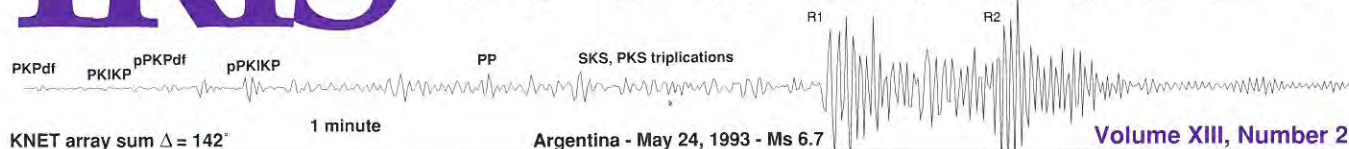


# IRIS Newsletter



## Contributions of IRIS Data to Nuclear Monitoring

Danny Harvey and Roger Hansen, IRIS Joint Seismic Program Center, University of Colorado

Since 1988, when the Joint Seismic Program (JSP) was established between the U.S. and the U.S.S.R., IRIS has played a pivotal role in the establishment of new seismic observatories throughout the world and especially in the vast and previously inaccessible regions of Central Asia. After the demise of the Soviet Union, this prolific increase in seismic instrumentation led by IRIS has, if anything, accelerated. Among the reasons for this acceleration have been the needs to reduce the danger to society from both earthquakes and the spread of nuclear weapons.

We expect the large numbers of seismic observations that have accrued from the IRIS deployments to significantly contribute toward solving the problems associated with nuclear monitoring especially in the context of nuclear nonproliferation. However, there have been no definitive studies to quantify the capabilities of IRIS data that have involved direct observations of both signal propagation characteristics as well as noise characteristics.

At the Joint Seismic Program Center (JSPC) we have recently conducted such a study for Central Asia using waveform data recorded by the various components of the IRIS JSP, including the Global Seismographic Network (GSN), the JSP networks in Kyrgyzstan and the Caucasus and the JSP seismic array in Turkmenistan, as well as other open data from the Chinese Digital Seismic Network (CDSN) and GEOSCOPE. Our intent was to quantify the detection capabilities of IRIS sites in order to predict detection and location magnitude threshold contours based upon direct

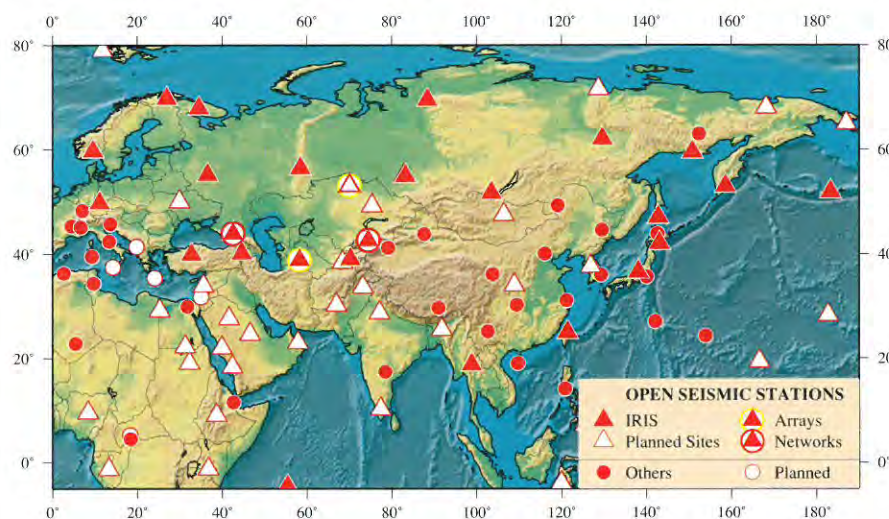


Figure 1. Overview map of Asia shows stations, networks and arrays used in this study.

observations of signal propagation characteristics in the study region. We also were interested in assessing other equally important contributions of IRIS data, such as the characterization of regional wave propagation, location of seismic "sweet spots" for clear seismic signal reception and the contributions of IRIS data toward source identification.

The IRIS JSP has a unique blend of seismic capabilities ranging from the very broad band capabilities of the IRIS GSN stations, which provide good

wavefield characterization at long periods to the very high frequency seismic array site in Turkmenistan, which provides good seismicity coverage and helps in our understanding of high frequency regional wave propagation in the Middle East. We have found in our analyses that combining these wide ranging resources provides a comprehensive view of seismology which can be used to address the important issues of nuclear monitoring: source detection and location, effects of

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## What's Inside

### Special Section on JSP Arrays and Nuclear Monitoring

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earth structure, wave propagation characteristics and source identification. An overview map of this region with the stations, networks and arrays used in this study is shown in Figure 1.

### Bulletin/Catalog Production from IRIS JSP Data

The first step in generating network magnitude thresholds involved the production of four event bulletins based upon waveform data from IRIS, CDSN and GEOSCOPE stations. The first bulletin used only triggered data streams from the JSP Kyrgyz Network (KNET) covering an 11 month period, starting in September of 1991. The second bulletin used only triggered data streams from the JSP Caucasus Network (CNET) covering an 11 month period, starting in January of 1992. The third bulletin combined continuous data from KNET with IRIS GSN data and triggered data from GEOSCOPE and the CDSN in the production of a Central Asian Bulletin (CAB) for the month of May 1992. The fourth bulletin consisted of continuous data streams of the small aperture JSP Geyokcha array, using beam triggering processing as well as corresponding waveform segments from the co-located GSN station, ABKT.

The bulletins and catalogs for the networks were produced in traditional fashion by measuring seismic arrival onset times from the waveform data and using these arrivals to locate events and/or to correlate observed arrivals with events from existing catalogs which, for these bulletins, was the USGS PDE catalog. Seismicity plots from these bulletins are shown in the following articles that are concerned with the JSP networks. The bulletin and catalog for the seismic array was produced by f-k analysis to determine azimuth and slowness in conjunction with measured P and S onset times from the best beams. In all we analyzed 58,144 waveform segments from 29 stations to pick 18,388 signal arrivals from 2,444 events. The event distribution includes known industrial explosions, underground

