INTEGRATION OF SEISMIC, HYDROACOUSTIC, INFRASOUND AND RADIONUCLIDE PROCESSING AT THE PROTOTYPE INTERNATIONAL DATA CENTRE

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ABSTRACT

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) calls for the establishment of networks of seismic, hydroacoustic, infrasound, and radionuclide sensors to monitor the earth for underground, underwater, and atmospheric nuclear tests.

Seismic processing at the prototype International Data Center (pIDC) has been operating continuously since the GSETT-3 experiment that took place throughout 1995. Seismic is the most mature of the four monitoring technologies for automatic processing and interactive analysis.

Since late 1996, efforts have been made, under the Multi-Sensor Data Fusion project funded by the Defense Threat Reduction Agency (DTRA), to integrate hydroacoustic and infrasound monitoring technologies into the existing automatic processing and interactive review framework. The project has contributed to the integration of the single-sensor signal processing of hydroacoustic and infrasound waveform data within the operational system and has enhanced network processing to include two hydroacoustic phase types, *H*-phase (in-water generated) and *T*-phase (underground generated) and one additional infrasound phase, *I*. A joint bulletin including the three technologies is produced at the pIDC on a continuous basis. The bulletin includes arrivals from natural and man-made events recorded at all three sensor types. Enhancements have been made to the travel-time handling system to take into account temporal variations which may be significant for both acoustic technologies.

Case studies have also been conducted under the project, involving marine and atmospheric ground-truth or near ground-truth explosions. A set of low-yield marine explosions off the coast of Japan has increased confidence in the path-dependent velocity and attenuation models used in hydroacoustic processing. Atmospheric explosions from the White Sands Missile Range were recorded at two infrasound stations, and we conducted automatic and interactive processing on that data set to gain knowledge about infrasound propagation and test our system on this ground-truth data. Mining explosions have been analyzed in the context of joined seismic and infrasound processing, showing the improved location accuracy expected when azimuth determined from the infrasound data is added to the seismic data.

Efforts are currently under way to extract azimuth information at multi-hydrophone hydroacoustic stations and to prototype joined automatic processing of radionuclide detection data.

Key Words: data fusion, seismic, hydroacoustic, infrasound, radionuclide, operational system, case studies.

OBJECTIVE

The Multi-Sensor Data Fusion Project, sponsored by the Defense Threat Reduction Agency (DTRA) was initiated in the fall of 1996 in support of the prototype International Data Center's (pIDC) effort to integrate operational processing of the four monitoring technologies, seismic, hydroacoustic, infrasound and radionuclide. The main objective of the project was to bring as much processing of the acoustic technologies into pIDC operations as the existing networks would allow, by integrating newly developed single-technology processing modules *DFX* and *StaPro* for hydroacoustic and infrasound as well as upgrading the seismic network processing module, *GA*, into a multi-technology network processing module. We also wanted to analyze the operational results of the joint processing of the different technologies to learn about single technology and multiple event detection and statistics from this initial implementation. To achieve the objective of upgrading the network processing software in the absence of fully implemented networks and to satisfy the need for its thorough testing, a synthetic detections generator, *SynGen*, has been developed to allow simulations of planned large size networks. To calibrate the processing parameters and evaluate earth models, several case studies were undertaken involving hydroacoustic and infrasound data.

RESEARCH ACCOMPLISHED

Introduction

At the initiation of the project, the seismic processing capability was by far the most developed, and the approach taken to integrate the additional technologies was a progression where first the hydroacoustic data was integrated into the processing suite, then the infrasound and finally the radionuclide, following an approach where the technologies closer in kind to seismic were integrated first.

Hydroacoustic and infrasound sensors record pressures on continuous waveform traces and measure physical phenomena similar to seismic data. For both technologies, the single-sensor processing suite adopted the same general approach as in seismic processing. Two distinct modules perform single-sensor processing. The first module, *DFX*, performs the detection and feature extraction on the waveforms and the second one, *StaPro*, uses the features extracted from the waveforms to classify detections among different types. This project served as the integrator of the single-sensor modules, developed under separate efforts (*Laney et al., 1996*, *Willeman et al., 1996*) into pIDC operations. Within this project, network processing for the acoustic technologies has been closely integrated with seismic network processing and detections of all three types are processed jointly within the same module. The initial phase type identification of seismic and acoustic phases is used to guide network processing.

