# INFRASONIC PROCESSING AT THE PROTOTYPE INTERNATIONAL DATA CENTER

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**ABSTRACT**

The PIDC has been developing an automatic and interactive data processing system to provide spatial and temporal source location information for highly-impulsive sources in any terrestrial environment. Here we review several recent refinements that have been made to the infrasonic data processing system. This system has been processing infrasonic data automatically since April 1998 and interactively since December 1998.

Improvements to the infrasonic data processing system are currently being implemented in a number of different areas.

First, we are incorporating seasonal travel-time information into location processing. A 3D propagation model based on the Eikonal equations for acoustic-gravity waves, which uses a seasonal atmospheric model to provide ambient wind and temperature information, is used to provide a set of azimuthally varying travel-time tables for each microbarographic array site.

The second area of improvement is in detector tuning. Sophisticated event detectors such as the infrasonic event detector under development at the PIDC require a significant number of tunable parameters, which can be written succinctly as a vector {P}. A comprehensive set of procedures for determining the optimal vector {P} have been established. These procedures involve determining a set of curves which yield the probability of detection (PD) as a function of signal to noise ratio (SNR) at a given false alarm rate for a specified vector {P} = {P0}. By varying {P} it is possible to determine the curve that yields the Minimum Detectable Level (MDL), i.e. the smallest SNR that gives a specified PD = PD0. In conjunction with efforts at the Los Alamos National Laboratory, tuning activities have focussed on the IMS prototype infrasonic array in New Mexico (DLIAR), but will culminate in a set of procedures that can be used to tune the detector for any IMS infrasonic array when the data becomes available.

Third, we have investigated the azimuth and slowness deviations due to the relative heights of the sensors. Our research indicates that significant errors in slowness, azimuth and signal power can be introduced into the signal feature extraction procedure if sensor height differences are not accommodated. Deviations in azimuth of up to several degrees, and a power loss of 10% seems to be possible if these factors are not accounted for.

Fourth, we have improved procedures for the interactive processing of infrasonic data. These procedures allow for infrasonic source locations based on two intersecting azimuths, and also provide rudimentary means for inferring source to receiver distance based on signal frequency composition. In addition, these procedures also provide event definition criteria in the case where an event is formed from a combination of seismic, hydroacoustic and infrasonic arrivals.

**Keywords**: Infrasound, Detector-tuning, infrasonic travel-times

## OBJECTIVES

The infrasonic processing subsystem at the Prototype International Data Center (PIDC) in Arlington, VA, forms part of a larger system currently under development at the PIDC where seismic, hydroacoustic, radionuclide and infrasonic methods are used to detect and locate impulsive sources with a yield of at least 1-kT in any terrestrial environment. The infrasonic processing subsystem gives the PIDC the ability to estimate the temporal and spatial source location for impulsive sources that couple in some part to the atmosphere. The infrasonic automatic data processing system is being completed in stages. Release two (of four releases) of the system is currently in operation at the PIDC. It is anticipated that the final version of the system will be operational by mid 2001.The objective of this current research is to enhance performance of the operational system and has four main aims. The first objective is to improve the traveltime information currently used in the infrasonic source location algorithm. The second aim is to ‘tune’ the detector so as to optimize its performance for events of interest (1-kT explosions located within approximately 3000 km from the receiver). The third objective is to determine the magnitude of errors in observed azimuth and slowness that occur due to relative height differences among the sensors in an infrasonic array.The fourth objective is to determine accurate interactive procedures for infrasonic analysis. It is intended that the completed system will process continuously transmitted data from the full 60-station International Monitoring System (IMS) infrasound network. It will therefore be necessary that reasonably accurate automatic event processing take place prior to any interactive analysis and production of the Reviewed Event Bulletin, the final product of the PIDC.

## RESEARCH ACCOMPLISHED

### 1.0 Travel-time information

Standard IMS array geometry implies that observed azimuth may be measured quite accurately for many recorded infrasonic signals (see Fig. 1).