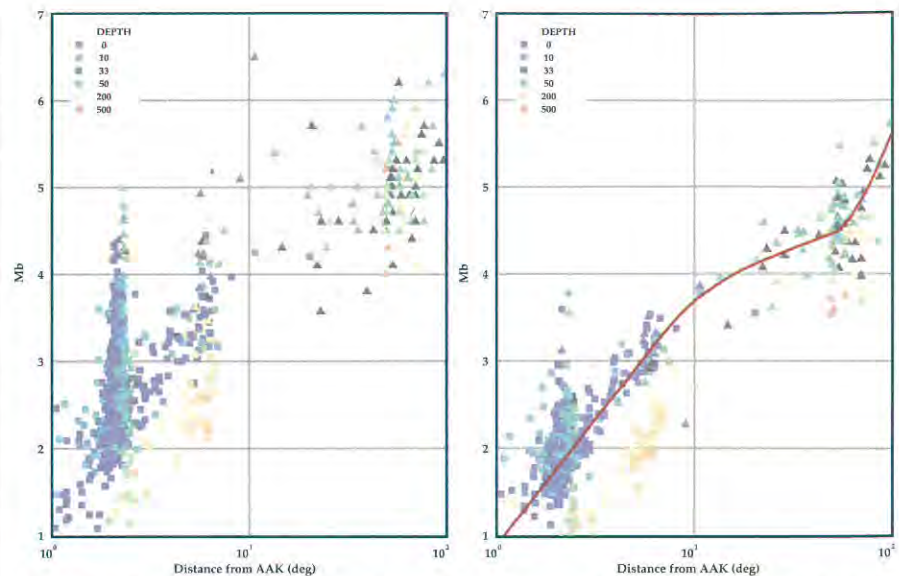


**Figure 2.** On the left (a) is a plot of  $m_b$  magnitudes vs. distance from station AAK with symbols color coded according to depth. The plot on the right (b) shows the same events after scaling the magnitudes to an equivalent signal to noise ratio of 2.0. A characteristic single site detection magnitude threshold function for shallow events seen at station AAK has been fit to the scaled magnitude points.

nuclear tests and earthquakes over a region extending from the Black Sea to the seismic zones of the Western Pacific. In addition to measuring onset times and onset time uncertainties for each P and S arrival, we also measured amplitude, period and signal to noise levels for P arrivals. All of these data, measurements and parameters are available, or soon will be available, from the IRIS DMC as JSPC Information Products.

In addition to the quantitative measurements that were made during the construction of these bulletins, we were able to make a number of qualitative observations about the nature of wave propagation in the Central Asian region as we were scanning the recorded waveforms. These include:

- Seismicity levels in the continental collision zones that typify this region are much higher than those in other areas that have received attention in the context of nuclear monitoring, such as the Western U.S., and the U.S.S.R. test sites. The nuclear test site at Lop Nor is the only site within this region of high seismicity. Consistent monitoring of this region to a low magnitude level will generate much larger catalogs than we have been used to dealing with.

- Wave propagation characteristics are highly variable over relatively short distance scales throughout this area especially at regional distances. We saw no consistent relationships between various regional phases, such as  $p_n$  and Lg. The most capricious phase was Lg. We observed a wide variety of propagation effects including blockage or enhancement of particular phases as well as blockage or enhancement of entire wave trains.

- The most consistent phases for picking arrivals and locating events were the direct P and S phases. Attempts to use other secondary phases for either detection or location purposes caused reductions in the completeness and accuracy of the catalogs. We interpreted this as being indicative of the complex dependence of wave propagation on three-dimensional structure in this area and points out how "standard" processing techniques for regional seismic data must adapt to areas of complex tectonic activity like Central Asia.

### Single Site Determination of Detection Magnitude Thresholds

Event  $m_b$  magnitudes were computed using either the reported PDE  $m_b$  values

or JSP network average  $m_b$  estimates. The  $m_b$  estimates from the JSP network data were corrected to produce zero mean statistics for the PDE relative residuals. All  $m_b$  estimates were made in the 0.8 to 3 Hertz pass band.

Single site  $m_b$  vs. distance functions give us the raw information for determining single site detection magnitude thresholds. Figure 2a shows such a function produced from events in the Central Asian Bulletin for station AAK, where triangles represent events that were in the PDE catalog, squares represent events that were not in the PDE catalog and the symbols are color coded according to event depth. In a traditional analysis of single site detection magnitude thresholds, one would create a map view equivalent of Figure 2a, put events into regional bins, compute magnitude-frequency functions for each bin and set the magnitude threshold for each in according to some roll-off criteria applied to the magnitude-frequency functions. However, this method requires very large numbers of events—certainly many more than were

available to us from the IRIS JSP catalogs.

Another problem with the magnitude-frequency method is that it is susceptible to biases related to performance of the data acquisition systems that are difficult to calibrate and remove from the results. In particular, we refer to the effects that triggering systems have upon detection statistics. All of the CDSN and GEOSCOPE data used in the preparation of the JSP bulletins as well as data from the Caucasus Network came from triggered data streams. Data from the IRIS GSN, the Geyokcha array and Kyrgyz network were from continuous data streams. In our experience with the Kyrgyz Network, which has both triggered and continuous broadband data streams, we found that we could consistently detect events on the continuous channels at almost a full magnitude unit below what the triggered channels were recording. We expect that the same thing is happening with the CDSN and GEOSCOPE data.

We have developed and applied an alternate method for determining single

site detection magnitude thresholds which should yield reasonable results from relatively small catalogs and should also help to eliminate the magnitude-frequency biases introduced by triggered systems. Our method is based upon using P wave signal to noise ratios observed at a given station to scale event magnitudes to equivalent threshold values for that station. This is done by adjusting the event magnitude by an amount equal to the logarithm of the ratio of the observed signal to noise level and a threshold signal to noise level representing the minimum level at which a signal would be detected. The assumption here is that the wave propagation is a linear process so that amplitude can be scaled directly. This approach allows us to scale down large magnitude events to equivalent smaller events that would be at the detection limit for each particular source-receiver geometry.

The results of this method applied to the events shown in Figure 2a are shown in Figure 2b for station AAK and for a specified detection threshold signal to noise level of two. We can see that the magnitude scatter in Figure 2a is considerably reduced by applying the signal to noise based scaling and the populations of shallow and deep events clearly separate as one would expect. We have fit a characteristic  $m_b$ -distance function for shallow events to the points in Figure 2b and this is shown as the solid line.