The initial implementation of the single-sensor hydroacoustic signal processing detector and initial phase identifier, developed in a separate effort as well as an upgraded network processing module were integrated into pIDC operations in January 1997. The experimental pIDC network has received signals on a semi-regular basis from a limited set of five stations, among which three of them (WK30, ASCN and VIB) are located at the International Monitoring System (IMS) sites specified by the Treaty. In this initial implementation, the station processing module used a set of feature-based default rules to differentiate between three types of hydroacoustic detections: noise (*N*), in-water explosion (*H*), or mostly earthquake-generated underground source (*T*). A neural-net approach to perform initial phase identification has been later tested and adopted at hydroacoustic stations PSUR and WK30. The neural net process performs the same differentiation between *N*, *H* and *T* arrivals.

Infrasound processing was first introduced in January 1998. All infrasound stations of the pIDC experimental network consist of an array of four microbarographs, most with separations of a few hundreds of meters, smaller than the standard IMS design. The detector in place at the pIDC is a combined coherency and signal to noise ratio detector. Both coherency and amplitude measures have to exceed a threshold for a detection to be declared. Station processing simply differentiates between noise arrivals (*N*) and signal (*I*) based on the value of the trace (or phase) velocity measured by the detector and feature extractor.

At the time of publication of this paper, the three waveform technologies are processed operationally at the pIDC for all available stations, including publication of automatic and analyst-reviewed bulletins containing arrivals from all three sensor types.

We have developed a plan to integrate the radionuclide detections into a bulletin fusing all four monitoring technologies. The plan calls for fusion processing of radionuclide detections at and above level 4 (anomalous level of anthropogenic radionuclides). An analysis will be conducted, using atmospheric transport results to determine the likelihood that an individual radionuclide detection has the same origin as a Seismic-Hydroacoustic-Infrasound (SHI) event.

Figure 1 is a schematic representation of the current set of three automated processing pipelines at the pIDC, with, in addition, the planned fourth pipeline envisioned to process radionuclide detections.

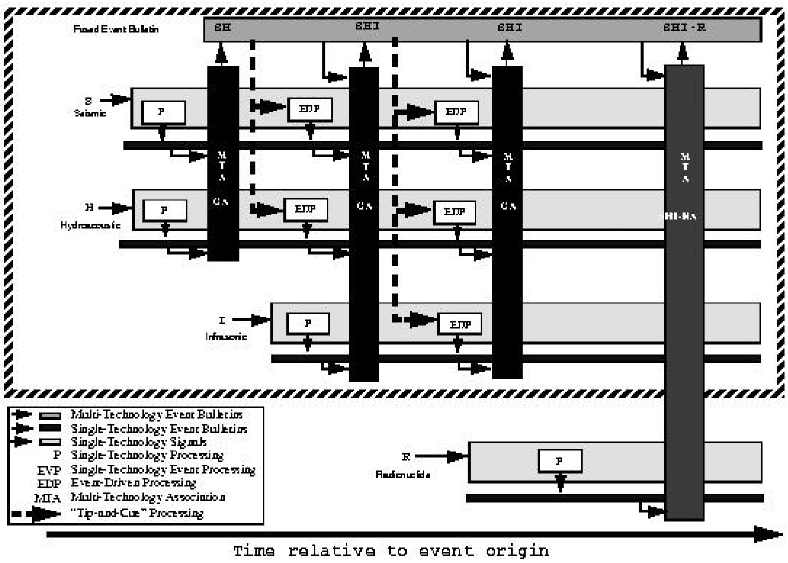

Figure 1. This schema represents the four pipeline processing configuration accomplishing fusion of all four monitoring technologies. The first three pipelines represented by the black vertical bars are currently implemented in pIDC operations by the GA system and produce multi-technology bulletins SEL1, SEL2 and SEL3, in order of increasing time. The fourth pipeline (in gray) represents the planned SHI-R fusion that will be done by a processing module to be developed, called SHI-RPA.

