resolution are achievable. Improvements to the weighting scheme may improve the resolution gain.
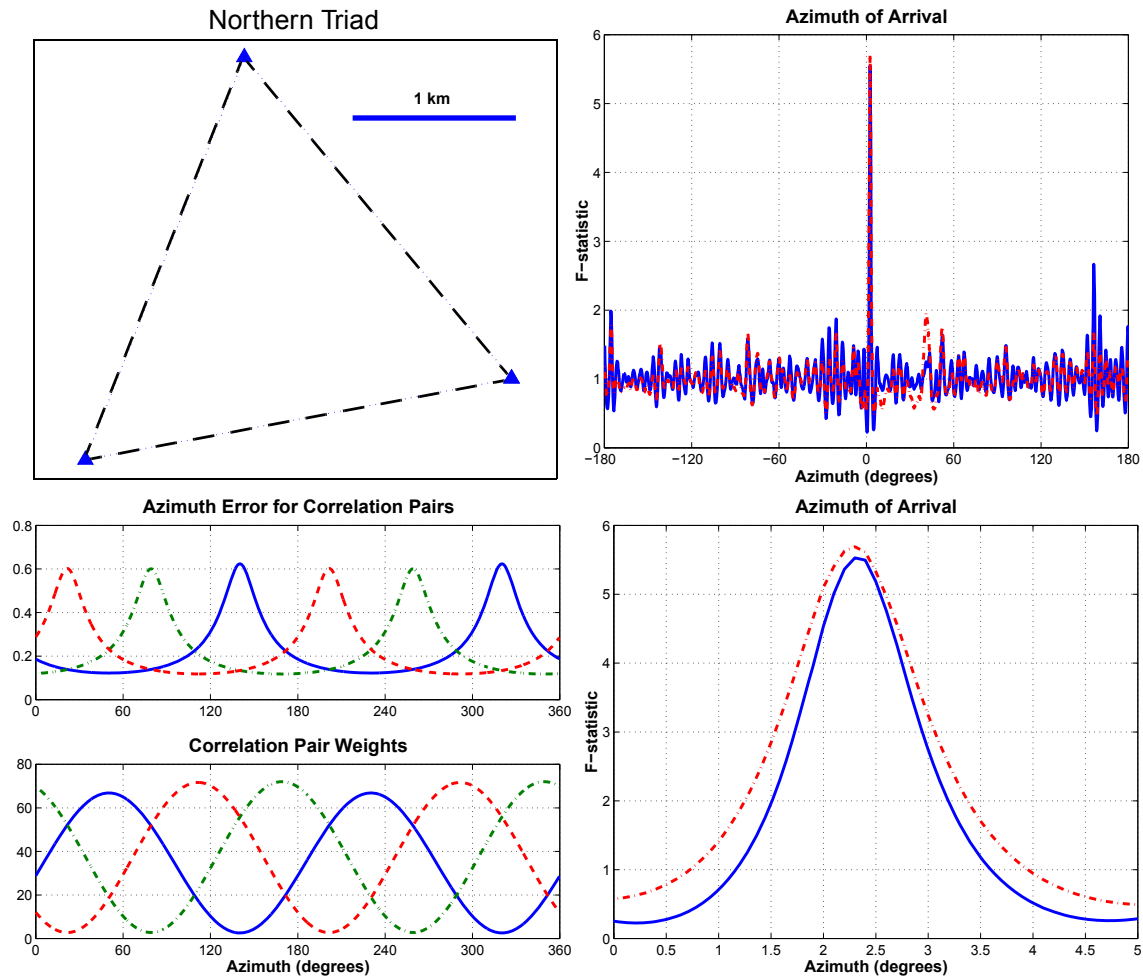

Figure 8. Determining Azimuth from Correlation Pairs. Azimuths are determined from lag times between sensors determined from cross-correlating waveforms. There are 3 pairs of sensors in a triad and

therefore 3 correlations. Because the phase velocity is known, the lag between two sensors is a function of azimuth only. More specifically, it is a function of the angle between the arrival azimuth and the baseline between sensors. By weighting the correlations, it is possible to improve the azimuth resolution. The trade-off is an increase in the side lobes (here at 150°). It may be possible to optimize the weighting functions beyond what is done here.

Explosion Data

The hydroacoustic network has generally lacked ground truth, which has hampered both improvements to the network processing as well as validating the current system. The most important type of data is, of course, explosion data. There are plans for a preliminary calibration experiment in the Indian Ocean for the fall (Blackman 2001), and perhaps a more comprehensive experiment a few years later. In the meantime, any explosion data will greatly help in answering some of the questions identified in this paper.