This signal to noise based method for determining single site detection magnitude thresholds has been applied to all of the CDSN sites, the GEOSCOPE site at WUS, the KNET sites of AAK, CHM, EKS2, TKM, KBK and USP, the CNET sites of KIV, NAG, GUM, MIC and KUB, the Geyokcha array site and the IRIS GSN sites of OBN, KIV, ABKT, AAK and GAR. A composite of the  $m_b$ -distance functions for these sites is shown in Figure 3 for shallow events. We can see large variation in single site detection magnitude thresholds spanning almost a full magnitude unit over all distances. The least sensitive sites are the CDSN

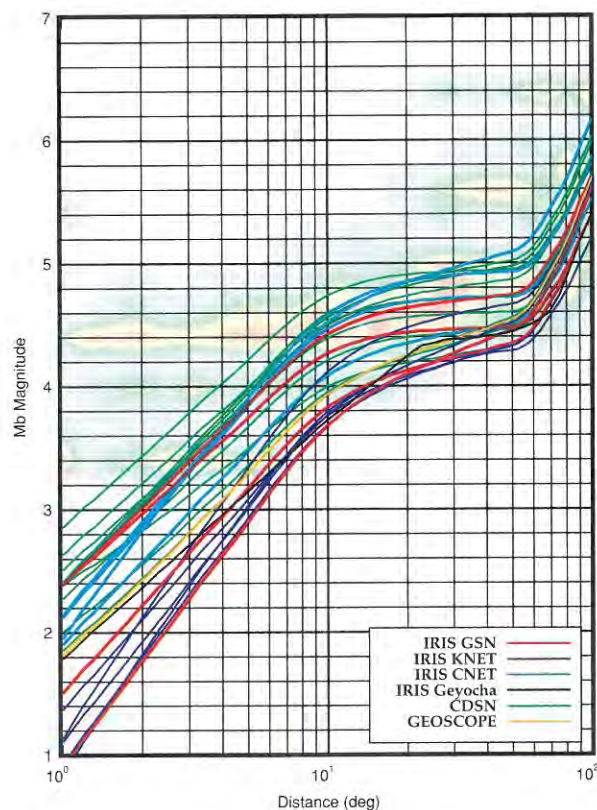


**Figure 3. A composite plot showing single site detection magnitude threshold functions for shallow events using signal to noise ratios of 2.0. The background color contours represent a distance normalized histogram function which was produced by counting the numbers of stations reporting P arrival picks as a function of event-station distance and  $m_b$  magnitude. The station bulletin used for the histogram contours came from the worldwide USGS Earthquake Data Report (EDR) for the month of May, 1992. Red contours represent high numbers and blue contours represent low numbers.**

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stations near the eastern Chinese coast and the most sensitive sites are those in the Kyrgyz network and surrounding areas. The IRIS GSN sites range from the sensitive sites of AAK and GAR to the average sites of KIV and ABKT, to the below average site at OBN.

One way of testing the validity of the functions shown in Figure 3 is to compare them with equivalent results from other bulletins. However, most bulletins do not include signal to noise measurements. In lieu of a direct comparison, we offer a comparison with the USGS EDR bulletin for the month of May, 1992 which is based upon a simple tally of the

numbers of stations reporting P arrivals as a function of magnitude and station-event distance. This is shown in Figure 3 as color contours. We can see that our estimates of detection magnitude thresholds are consistent with the worldwide single site characteristics determined from the EDR bulletin.

### Network Location and Detection Magnitude Thresholds

Empirically derived single site detection magnitude threshold functions provide the input for the determination of network detection and location magnitude thresholds. By using functions such as those shown in Figure

3, which implicitly account for both noise levels and wave propagation effects, the task of computing network magnitude thresholds is relatively straight forward, at least in principle. The approach is:

- Grid out a region of interest in map view.
- At each grid point compute a list of distances to the stations in the network.
- Look up the associated detection magnitude threshold value for each station and place these magnitude values in a list.
- Sort the magnitude list by increasing order.
- Take the  $n$ 'th magnitude value from the sorted list as the network magnitude threshold for that grid point. The number  $n$  is the minimum number of stations requirement for producing a reasonable location estimate.

There is a problem with following this simple recipe for determining

location thresholds when the mix of sites includes single stations, local networks and seismic arrays. We could treat each seismic sensor location as a single "station" in determining a phase threshold, however this would accentuate the networks and arrays over the single stations. This accentuation of the networks and arrays is proper close-in to the sites, since they can operate to locate an event with a reasonable degree of accuracy, however, for a network or array, the location accuracy will deteriorate until, at teleseismic distances, the event location will be poorly determined. At the other extreme, if we treat a seismic array or network as a single station, then we are neglecting the additional azimuth and slowness information that these sites provide.

Our approach in combining data from single stations and networks/arrays is to count each network or array as two single stations in determining location thresholds at far distances. This takes into account the fact that networks and arrays provide additional azimuth and slowness information which is difficult or impossible to reliably obtain through polarization analysis of single stations. Thus, using a three station criterion, an event could be located with either three single stations, one network/array and one single station, or two networks/arrays. This provides us with a reasonable way of integrating the different elements within the IRIS JSP.

Applying the rules described above, we have constructed a network location magnitude threshold plot for Europe and Asia, shown in Figure 4, using a three station criterion, for all IRIS, GEOSCOPE, CDSN and MEDNET open sites that exist now, or are planned in the next several years. The single site detection threshold functions were determined according to the single site analyses we described previously for a threshold signal to noise level of two. For new sites or for sites that we have not analyzed, we assigned average single site detection threshold functions except in a few cases where we expect the site characteristics to be significantly

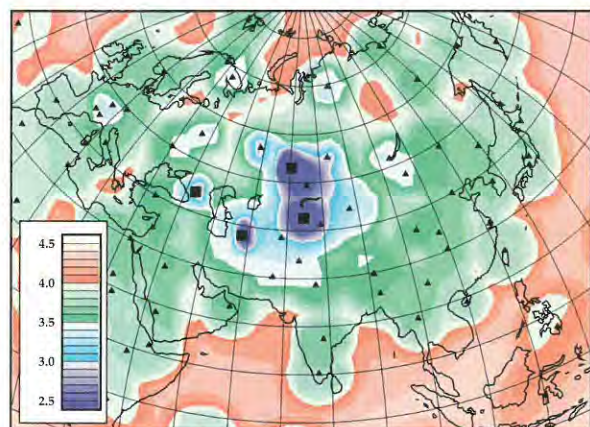


**Figure 4.** Location magnitude threshold contours using all current and planned IRIS, CDSN, GEOSCOPE and MEDNET stations. Threshold parameters are three stations with a signal to noise level of 2 in the 0.8 to 3.0 Hertz frequency band at the least sensitive station. Networks and arrays count as two stations at far distances. Triangles are GSN stations and squares are networks or arrays.