In the course of testing the different processing modules, we have gathered data from events of interest for all waveform technologies and performed a number of case studies. These case studies include sets of marine explosions from seismic refraction experiments in the Western Pacific, two atmospheric explosions with ground truth origin time and location, and mining events recorded at co-located seismic and infrasound arrays in Western Texas (TXIAR and TXAR). The marine explosions have provided useful data to test the hydroacoustic station processing module and in particular have allowed us to evaluate the phase identification module and test a cepstral-based bubble pulse delay extractor. Examination of the data from the atmospheric events in the White Sands Missile Range, for which ground-truth origin data is available, allowed evaluation of the detector and location modules. The mining events generated both seismic and infrasound arrivals and provided an opportunity to evaluate the usefulness of processing these two data types jointly.

<u>Operational Plans and Implementation at the pIDC</u>

Hydroacoustic

The principal mission of the hydroacoustic network is to detect underwater explosions and help in detecting lower atmospheric explosions. A large number of detections are recorded daily at the hydroacoustic stations when the current short-term average to long-term average (STA/LTA) signal to noise ratios are used in the detector. In the absence of discrimination between different types of arrivals, and of azimuthal information, since the current stations consist of single hydrophones, this large number of detections would lead the current network processing system to an unmanageably large proportion of false events (*Le Bras and Sereno, 1996*). Fortunately, station processing cuts down the number of detections to be considered by network processing by differentiating between underwater explosions (*H*), underground sources, mostly earthquake-generated (*T*), and noise detections (*N*). Whereas single-sensor seismic processing classifies individual detections based on their path of propagation, the approach taken by the single-sensor processing of hydroacoustic signals includes the source characteristics into the classification, thus performing some level of source discrimination at the level of single-station processing. A large number of features are measured on the hydroacoustic waveforms, for each of up to eight frequency bands. Classification into the three types of phases is performed either using a default set of rules on the frequency-dependent features or neural network weights adapted for individual stations. The default rules attempt to first identify positively the *T* phases mostly through their main characteristics of a long duration and low relative frequency content. Noise phases (*N*) are the next set of phases to be identified. Their frequency content characteristics overlap the *T* phase's frequency content, but they usually have a shorter duration. Finally, phases that do not fit into the *T* or *N* class are identified as in-water explosions (*H*). The main feature differentiators are a large ratio of high frequency to low frequency content and a short duration.

Network processing has been adapted to process hydroacoustic phase types. One of the main characteristics of hydroacoustic phases is that they propagate efficiently in the water column and that they can be blocked by significant continental masses after a few kilometers of underground propagation. To take this into account, blockage maps have been developed for individual hydroacoustic stations. They are taken into account by network processing to determine whether an association is expected or not given the blockage constraints on the path. The maximum distance of propagation in a given azimuthal direction obtained from the blockage maps is compared against the distance between source and station in every hydroacoustic association. Associations that are found to be along blocked paths are disallowed.

Blockage is taken into account at several stages of the automatic association process (or network processing). This includes an initial grid-based exhaustive search where the phase list attached to each grid point takes it into account for every station. Blockage is also checked after location to verify the legitimacy of each hydroacoustic association. Finally, blockage maps are first checked at the prediction stage before adding a hydroacoustic phase to an association set. An interactive tool has also been developed and presents either an alphanumeric window indicating whether a path is blocked or clear or a map showing the great circle path color-coded according to its blockage status.

At the time of the initial implementation of hydroacoustic processing, travel time for hydroacoustic phases was handled using a simple constant velocity (1485 m/s) model. This has been upgraded starting with release PIDC_6.0 where path-dependency was introduced. The travel time handler was further upgraded with release PIDC_6.1 to allow for seasonal dependency in addition to path-dependency. In addition, this last improvement included the capability to specify path-specific modeling errors for acoustic phases. The season and path-specific travel times can be generated for any hydroacoustic station with known location. Each station is user-configurable where the travel time uses by default the constant velocity model unless it is specified that the season and path-specific set of tables exist for the station and should be used. The path and season-dependent tables are generated using a ray-mode computation software, the Active Sonar Performance Model (ASPM), with DBDB5, a standard 5 minute bathymetry US Navy-provided oceanic velocity database. The theoretical travel time differences between a constant velocity model and these path-dependent travel times reaches a few tens of seconds and it is expected that their implementation will improve the fit with observed travel times. This has been observed and confirmed for a few specific paths (see section on case studies, in particular Figure 2). The seasonal dependence on a given path is not as significant as the difference between the constant velocity travel time and the path-dependent travel time and so far we have not put found any systematic variation with the seasons on pIDC hydroacoustic data.