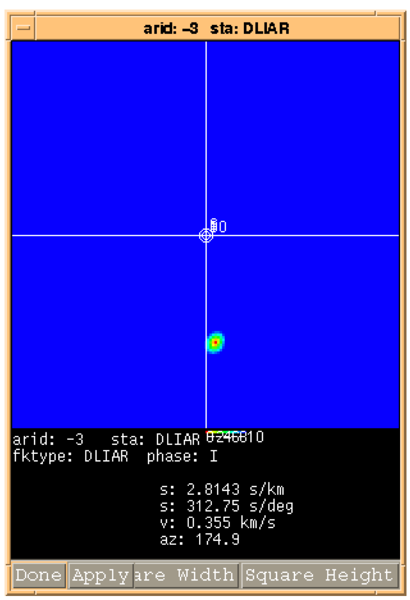



**Figure 1**: *XfkDisplay* output showing the slowness plane location of an infrasonic source. Diagram indicates zero slowness at the center and 5 sec/deg at the domain boundaries.

In view of the relatively poor constraint one has on the predicted travel-time for infrasonic arrivals, it is reasonable, therefore, to make observed azimuth the primary source location parameter for infrasonic sources. Travel-times still need to be estimated, however, for the purpose of temporal source location and refinement of spatial location, as well as preventing causal violations.

The infrasonic travel-time model presently in use at the PIDC is particularly crude as it assumes that all signals have horizontal speeds across the ground of 320 m/s. This obviously necessitates the inclusion of large variances on the travel-time.

In order to refine the determination of infrasonic travel-times, a more sophisticated propagation model is being introduced. An eikonal ray-tracing algorithm for acoustic waves in an atmosphere with seasonal variations in wind and temperature is being used to provide travel-time information for infrasonic signals recorded at each infrasonic array. The philosophy at the present time is to incorporate only seasonal influences in the determination of travel-times. The refined seasonal travel-time information will be introduced in stages. In its final form, the automatic processing system will attempt to identify all infrasonic arrivals based on a hypothesized propagation path. As an interim measure, however, only a single possible infrasonic phase-type will be used. The ray-tracing algorithm will be used to infer travel-times for each arrival at an infrasonic array. Based on the behavior of a multitude of rays emanating from a given source with a given azimuth of departure, the time and range of each bounce will be noted. A single interpolating curve, which focuses on the stratospheric arrival when it exists and the dominant thermospheric arrival otherwise, will be calculated for each operational array, for every 1 degree of azimuth and for each season. In its final form, the source location algorithm will use a separate interpolating curve for each of the different phase types (tropospheric, stratospheric and thermospheric). In the event that a predicted arrival type doesn't exist, a generic curve will be used. An example of such a set of curves is indicated in Fig. 2.

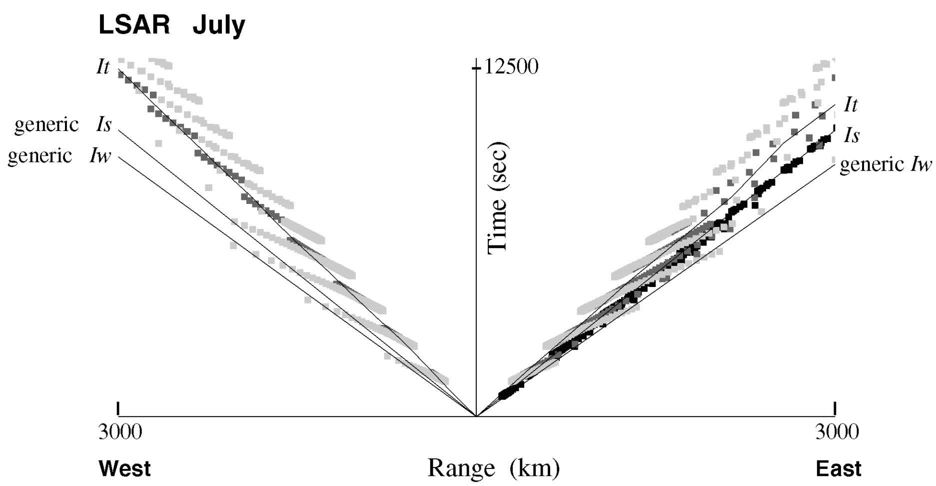



**Figure 2:** Theoretical bounce-point locations determined via an Eikonal ray-tracing model for acoustic waves propagating in an atmosphere with seasonal variation in wind and temperature. Travel-time curves for the three different arrival types have been shown. (Adapted from Brown et al. (1999))

It will ultimately be necessary to accommodate the wind-generated azimuthal deviations in the source location algorithm. It has been shown (Brown, *In preparation*) that these effects can be quite significant, at least 5-6 degrees in some circumstances.