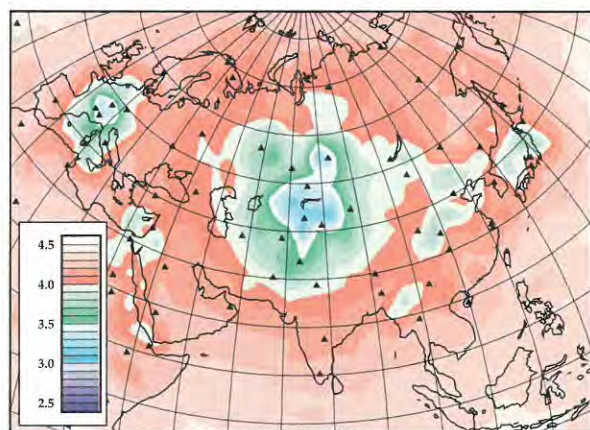


**Figure 5.** Location magnitude threshold contours using the same data as in Figure 4 but removing the IRIS JSP networks and arrays.

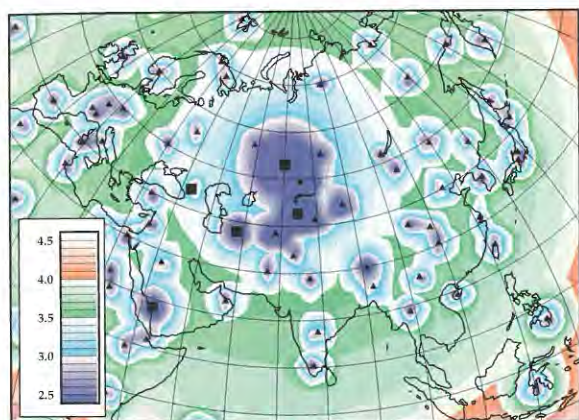


Figure 6. Single station detection magnitude threshold contours using the same data as in Figure 4.

different from the average. These exceptions include the two planned sites in Kazakhstan, at Borovoye and Karkaralinsk, and the replacement site for Garm, Tadjikistan, where we have experience which indicates that these sites will be better than average. For the planned seismic array site at Borovoye, Kazakhstan, we used the Borovoye single site function and decreased the threshold values uniformly by 0.6 magnitude units.

We can see from Figure 4 that the IRIS data, combined with other single station open data, provides a location threshold of somewhat below  $m_b = 4.0$  over most of Eurasia with good coverage of the Middle East. The location magnitude threshold enhancement of the JSP networks and arrays can be clearly seen by comparing the results in Figure 4 with those of Figure 5, which shows the location magnitude thresholds when we remove the networks and arrays and include only the GSN stations. Removal of the arrays results in an increase in the location threshold of about 0.5 magnitude unit over most of Asia. However, by combining the far ranging sensitivity of the arrays with the close-in recordings from the nearest GSN stations, we can achieve reasonable location accuracy while obtaining local/regional recordings which will be vital for source identification of small events.

In order to assess the capability of IRIS data to contribute to the parameterization and identification of

events that have been detected, at least in a preliminary fashion, by a primary or alpha network, we show single station detection threshold contours in Figure 7. This shows the areas over which seismic events of various magnitudes will be recorded by at least one GSN, network or array facility. As can be seen in the figure, IRIS data will enhance event

identification down to magnitude 3.0 - 3.5 in most areas, and below magnitude 3.0 in many areas.

### Other Issues Relevant to Nuclear Monitoring

The process of determining location magnitude thresholds involves a certain amount of averaging that obscures the importance of particular sites. In this study we have averaged single site detection thresholds over azimuth. In most other studies that try to predict or compute network location thresholds, averaging is implied at some level. We have learned from our Russian colleagues that one of their approaches for monitoring the U.S. nuclear test site in Nevada involved looking for seismic "sweet spots" for signal reception in the old Soviet Union to the U.S. NTS and this search resulted in the site at Borovoye which has remarkably good seismic sensitivity to NTS.

Some seismic sites have good

propagation characteristics to specific spots on the Earth and others such as Borovoye, have good propagation characteristics to most regions of the Earth. Identifying such sites is mostly a trial and error process that involves putting in as many stations as possible and picking out the good ones. We know that it is usually difficult or impossible to predict where a seismic "sweet spot" will occur. The siting of the NORESS array was determined by picking out the sub-array of the original NORSAR which was most sensitive to the Kazakh Soviet test site — a procedure based upon observations and not predictions.

The numbers and coverage of IRIS stations provide an example of the spatial sampling that we need to locate particularly good seismic sites and this is illustrated in Figure 7. This figure shows seismic waveform data from a Chinese nuclear test at two stations of the Kyrgyz network within several degrees of each other, at a distance of about 10 degrees. We can see a large disparity in amplitudes at regional distances for the KNET stations. Noise levels are about the same at both sites and when we observe teleseismic arrivals at the two sites the amplitudes are approximately the same. From this example we observe that the site at KBK provides much better regional sensitivity to the Chinese test site at Lop Nor than the site at EKS2.

### Conclusions

The IRIS JSP has lead the way in establishing new state-of-the-art seismic

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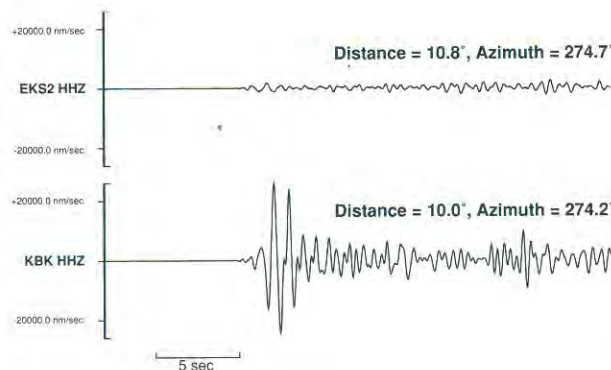


Figure 7. Waveform comparisons for the Chinese nuclear test of 5 October 1993. Both traces are have been bandpass filtered from 0.8 to 3.0 Hz and converted to physical ground velocity units which are shown on the scales to the left. Amplitude plot scales are constant for both stations.

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instrumentation throughout the world and especially in Central Asia and the Middle East. Just as important, the IRIS JSP has endorsed and supported a wide variety of siting configurations including single stations, local/regional networks and arrays. The network and array data provided by IRIS to the scientific community represent the only generally available digital seismic data of this type from the Central Asian and Middle Eastern regions, other than from short running experiments.