The season and path-specific travel times are used for both *T* and *H* phases, however two differences are worth noting in the current configuration between these phase types. The first is that the travel time for *T* phases includes an underground path, usually short in length compared to the total distance between source and receiver, but undetermined. This is taken into account by adding a coupling term to the modeling errors for *T* phases. The second and most significant difference is that the *T* phases's travel time is not taken into account in the location as opposed to the *H* phase's travel time. The system is capable of locating a purely hydroacoustic event provided *H* arrivals have been detected and identified at a minimum of three stations. In the current configuration, *T* phases alone cannot form an event and they are always associated to pre-existing seismic events as non-defining phases and acquired by travel time prediction based on the origin time and location of the seismic event.

The vast majority of hydroacoustic phases associated to pIDC events are earthquake-generated *T* phases. A statistical analysis of the hydroacoustic results at the pIDC shows that for a two-year period starting in May 1997, the Reviewed Event Bulletin (REB) contains 13,532 *T* phases that are associated to 8,437 events. The number of events possessing a hydroacoustic *T* phase is about 25% of the total number of REB events when taking into account hydroacoustic stations down time.

At press time of this paper, no explosive marine events have been automatically detected and formed by the system, although there have been examples of automatic detections emanating from two series of small-yield marine explosions. Because of the low number of stations, the automatic detections were made at one or two stations and correctly identified as explosion-generated. The arrivals at the stations missing the detections had too low a signal to noise ratio to be detected. The fact that automatic processing correctly identified some of the arrivals as originating from in-water explosions incited the analyst into looking for additional detections and thus later completing the association set to a total of three stations. In both cases, the occurrence of the small yield explosions was independently confirmed.

A serious drawback of the current hydroacoustic network is that, although two existing stations (Wake Island and Ascension) as well as planned IMS stations consist of multiple hydrophones, no advantage is currently taken from that multiple hydrophone configuration. We are in the process of developing this capability and we are planning to include it within release PIDC_7.0.

Infrasound

The planned IMS infrasonic network is intended to detect unannounced atmospheric explosions anywhere on the globe. The design for IMS infrasound stations consists of an array of four microbarographs in a triangular pattern with a center element. Array processing for infrasound sensors is most similar to seismic array processing with the exception that the detections are based on a more sophisticated hybrid algorithm that takes into account a measure of waveform coherency in addition to the usual STA/LTA signal to noise measure. For a detection to be declared at an infrasound station, both measures must coincidently exceed a threshold specific to each measure.

The atmosphere is traditionally divided into different layers with altitude: the troposphere, stratosphere, mesosphere and thermosphere, in order of increasing altitude. Propagation of sound in the atmosphere is complex even in the absence of winds, due to the presence of two low velocity zones. For an atmosphere at rest, this sound velocity structure gives rise to three main groups of arrivals: the tropospheric, stratospheric and thermospheric arrivals. We are currently not attempting to differentiate between these different arrival types at the station processing level, although we are collecting a large set of feature measurements for each detection, which should help us in the future to identify these arrivals. In the current implementation of the initial phase identification module, a very simple phase velocity-based rule is used to differentiate detections between noise detections which are called *N* and signals of interest, which are all indiscriminately assigned the generic phase type *I*. Detections are considered to be signal of interest (*I*) when their phase velocity is between two bounding values, currently set at 290 m/s and 660 m/s.