We have identified a few signals recorded at the northern triad that appear to be from in-water explosions (Figure 10). The signals arrive from the north, but we are unable to locate them since the southern triad is blocked. However these data are still important because they help validate (or show deficiencies in) current processing techniques. The coherency of these signals can improve our understanding of how best to estimate azimuth. They can also be used to estimate the precision of azimuth estimates if not the overall accuracy.
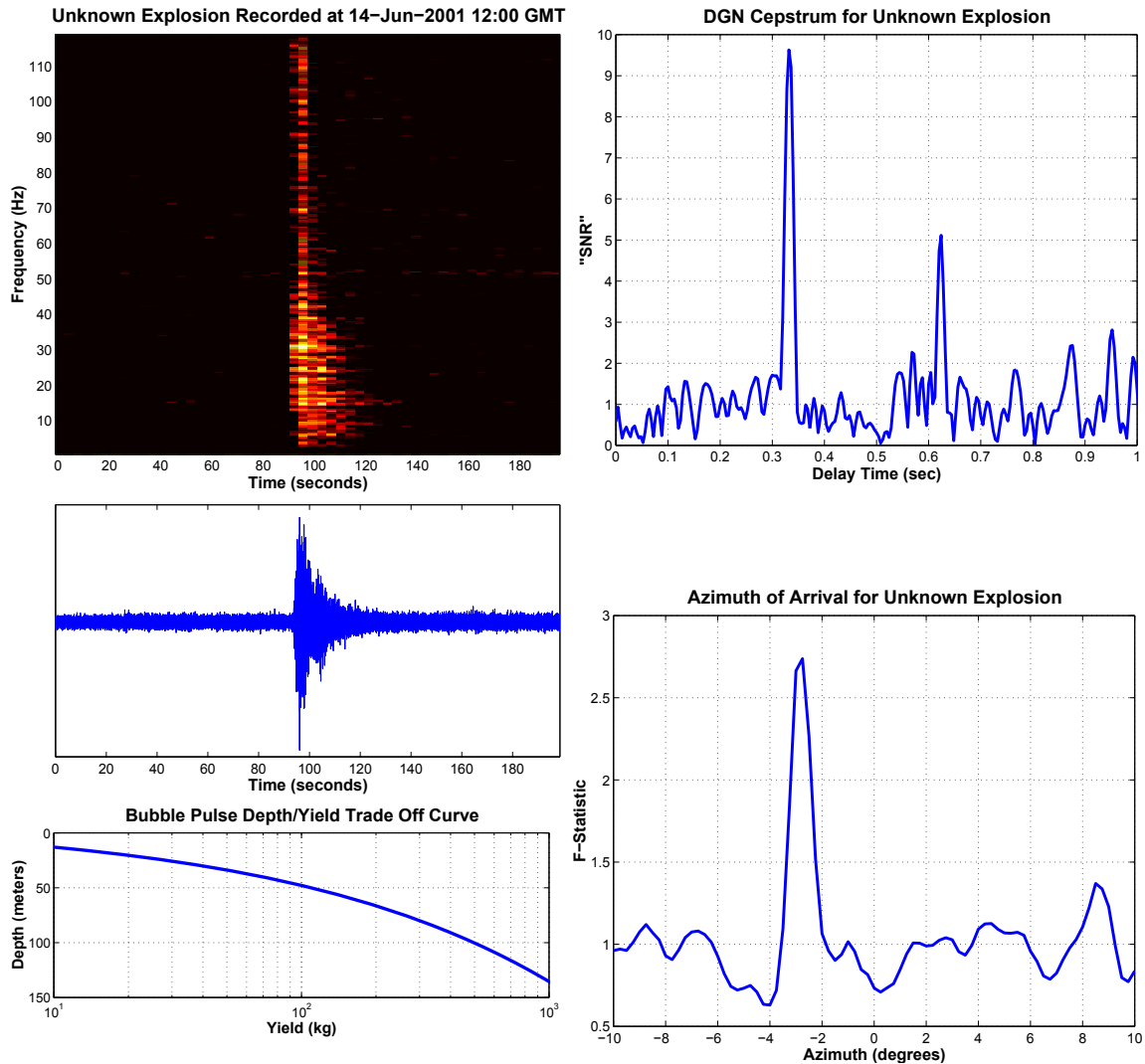
Figure 9. A signal recorded at northern triad that appears to be from an explosion. The scalloping in the spectrum from the bubble pulse is evident in the spectrogram and results in the strong peaks in the cepstrum. The first two peaks in the cepstrum correspond to the first and second collapse of the gas bubble created by the explosion. As expected, the second peak is at a delay time value slightly less than twice the first peak. The depth/yield trade-off curve shows what size explosion it would take to produce a bubble pulse with the observed delay time as a function of source depth (Cole, 1948). The source is almost due north of the northern triad.

CONCLUSIONS AND RECOMMENDATIONS

The PIDC has processed data from the new Diego Garcia hydrophone station for over six months. The station provides high-quality data that provide many opportunities not possible with the older hydroacoustic stations. The noise levels at the two triads are within expected values for deep water locations. The new instrumentation at Diego exhibits a minimum 50-dB gain in dynamic range over the older stations. Hundreds of signals are detected each day at the Diego hydrophones. The current algorithm used to classify signals identifies many to be of "in-water" origin (H), but these are usually signals from local earthquakes. The signals recorded at sensors within a triad can be coherent almost up to the nyquist frequency, but this is not always the case. Some T phases lose coherence at frequencies above 5 Hz.

21

Azimuth estimation relies on the signal coherence and bandwidth to remove the spatial aliasing inherent in the triad design. Azimuths accurate to within a few degrees are generally achievable, but can fail due to lack of coherence. More investigation needs to be conducted to understand what contributes to this. The ability to achieve very accurate azimuths appears possible and could greatly improve the sparse hydroacoustic network's location ability. The network localization ability based on a more comprehensive understanding of azimuth and arrival time uncertainty needs to be conducted.

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