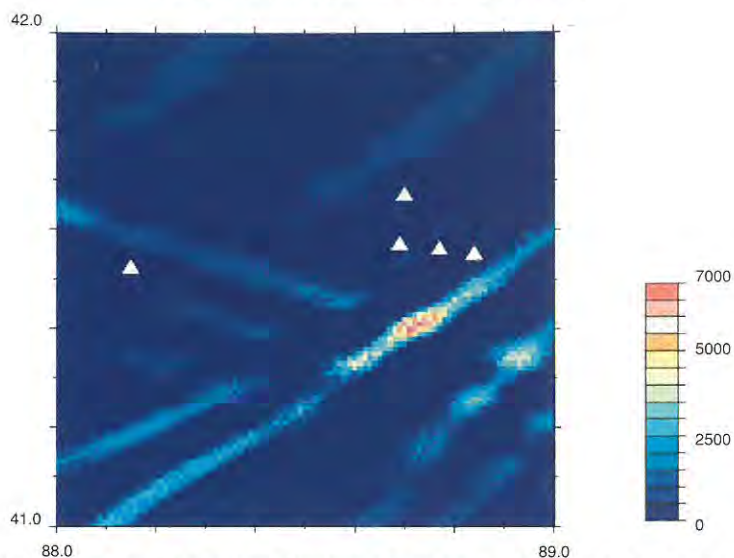
The characterization of regional wave propagation in complex tectonic regions like Central Asia requires direct observations and cannot be reliably extrapolated from the characteristics of other regions. The nature of regional wave propagation has a direct influence on our ability to locate and identify seismic sources.

The identification of particularly good seismic propagation paths requires the establishment of as many seismic sites as possible at local, regional and teleseismic scales. The IRIS JSP provides an optimum mechanism for making such assessments. Data from IRIS sites will be essential for determining the locations of permanent monitoring facilities.

The uniform spacing approach of the GSN gives us good wavefield coverage, especially for longer periods, at the expense of seismicity coverage for smaller events. We have found that clustered spacing, using seismic networks and arrays, significantly enhances seismicity coverage of small events in relatively large regions of interest. Other articles in this issue will show how networks and arrays contribute to wavefield coverage, especially in the higher frequency bands. By combining the capabilities of a global, single station, network with those of appropriately sited regional networks and arrays, we can bring a comprehensive range of seismic data resources to bear upon the scientific and technical problems relevant to nuclear monitoring. •

## Chinese Nuclear Test - June, 1994

*Terry Wallace, University of Arizona*



**Map of the area around the Lop Nor test site in northwest China. A twenty second window centered on the P wave is stacked for 11 GSN stations. The stacking is done by assuming a location and origin time. The area is gridded on .01 degree squares, and time is gridded on .1 second intervals. The map shows the "power" of a 3 second window for 10,000 possible locations — the best location from the stacking is about 41.41 N 88.72 E. The white triangles give the locations of Lop Nor explosions since 1988.**

On June 10, 1994 the Peoples Republic of China conducted a nuclear weapons test at the Lop Nor test site located in Xinjiang Uygur Autonomous Region. The explosion was well recorded by the GSN. The JSP Center located the event at 41.90 N, 88.67 E and determined a magnitude of 5.81.

The Chinese have conducted 18 underground tests at Lop Nor and this was the second test in less that a year. Since the fall of 1992 the rest of the nuclear powers have observed a moratorium on weapons testing as a prelude to negotiations for the renewal of the Non-Proliferation Treaty (NPT). The Chinese test was widely anticipated and China may now join the testing moratorium.

Telemetry and SYPDER made it possible to perform analysis of the Chinese explosion in near real time. The utilization of true "open" data may serve as a role model for future monitoring strategies.

As illustrated in the above figure, it is possible to use the waveforms from broadband recordings to locate the Chinese test. Instead of using travel times we "stack" the waveforms assuming a grid of locations. Using the IASPEI-91 travel time tables we shift the waveforms along the expected P-wave times and sum the waveforms. When the "correct" location is found the stacked waveform has the maximum coherence, or power. •

**This Issue's Bannergram:** The bannergram on the cover is the beam of the vertical channel from the KNET broadband array. The earthquake recorded here is a Ms=6.7 event that occurred in northern Argentina on May 24, 1993 at a depth of 221 km. The event is at 142 degrees from the reference station which puts it at an interesting distance for observing core phases. Some of the clearer ones for this vertical component are shown. The beam was constructed by stacking the array in the 0.05 to 1 Hz band at 33 km/s from a 312 degree backazimuth. •

*Gary Pavlis, Indiana University*

# The Kyrgyz Seismic Network

Frank Vernon, IGPP, University of California, San Diego

In September of 1991 the ten station Kyrgyz broadband seismic network (KNET) became operational. In its short lifetime it has so far survived the economic and political turbulence from the breakup of the former Soviet Union and the formation of the Republic of Kyrgyzstan, as well as the occurrence of the 19 August 1992 magnitude 7.4 Susamyr earthquake located underneath the network station Almayashu (AML).

The network utilizes Streckeisen STS-2 sensors with PASSCAL dataloggers which are combined with advanced digital telemetry and data processing techniques to provide very high dynamic range (132 dB) and very broadband (0.008 - 50 Hz.) seismic data. The geometry of the network was dictated by maximizing earthquake monitoring capability with line-of-sight telemetry constraints. Since this network was deployed with broadband sensors, it may also be used as a long-period array which will enhance signals with apparent wavelengths in the range of 10 to 100 kilometers.

Currently nine stations of KNET are being recorded by triggered and continuous data streams (IRIS Newsletter, Vol. XI, No. 1). The equipment at one station (BGK) was vandalized in September, 1993, and has not been replaced yet. This station is being moved to a more secure location near the

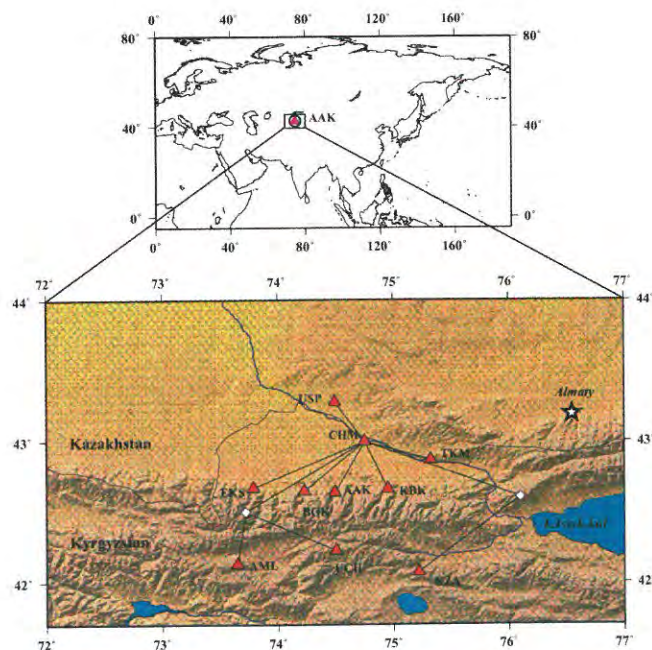


Figure 1. Top map shows the location of the KNET in central Asia. The bottom map shows the station locations and telemetry links. The central telemetry station is Chumysh. Data are recorded and processed at the Kyrgyz Institute of Seismology in Bishkek.