The current version of network processing (PIDC_6.1) has integrated the infrasound phase type by modeling the infrasound propagation as a single phase with a large time modeling error to account for the possibility that a given observed phase may be one of the three arrival types. The azimuth measurement is very precise and contributes the most to event location. The location algorithm will always locate an event at the surface if it includes an infrasound arrival (either purely infrasound or mixed event). There is currently an upper limit of 60 degrees on the range at which infrasound arrivals will be associated.

The travel time handling system has the capability to use station-specific and path-dependent travel times calculated using average seasonal wind patterns and we are in the process of integrating such tables for operational stations into the PIDC_7.0 release.

The operational results at the PIDC show on average a low number of automatic infrasound associations (492) and automatic pure infrasound events (57) since implementation of release PIDC_6.1, between December 2, 1998 and August 2, 1999. The main characteristic of the distribution of pure infrasound events is its extreme irregularity with time. We observed a large number of automatic events in early December 1998, including one that was later confirmed and included in the REB.

Radionuclides

Twenty-two radionuclide stations currently exist and are operational, with an additional 58 stations planned to reach the total of 80 stations proposed in the CTBT. At each station, particles are collected continuously from the passing airmass for 24 hours. Each sample is then allowed to age for another 24 hours so that "background" radionuclides that may interfere with measurement can decay away. The radionuclide content of the sample is then determined through gamma ray spectroscopy. If anthropogenic radionuclides are detected, the sample is assigned a level 4 or 5 (respectively single or multiple anthropogenic radionuclides) alert status.

Meteorological measurements from the NOAA database and meteorological modeling software are used to determine the trajectories covered by the airmass. This locus of points in time and space from which the detected radionuclides might have been released is called the Field of Regard (FOR) of the sample.
The NOAA data set consists of wind velocity measurements gathered at 24-hour intervals at points on a regular grid covering the globe. OMEGA is a weather modeling prediction program used to calculate wind velocities at the grid points to a temporal resolution of 1 hour by modeling the airflow between the two endpoints that bound the 24-hour interval.

This information is used to simulate particle releases from each grid point at 1-hour intervals for a period of 3-14 days before a given sampling period. The locus of points from which a particle released a certain period of time before a sampling period has a significant probability of being detected in the sample is called the sample's Field of Regard for that time period used to calculate high resolution FORs and several other related data products. A radionuclide detection with a level 4 or 5 alert status triggers OMEGA to calculate 72, 48 and 24 hour FORs for the detecting station and sampling period. Automating radionuclide association to SHI events, then, consists simply of searching for events from the Standard Screened Events Bulletin (SSEB) whose error ellipse has an intersection with a field of regard for a level 4-5 alert sample and whose origin time is compatible with the FOR's time period.

Particle trajectories could also be used to improve on the 24-hour granularity of the FORs, however the size of the FORs is usually of the order of at most a few error ellipses and the added complication of performing trajectory interpolation may not be worth the small gain in resolution.
Unlike the other three technologies in the Fused Event Bulletin, radionuclide detections represent direct physical evidence of a nuclear reaction at least, possibly of an explosion. Hence, greater care must be taken when publishing data relevant to this technology to avoid the appearance of making an accusation. In the context of the automated IDC system, an association drawn between a radionuclide detection and an SSEB event should not and cannot be construed as a claim that the SSEB event was indeed the source of the radionuclides. The association must be understood to indicate only that a detection of anthropogenic radionuclides was made at a station and that if such nuclides had been released from the location/time of the SSEB event, the probability of their being detected at that station in that sample is significant. Neither

of these offers any basis on which to calculate the probability that such radionuclides *actually were* released from the location/time of the SSEB event.

Case studies

Marine explosions

In the course of testing hydroacoustic signal processing algorithms to characterize explosion sources from earthquake-generated *T* phases, a series of over 100 distinct signals were identified at the two Pacific hydroacoustic stations: Point Sur, California (PSUR), and Wake Island (WK30). The distance between the two stations is about 41°. The signals were grouped in three distinct 8- to 10-hour long subsets from September 6 to 10, 1996, and clearly emanated from in-water explosions because of the presence of bubble pulses identifiable in their spectrum, cepstrum and autocorrelation. Furthermore, individual events could be correlated between the two stations and the time separation between them was quasi-constant (12-15 minutes). These characteristics pointed to human activity, and more specifically, to a seismic refraction survey as the source of these events. Since PSUR and WK30 were the only stations that recorded the series of explosions, no definite location was attempted. The locus of possible locations was a line crossing the Pacific Ocean from the coast of Antarctica, passing between Australia and New Zealand up to Northern Japan.