**2.0 Deviations in observed azimuth and slowness due to relative height differences of the sensors**.

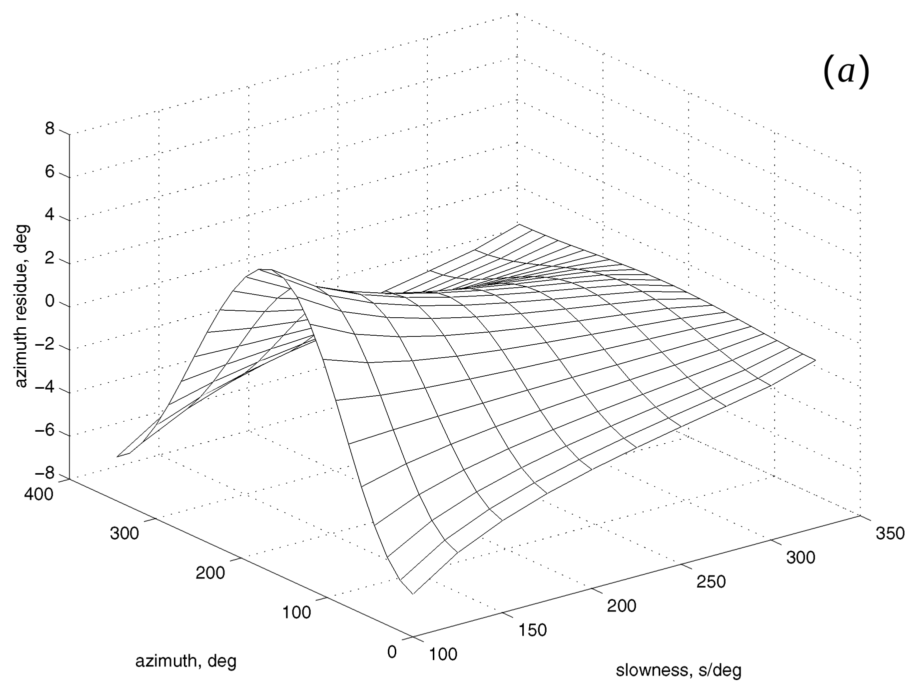
One aspect of infrasonic signal processing that has received little or no attention in recent years is the influence that sensor height differences have on the estimated azimuth and slowness of infrasonic signals impinging on an array. With the commencement of the installation of the International Monitoring System (IMS) infrasonic network, and subsequent processing of the array data, it becomes important to investigate the magnitude of these effects.

Table 1 shows the relative heights of the sensors comprising the DLIAR infrasonic array.

| element | Northerly deviation rel. to center (m) | Easterly deviation rel. to center (m) | height rel. to center (m) |
|---|---|---|---|
| North | 728.5 | 151.7 | -11.9 |
| East | -437.7 | 789.0 | -24.8 |
| Center | 0.0 | 0.0 | 0.0 |
| West | -226.2 | -534.3 | 16.0 |

**Table 1: DLIAR array sensor locations.**

Figure 3 shows the deviation in observed azimuth and slowness that will occur at the DLIAR infrasound array due to the relative height differences of the 4 sensors (Wang et al, 1999 provide details on the algorithm used).