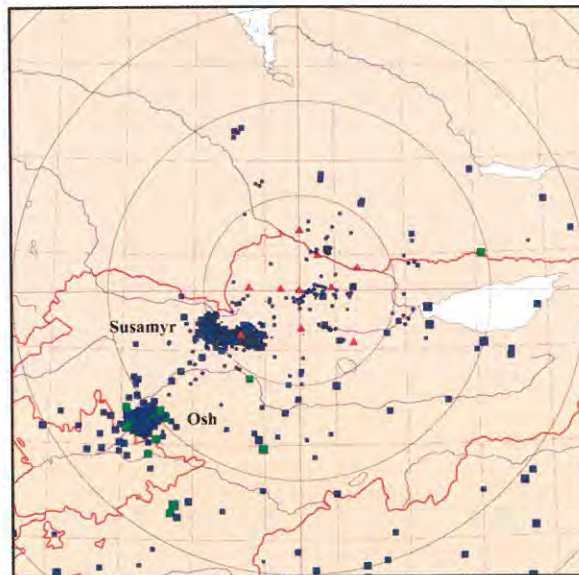


Figure 2. Epicenters of triggered events within 3 degrees of KNET recorded through the end of 1993. Blue symbols are events not found in the PDE and green squares indicate events in the PDE.

eastern repeater site this summer. This past year the telemetry system was modified to include 20 sps continuous recording of high and low gain channels. In addition a more robust data retransmission scheme was implemented. To acquire more relevant data for verification research the continuous data stream from KNET will be changed this year from 20 sps to 40 sps.

Probably the most significant enhancement to KNET is the establishment of an Internet link between the Kyrgyz Institute of Seismology and the University of California, San Diego. At present this link relies on a dedicated telephone line between Bishkek and Obninsk, Russia. In spite of the intermittent continuity of the phone lines, data from significant events (e.g. the Chinese nuclear test in October, 1993) can normally be retrieved within hours of the event notification.

Phase arrival times from the Kyrgyz network are measured as part of normal network operations. A magnitude scale calibrated to U.S. standards has been developed, and is being applied to all local events recorded by the network.  $M_b$  estimates are made for regional events using a network average that has been corrected to produce zero mean statistics when compared against USGS PDE  $m_b$  values. Events are being compared with those listed in the PDE to verify detection capabilities of this network. All events within twenty degrees of the network are located from KNET arrival picks using

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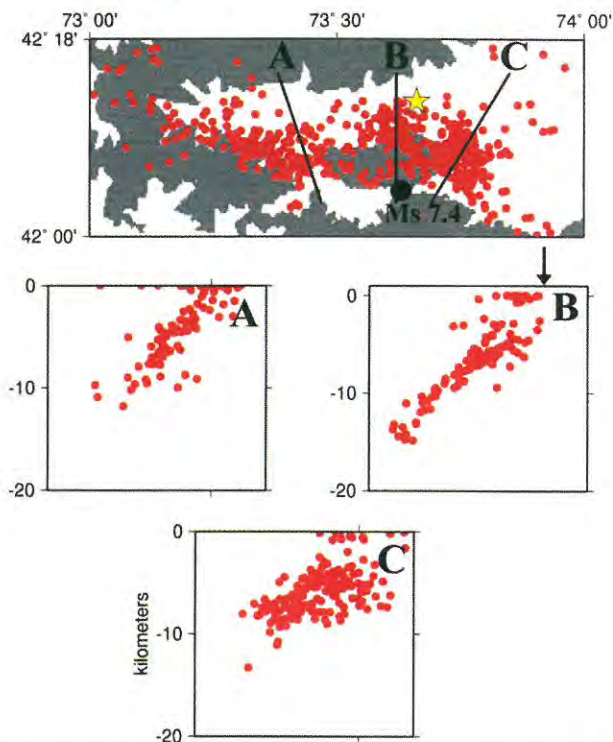


**Figure 3.** Detailed view of the epicenters following the  $M_s=7.4$  August 19, 1992 Susamyr earthquake. Three cross-sections are shown. The black dot is the main-shock epicenter and the yellow star indicates where surface rupture was found.

conventional earthquake location algorithms and Kyrgyz network bulletins are produced regularly.

The network is located along part of the boundary between the northern Tien Shan mountains and the Kazakh platform. Several major tectonic features are spanned by the network including a series of thrust faults in the Tien Shan, the Chu Valley, and the NWSE trending ridges north of Bishkek. At present there exist over 2000 triggered events which are shown in Figure 2. These sources are dominated by the aftershock sequences for the magnitude 6.2 earthquake near the city of Osh (~200 km from the network) in May 1992 and the 19 August 1992 magnitude 7.4 Susamyr event located under the KNET station AML. A more detailed view of the Susamyr aftershocks based on the work of Rob Mellors at Indiana University is shown in the cross-sections in Figure 3. These locations are based on data from KNET and a portable deployment of PASSCAL dataloggers operated by Volodya Mishatkin and sponsored by the Institute of Physics of the Earth of the Russian Academy of Sciences.

In addition to the triggered data set, is over a year of network continuous 20 sps data is available at present. Figure 4 shows the seismicity within a  $90^\circ$  radius of KNET detected during a very detailed analysis of the KNET continuous data from the month of May, 1992. This figure is based on results by the Joint Seismic Program Center at the University of Colorado. An example of teleseismic data recorded by KNET is found in the vertical components from the 17 January 1994 Northridge, California earthquake (Figure 5) located at a distance of  $102^\circ$  from the center of the network.