After some investigation, we established that the signals observed at these two stations emanated from a seismic refraction survey conducted by a Japanese scientific crew offshore northern Honshu, Japan (*Ryota Hino, 1998, personal communication*). The underwater explosions ranged from 20 to 400 *kg* in size, and were detonated at approximately 28° from WK30 and 71° from PSUR. The comparatively small size of these explosions, and the fact that they were recorded with good signal to noise ratios at cross-oceanic distances illustrate the extremely good propagation characteristics of the oceans. An explosion of interest to the monitoring community would be detected at long distance ranges provided that there exists an oceanic path between the location of the source and the hydrophone. The signals generated by the refraction survey allowed us to evaluate the performance of automated processing programs and partially validate path-dependent hydroacoustic travel times tables. Marine refraction surveys such as this are now rare in the oceans and this ground truth data set is of great interest to validate propagation models and processing techniques.

Knowledge of the ground truth information for this set of marine explosions allowed us to establish the reliability of our detection and phase identification processes as well as of the cepstral delay time measurements. We established the extreme consistency of the delay times between the two stations that recorded the explosions. While variations from explosion to explosion were found to vary by about 0.02 seconds, likely due to differences in yield and depth, the difference between measurements at the two stations for the same explosion are within 0.002 second of each other. This makes the cepstral delay a suitable attribute to use as an association criterion. We were able to evaluate and validate path-dependent hydroacoustic travel times derived from a standard database of US Navy measurements. Synthetic travel times computed with the 2D station-specific travel time model were within five seconds of the observed travel times, whereas travel times generated assuming a constant hydroacoustic velocity were up to 40 seconds too early. Clearly, the predicted travel times benefit from using path-dependent travel time tables for each station, rather than a constant velocity model.