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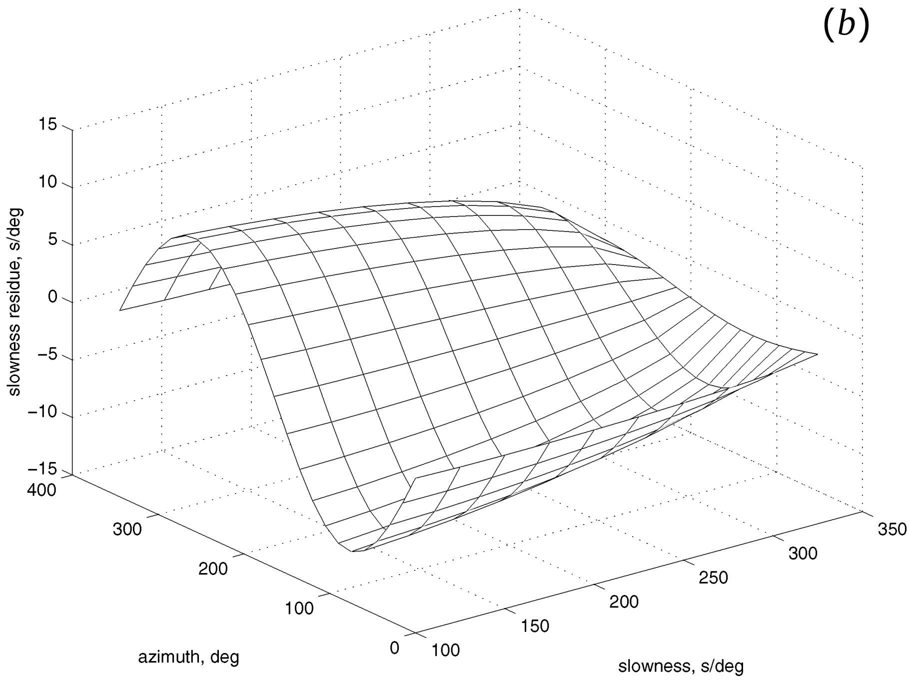


**Figure 3**: azimuth and slowness residues due to sensor elevation differences at the DLIAR array. (a) azimuthal deviation (deg)., (b) slowness deviation (s/deg)

Figure 3a. shows a steady increase in maximal azimuthal deviation from about 0.2 degrees at 340 m/s and 180 degrees, to about 2.0 degree at 500 m/s and 180 degrees. Similarly, Fig 3b. shows a steady increase in maximal speed deviation from about 1.2 m/s at 340 m/s and 250 degrees, to about 17.6 m/s at 500 m/s and 250 degrees. These values are significant and need to be accommodated in the feature extraction algorithm.

**3.0 Detector Tuning**

The infrasonic processing system at the PIDC has had to be developed largely in the absence of IMS quality data. Nevertheless, the infrasonic signal detector needs to be ‘tuned’ for the events of interest (i.e., a 1-kT source located up to 3000 km from the receiver). With LANL involvement, a substantial and sophisticated tuning exercise using synthetic waveforms that represent signals of interest is being undertaken. The tuning exercise, which at the time of writing is far from complete, consists of the following steps:

1. Approximately 100 hours of data from the DLIAR array (an IMS-type array) are selected. This data is chosen to represent the complete set of possible ambient conditions, from quiescent to windy, with and without microbarom clutter. The time interval chosen is from Feb 21, 1998 00:00:00 to Feb 25, 1998 00:00:00 and appears to be relatively free of highly-impulsive signals.
2. The waveform data is scanned, both manually and with the detector set to a low detection threshold, to determine where all possible signals are located; these areas are to be avoided as much as possible in the subsequent analysis. Due to the ubiquitous nature of the microbaroms, however, it may be impossible to avoid coherent energy due to the microbaroms. Although the microbaroms tend to come from a restricted direction at DLIAR, the side-lobe energy generate by the sensor locations may not be insignificant. Figure 4 shows the array response for a source with frequency 0.33 Hz, due West of the array with an apparent speed of 340 m/s. When considering a band of possible arrival azimuths, it becomes obvious that it will be nearly impossible to avoid the microbarom activity or dominant side-lobe activity. It is, of course, of interest to perform the tuning exercise at some stage with a strong microbarom presence, but in the early stages of the tuning exercise it is desirable to reduce the microbarom influence as much as possible.