KNET is a cooperative project sponsored by IRIS and the government of Kyrgyzstan. It is operated by the Kyrgyz Institute of Seismology and the Institute of High Temperature Physics of the Russian Academy of Sciences. The IRIS participants in this project include University of California at San Diego, Indiana University, and the University of Colorado. All triggered and continuous data along with several technical reports are available through the IRIS Data Management Center in Seattle, Washington. •

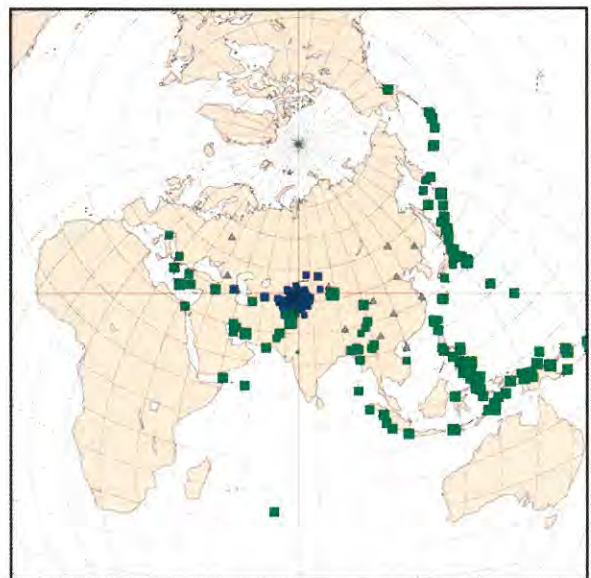


**Figure 4.** Epicenters of events found in the continuous data stream. These events are within  $90^\circ$  degrees of KNET and were recorded in the month of May 1992. Blue symbols are events not found in the PDE and green squares indicate events in the PDE.

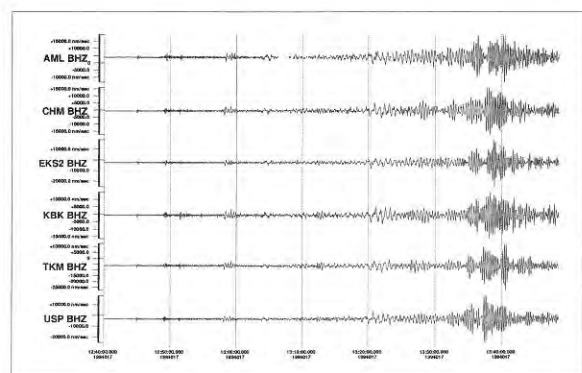


**Figure 5.** Seismograms from the 17 January 1994 magnitude 6.7 Northridge, California earthquake recorded on the vertical components of KNET. This event was  $102^\circ$  degrees from the center of the network.

## JSP Arrays and Networks in Central Asia

Gary Pavlis, Haydar Al-Shukri, Hanan Mahdi, and Dimitri Repin, Indiana University  
Frank Vernon, University of California, San Diego

In the summer of 1991 the first permanent array of the IRIS Joint Seismic Program (JSP) was installed in Kyrgyzstan. This "array", which we refer to as KNET, is described in its more conventional role as a regional seismic network in a separate article in this newsletter. Because KNET is equipped with broadband STS-2 sensors, this same facility is an excellent long-period, teleseismic array that can be used to investigate wave propagation from regional to global scales. The first objective of this article is to demonstrate this capability of KNET to encourage further use of these data in this manner.

A further step in its development of JSP facilities in Central Asia took place in August 1993 when an experimental high-frequency array was installed in Turkmenistan (Figure 1) adjacent to the GSN station ABKT (Figure 2). This array, which we refer to as the Geyocha array, was designed to operate at the opposite end of the earthquake seismology recording band from KNET. That is, while KNET is a functional array at long-periods, the Geyocha array was designed to try to push array signal enhancement capabilities to higher frequencies than existing array designs such as NORESS. This requirement was driven by a long-term goal of the JSP array group to try to extend the performance of seismic arrays to wider frequency bands than those exploited in existing monitoring facilities. This is important because most seismic discrimination methods that use any form of signal processing are fundamentally spectral. That is, they look for some type of difference in the output of a source at different time scales (e.g. the  $M_S$ - $m_b$  discriminant compares long-period surface wave to P wave signal levels.). The high-frequency end of the spectrum is especially troublesome due to some fundamental processes related to interaction of seismic waves with the uppermost part of the crust. The Geyocha array has proven valuable in the more conventional role of a seismic array. The existence of the Geyocha array significantly lowers the detection thresholds in this area of the world (see related article by Harvey and Hansen, page 1). In addition, however, this array has collected a wealth of fundamental data on high-frequency wave propagation that we can exploit for improving our basic understanding of how high-frequency seismic waves propagate in the real world. The second major point of this article is to demonstrate the scientific benefits of this type of three-component, broadband array.

### KNET Array Processing Results

Figures 3 to 5 show array processing results of signals recorded by KNET from a  $M_S=5.8$  earthquake located in south-central Tibet that occurred on March 20, 1993. These results suggest three observations of note.

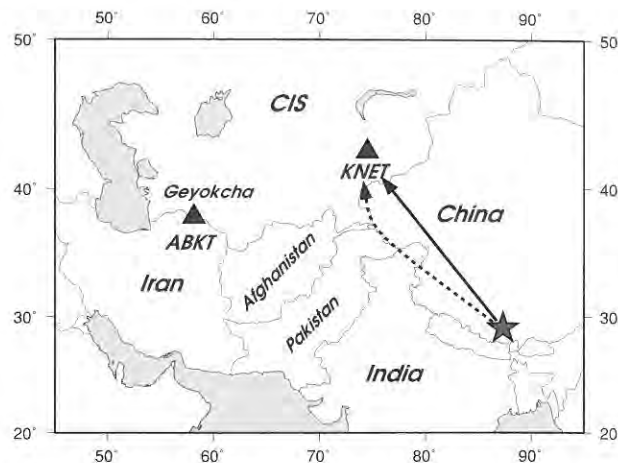


**Figure 1. Location of JSP arrays.** Triangles show locations of KNET and Geyocha arrays. Straight line shows the approximate direct path between an event in Tibet (star) and KNET while the dashed line shows the strong multipath phase observed in the Love waves from this event.

1. Figure 3 indicates that the P wave and the string of arrivals between P and S consistently arrive with a phase velocity approximately 10° north of the expected back azimuth (138°). This suggests some sort of large-scale structure in the upper mantle may be refracting P waves laterally along this path.

2. Although not shown here, the S wave arrives at nearly the correct back-azimuth for this path. This suggests a possible difference in P and S velocity structure in the vicinity of this path.