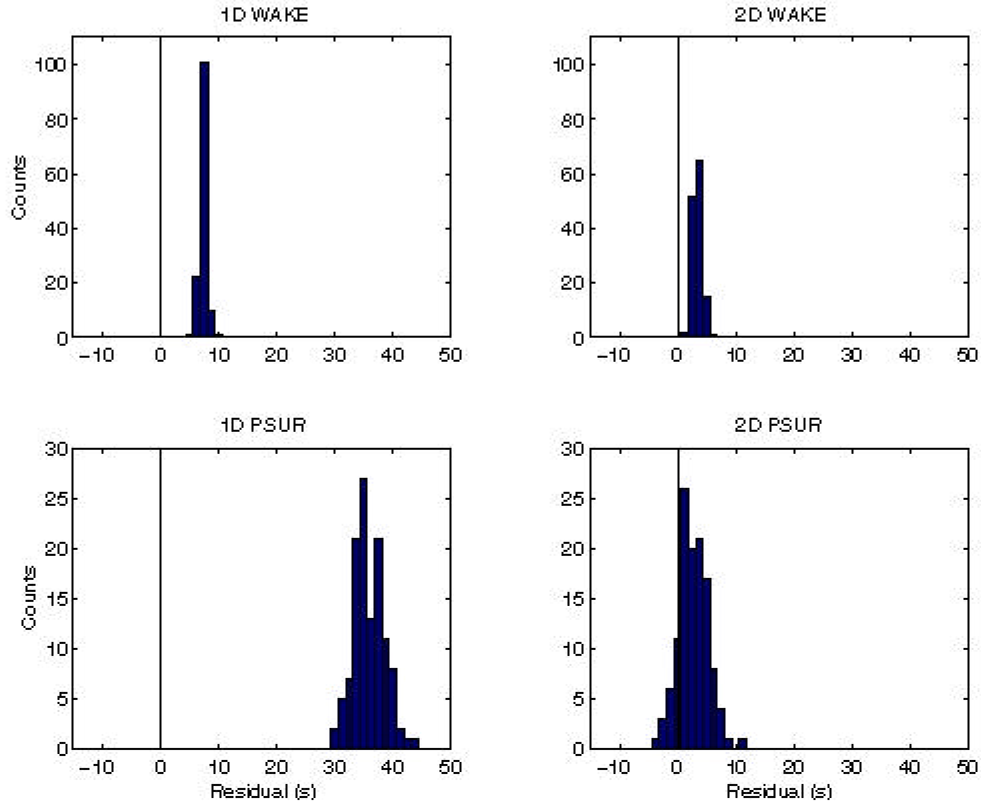

Figure 2. Histograms of travel time residuals (observed minus predicted travel times) computed at WK30 and PSUR using both the 1D constant velocity model and the 2D travel time tables. Note the vertical scale on the histograms differs between WK30 and PSUR. A significant improvement in travel time accuracy is obtained when the 2D travel time tables are employed, particularly for PSUR detections.

Low altitude atmospheric explosions

Two lower atmospheric explosions at the White Sands Missile Range in November 1997 provided us with ground truth data against which to test our infrasound processing modules and propagation models. A detailed study (*Jenkins et al., 1998*) of these two explosions, which occurred at one week interval from each other, pointed out variations in travel time (17 seconds difference at station LSAR for the first arrivals) and character of the waveforms between the two events. There were however similarities in the duration of the wavetrain within which individual arrivals can be correlated from one event to the other at both stations. A general observation is that the phase velocities of arrivals show an increasing trend with time within the wavetrain, consistent with the interpretation that they are sampling higher and higher layers of the atmosphere.

Mining events

Examination of two mining events for which both seismic and infrasound waveforms were available has yielded information on infrasound propagation at close regional distances. Both events were recorded at seismic station TXAR and infrasound station TXIAR and the data were provided to us by J. Bonner from Southern Methodist University (*Sorrels et al., 1997*). One of the events occurred on October 4, 1996 in the Micare coal-mining district in Northern Mexico and is referred to as the Micare event. The other event occurred on October 11, 1996 in a mining district in New Mexico and is referred to as the Tyrone event. A detailed study of the events is available in *Flanagan et al. (1999)*.

The observed lone infrasonic arrival from the Micare event is likely a thermospheric arrival. The infrasound arrival from that event has a total travel time of 20 m 18.3 s, is more consistent with the expected wave group velocity from thermospheric arrivals (around 245 m/s) than for tropospheric arrivals (around 320 m/s). This is further confirmed by its high phase velocity (376 m/s). The Tyrone event, with its seven separate infrasound arrivals, yields a variety of phase velocities, but it is difficult to observe a strong trend of increasing phase velocities with increasing travel time, such as was observed for the White Sands ground-truth explosions in *Jenkins et al.* (1998), as the quality of the arrivals for this event is not as high. The main conclusion of this study is the apparent ability of the infrasound sensors to contribute significantly to the location process by decreasing the size of the error ellipses when infrasound detections are combined with seismic detections, as illustrated by Figure 3. The default modeling errors for azimuth currently in place at the PIDC (0.102 s/km) were used in the locations and were found to lead to location solutions that include our best estimates of the ground-truth locations.

Another significant conclusion is that processing of infrasound data may benefit from using an approach complementary to the classical F-K analysis. An envelope function approach to slowness-azimuth determination was successful in determining a more accurate azimuth than a classical F-K approach. This suggests that envelope functions may be more reliable for characterizing infrasound data when a lack of signal coherency across the array prevents a classical FK analysis.