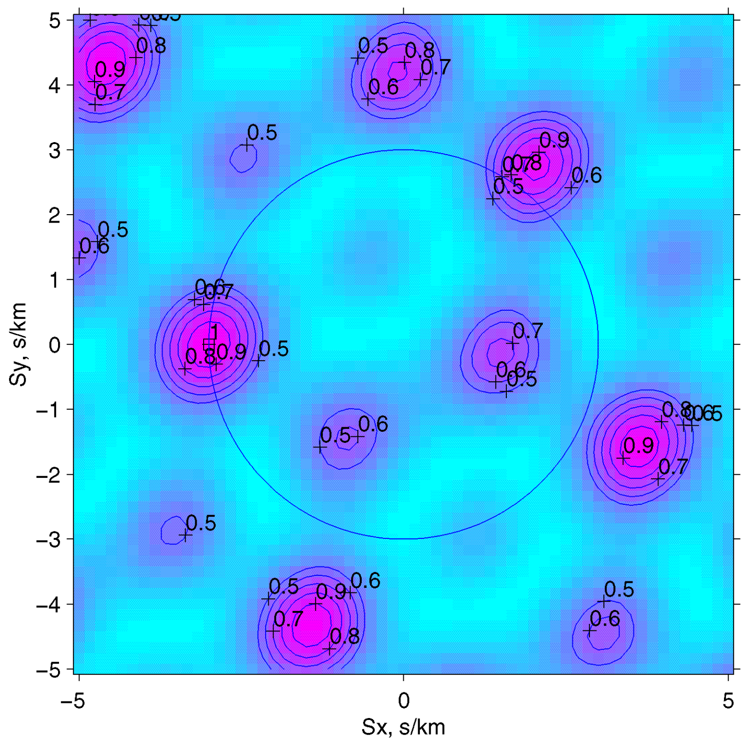


**Figure 4**: Array response for DLIAR array at 0.33Hz for signal travelling at 340 m/s from an azimuth of 270 degrees.

Manual scanning of the slowness plane in the frequency band 0.125 Hz to 0.333 Hz with 8-pole tapering for the 100 hours of data, yields the distribution of coherent SNR, observed azimuth, and speed as a function of time that is shown in Fig. 5. This figure provides information about the quiet times for microbarom activity and are the desirable locations for the initial implantation of the signals.

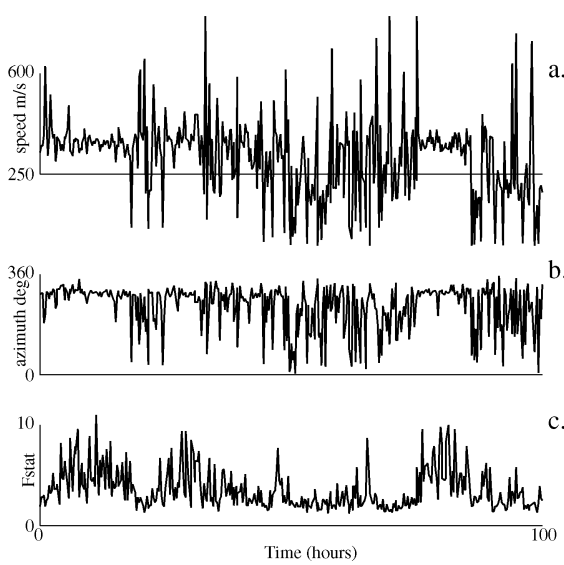


**Figure 5:** Microbarom activity for the 100 hours of test data. a.) speed versus time. b.) azimuth versus time. c.) Fstat versus time.

3. A signal of interest is chosen to implant into the background data. It is intended to use an artificially generated signal, designed to represent the signal from a 1-kT explosion located 2000 km away from the sensor. The synthetic signal decided on is that described by Dighe at al (1998) in relation to the modeling of infrasonic signals from low yield sources up to distances of several thousand kilometers. A representative signal is shown in Fig. 6, and represents the signal recorded down-wind from a hypothesized source located 2500 km away.

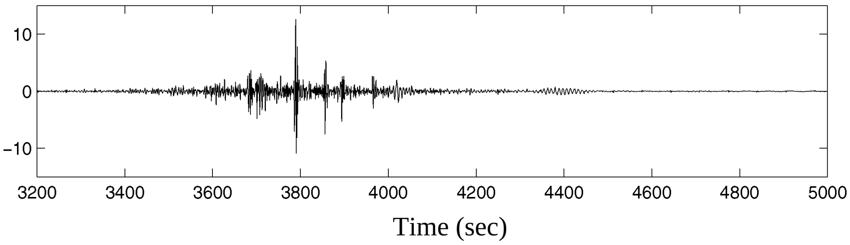


**Figure 6:** Representative synthetic waveform used in the detector tuning exercise. Units are pressure in dynes/cm$^2$ [adapthed from Dighe et al, 1998]

The down-wind signal is used because it predicts both stratospheric and thermospheric arrivals.