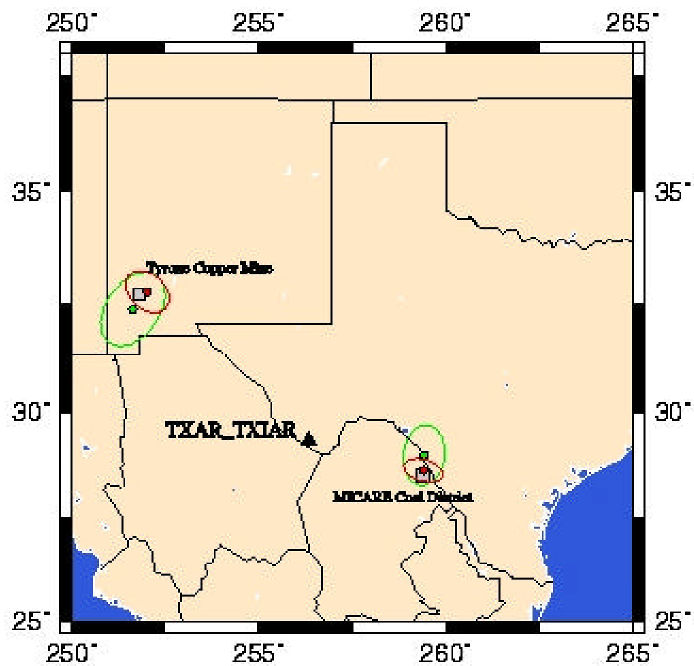

Figure 3. Estimated locations of October 4 and October 11, 1996 explosions. The circles on which the larger error ellipses (green) are centered indicate locations estimated using the Pn and Lg arrivals only while the centers of the smaller error ellipses (red) indicate the final locations estimated using the first infrasound arrival, I, together with Pn and Lg to form the location. The 90% error ellipses are computed in all cases. Note the improvement in the azimuth and reduced area error ellipse of the combined seismic-infrasound location. The actual mine locations are represented by the gray squares.

CONCLUSIONS AND RECOMMENDATIONS

We have implemented in pIDC operations a processing suite that demonstrates the feasibility of doing joint network processing of detections from the three waveform technologies, seismic, hydroacoustic and

infrasound. We have also analyzed a few examples of waveform data from events of interest to the monitoring community to show the validity of our processing suite on these special events.
More work remains to be done to take full advantage of the acoustic data types. For instance, the hydroacoustic stations of the IMS are planned to consist of groups of multiple hydrophones. To take advantage of this configuration and enhance the usefulness of hydroacoustic arrays, we are in the process of developing a module to jointly process hydroacoustic arrivals to obtain an azimuth at hydroacoustic stations.

While the hydroacoustic propagation model in place takes into account blockage as well as path-dependent and seasonal variations and is thus quite elaborate, infrasound is still using a constant velocity model. This implies that the modeling errors are large, leading to potentially erroneous associations. One of the goals of planned enhancements to the infrasound propagation model is to match travel times better and allow for smaller travel time modeling errors.

Case studies have proven quite useful in evaluating the pIDC processing software and more should be conducted to evaluate the planned enhancements, for example comparison of ground truth infrasonic travel time data with existing models.

REFERENCES

Hanson, J., R. Le Bras, P. Dysart, D. Brumbaugh, A. Gault and J. Guern, Operational Processing and Special Studies of Hydroacoustics at the Prototype International Data Center, submitted to *P. A. Geoph.*

Flanagan, M., R. Le Bras, J. Hanson and R. Jenkins, Analysis of Two Mining Explosions Recordings at the TXAR Seismic and Infrasound Arrays, *SAIC Tech. Report, 99/3002*, 25pp., (1999).

Jenkins, R., C. N. Katz, R. Le Bras, and T. Sereno. Ground-Truth Analysis of Explosions Recordings at LSAR and TXIAR Infrasound Arrays, *SAIC Tech. Report 98/3035*, 25pp., (1998).

Laney, H., P. Dysart, H. Freese and R. Willemann, An automated system for detecting and classifying in-water explosions and T-phases, *J. Acoust. Soc. Am., 100, 2641*, (1996).

Le Bras, R. and T. Sereno, Monitoring the Earth for Nuclear Testing in Underground and Underwater Environments, *Processings of the 1996 AGU Fall Meeting* (1996).

Sorrells, G. G., E. T. Herrin, and J. L. Bonner, Construction of regional ground-truth databases using seismic and infrasound data, *Seism. Res. Lett., vol. 68, no. 5,* 743-752, (1997).

Willeman, R., H. Laney, P. Dysart and H. Freese, A global monitoring system for a nuclear test ban treaty, *J. Acoust. Soc. Am., 100, 2642,* (1996).