4. The signal is treated so that it matches the various properties of the background data and so that when duplicated across the channels, the correlation is physically realistic. Additionally, the multipathing character of the signal is preserved.
5. An acceptable False Alarm Rate (FAR0) is selected, and the detector passed over the background data a number of times with the set of tuning parameters changed each time until the FAR0 level is achieved.
6. Approximately 100 representations of the signal with varying SNR are implanted randomly throughout the data so as to avoid the regions with signals. The set of tuning parameters are systematically changed so that the same FAR0 value is obtained on the data free of implanted signals. As the SNRs of the implanted signals vary from very small to very large, certain signals will be detected and some will not. In this way a probability of detection versus SNR curve can be obtained. For a given probability of detection, PD0, and the prescribed false alarm rate FAR0, we seek the arrangement of the tuning parameters which yields the smallest SNR. This is known as the Minimal Detectable Level (MDL).

### 4.0 Interactive Review of Infrasonic Data

Analysts have been reviewing infrasound data at the Prototype International Data Centre (PIDC) since December, 1998. The last of the technologies to be integrated into the PIDC interactive system, infrasound has necessitated some modifications to the existing analysis interface, and to analysis procedures.

### 4.1 Analyst Review Station

Analysts perform their review on an interactive display known as the Analyst Review System (ARS) (Fig. 7). Compliments to this interface include a slowness determination tool (*XfkDisplay)* -which also indicates the level of spatial coherence of the most coherent arrival, and a spectral analysis tool (*SpectraPlot*).

ARS is the main interface through which all time-series technologies are analyzed. Operational analysts typically review infrasound data at approximately 12 hours behind real time. Although future plans include the evaluation of all infrasound detections, analysts currently examine only those infrasound events that have been detected by the automatic processing, shallow terrestrial events for possible infrasound associations, and shallow oceanic events for possible infrasound associations.

The functionality in ARS includes the ability to display waveforms, add phases, evaluate and modify phases, and to save events to several databases. For the integration of infrasound into ARS, which was formally used for seismic and hydroacoustic data evaluation, new functionality had to be added to handle this new technology. Most important is the inclusion of an *mx* trace along with the waveform display. The *mx* trace is a beam that indicates the level of signal coherence across the elements of a given array. ARS also now has the ability to retrieve six hours of data from the calculated event time, in order for the comparatively late-arriving infrasound data to be included in the event.

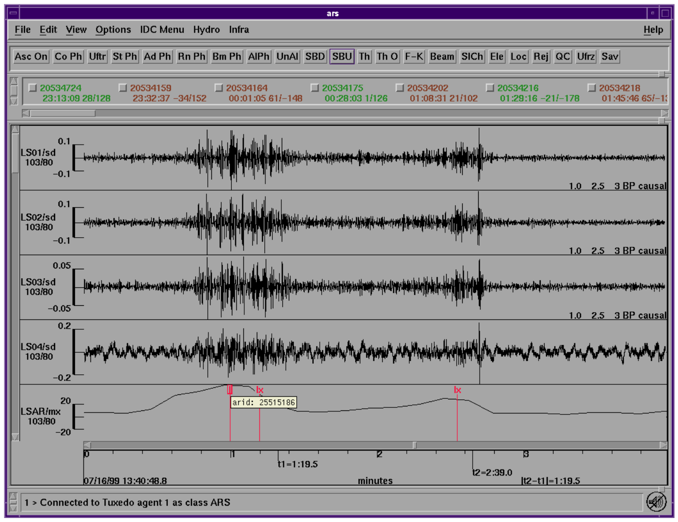


**Figure 7**: Analyst Review Station display

Besides filtering, the two most powerful tools that analysts use to evaluate infrasound data are the *XfkDisplay* tool and the *SpectraPlot* tool.

The *XfkDisplay* tool computes the apparent velocity recorded at an array and, as such, can provide an indication of the steepness of the vertical incidence angle. This is what analysts use to judge relative heights of the atmospheric layers at which the signals are refracted, and hence provide an idea of the phase of the arrival. Analysts use an increasing apparent velocity through multiple arrivals to suggest a single source.

*SpectraPlot* provides a visual display of the total power of the sampled energy at a given frequency. Analysts use *SpectraPlot* to determine if signals recorded at different stations belong to the same event by looking for decreasing dominant frequencies as distance from the event increases.

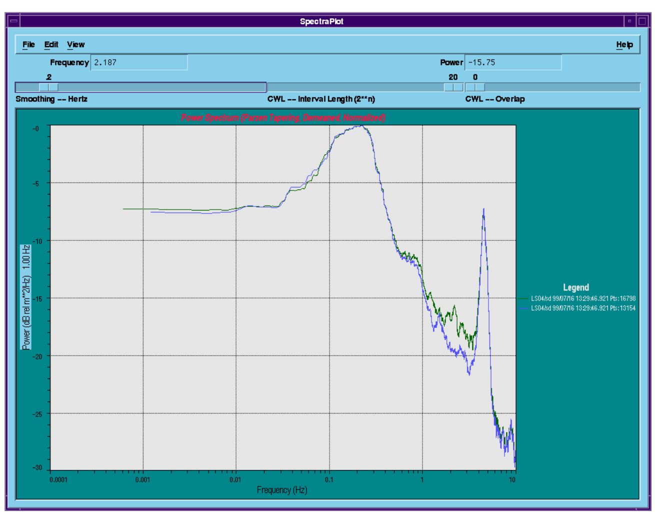


**Figure 8**: *SpectraPlot*

Analysts apply a number of narrow-band filters to waveforms when performing their analysis. The recommended initial filter is set at 1-3 Hz for the shorter baseline arrays, and 0.1-2 Hz for the IMS-type arrays. However, analysts have been cautioned against becoming too familiar with data from the smaller infrasound arrays, as signal characteristics at these arrays are considerably different than those recorded at the larger, IMS standard arrays. Other than the special microbarom analysis band [0.125-0.333 Hz], analysts have also been alerted to the risk of using filter bands below 0.5 Hz on small arrays; below this frequency, most energy appears to be spatially coherent.

To the extent that waveform data is available at the PIDC, a significant number of infrasound events have been recorded. These include a swarm of events from early December 1998, a number of chemical explosions, shuttle launches, and bolides. Since the automatic pipeline started processing infrasound data in April 1998, there have been 460 automatically associated detections and 18 analyst-reviewed detections used to build infrasound events.

Since infrasound is still in the early stages of being used operationally, strict event definition criteria have been imposed until more results are studied. Restrictions on event definition include the following:

1. I-phases must be seen on at least 2 stations for the event to be saved to the Late Event Bulletin (LEB), but must be seen on at least 3 stations to be saved to the Reviewed Event Bulletin (REB). The difference between the two bulletins is subtle. The LEB contains the results of analyst review, and is mostly used internally as a research tool. The REB is the official PIDC published bulletin. It was decided by development and operations staff that more defining parameters be required for the published bulletin until more events are analyzed and archived.

2. Time and azimuth are the only defining parameters, that is; time and azimuth contribute to the event time and location calculations, whereas slowness does not.

3. For time to be a defining parameter, we currently allow the very loose criteria of a 30 minute time residual. The azimuth residual must not be greater than 15 degrees. No seismic events with estimated depth greater than 40 km may have infrasonic associations.

## CONCLUSIONS AND RECOMMENDATIONS

In this paper we present refinements to the PIDC infrasonic processing system that are currently being implemented. The first, improved travel-time information, will improve the knowledge of the spatial and temporal location of a source. The second, detector tuning has never been performed prior to this exercise and will yield optimal detection parameters for the events of interest. In the absence of sources of interest to the IMS/IDC it is suggested that these studies be used as a basis for detector tuning procedures for the individual IMS arrays as they come online. Procedures along similar lines can be used to test source location procedures as the IMS infrasonic net is progressively installed. The third refinement deals with the errors in observed azimuth and slowness that can occur simply because the array sensors don't all lie in the same horizontal plane. The studies indicate that significant errors can occur and should be accommodated in the feature extraction part of the detection algorithm. The fourth refinement concerns the development of interactive procedures for the examination of infrasonic signals. Although at an early stage of development, these analyst procedures have allowed infrasonic associated events to contribute to the Reviewed Event Bulletin.

## ACKNOWLEDGEMENTS

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