3. The surface waves produced by this earthquake show evidence of strong multipathing that can be analyzed in a unique way by a broadband array. Figure 4 shows results of an f-k analysis of the early, low-frequency portion of the Love wave signal. Note the measured phase velocity of this signal is reasonable for 20-30 s period Love waves, but the azimuth is skewed about 10° and arrives from about the same azimuth as P. Figure 5, however, demonstrates that between 400 and 450 s the Love wave energy is propagating across the array from a drastically different direction. The dominate f-k peak is now at around 159°, which is over 20° south from the expected back azimuth. This wave packet forms the group arrival of Love waves with periods of approximately 10-12 s. Apparently there is a rather drastic difference between the propagation characteristics of 10 s surface waves on this path and surface waves at lower frequencies. We also observed that the Rayleigh wave recorded on the vertical component shows the same pattern, but the arrival times are different. A tentative explanation for this observation is that the dominant path for

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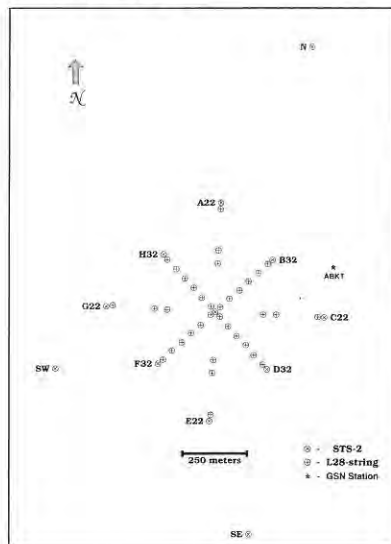


**Figure 2. Geyocha array.** Geophone strings are deployed as linear subarrays (twelve elements per string) oriented parallel to the "arm" of the array on which they lie. The location of the new IRIS/IDA GSN station, ABKT, is also shown for reference.

10-12 s surface waves is not along the great circle path, but along a path of enhanced crustal thickness unique to central Asia. This multipathing could be explained by propagation through the continuous waveguide of extremely thick continental crust beneath the Tibet plateau and its northward extension through the Pamir and into the Tien Shan. Why this becomes the dominate path at 10 s periods is an open question, but we suggest it may related to blockage of long-period surface waves across the boundary between the Tibetan plateau and the Tarim basin due to drastic differences in the crustal waveguide in these two regions.

### Geyocha Array

A unique design feature of the Geyocha array (Figure 2) is that it is a hybrid of two very different technologies. Twelve stations in the array are equipped with state-of-the-art STS-2 broadband sensors, which allow the array to record signals at frequencies as low as 0.01 Hz. The remaining 36 stations in the array are equipped with 12 element strings of triaxial L-28 geophones. This equals a total of 1296 total sensors located at 432 different spots on the ground. This is a large number of sensors in a small piece of real estate, but the idea of this design is founded on well developed technology for data acquisition at frequencies over 10 Hz in reflection seismology.

We are in the process of evaluating the overall effectiveness of this array in stacking signals at high frequencies. One example is presented in Figures 6. There we analyze the relative fidelity of stacking signals from four different array subsets: (1) all 12 broadband stations, (2) the full geophone array of 36 stations, (3) the 9 innermost broadband stations, and (4) a 20 element reduced aperture geophone subarray (4 inner elements on the B, D, F, and H arrays and 2 inner stations on others). Results shown are for a large local event. The upper panel shows the median spectrum of the P wave and pre-event noise for the array. Note the high signal-to-noise for this event.

The median spectrum is used as a reference for appraising the influence of stacking. That is, f-k analysis of the vertical component was used to identify the best slowness vector for this event. We then generated a simple delay and sum beam for each of the array subsets and normalize each beam by the reciprocal of the number of stations used in the stack. We next calculate the P wave spectrum for each of these beam seismograms and form a spectral ratio relative to the median array spectrum. The resulting spectral ratios demonstrate where stacking begins to become ineffective. We see that at low frequencies the stacking is nearly perfect. Almost no power is lost in the normalized beam as revealed by spectral ratios close to unity. However, in all cases progressively more power is lost in the beam with increasing frequency. All the spectral ratio plots drop to approximately the theoretical lower bound for random noise ( $1/N$  in power where  $N$ =number of stations used in the stack). The transition, however, occurs at different frequencies for different subarrays. There are two important results that can be gleaned from this figure. First, by comparing the results for the L28 array and the 9 element STS-2 array, we see that the geophone array has somewhat better performance in the 10-20 Hz band, but the overall advantage is not very significant considering the huge effort required to install this part of the array. Secondly, the frequency dependence of stacking performance scales directly with the scale of the subarray we use. That is, we get better high-frequency stacking performance from the smallest subarray used here (the 20 station geophone array), and the poorest performance from the largest aperture array (the 12 element broadband array). This

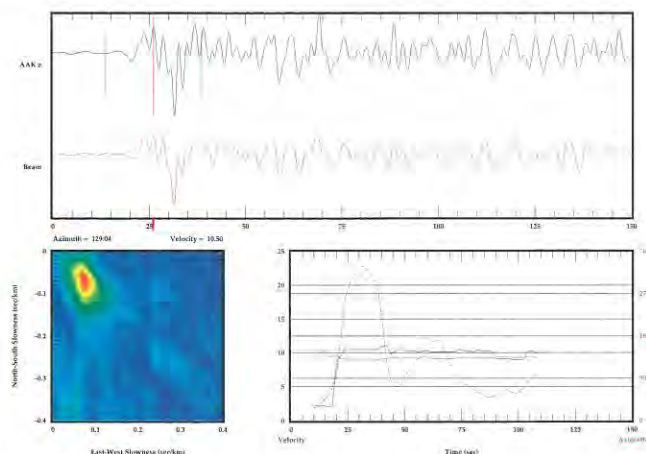


**Figure 3. Array analysis of P-wave from event in south-central Tibet (Figure 1) using KNET broadband array.** The top panel shows the vertical component recorded at station AAK (the reference), along with the best beam calculated from f-k analysis (lower left panel). The method used is a conventional broadband f-k stack in the 0.01 to 0.5 Hz passband. The analysis window is delineated by the vertical green bars. The lower right panel displays results of f-k analysis over the first 100 s of the P wave signal, computed by translating the analysis window (25 s in length) in time and doing an f-k analysis at each time step. Blue curve - computed velocity; red curve - computed azimuth; dotted line - relative power of the best beam.

is consistent with comparable studies done at NORESS where high-frequency signals could be stacked to improve signal-to-noise provided a smaller dimension subarray was used.

The results shown in Figures 6 are just one of a number of related analysis results that could be presented here that relate to what we would argue is the one overriding issue of high-frequency array seismology: signal coherence is strongly affected by complicated near-surface scattering effects that are poorly understood. The Earth's surface where humans live is a profoundly irregular thing which has drastic effects on seismic waves at all scales. Nearly everywhere at frequencies from 1 to 10 Hz and higher, seismic waves begin to approach wavelengths of a scale directly perceived by you and I as we view our world. Rock outcrops, hills, soil thickness variations, trees, buildings, and a host of other things we can see all around us are capable of scattering seismic waves at these frequencies. One important reason is the outrageously low velocities P and especially S wave velocities of soils and strongly weathered rock. For example, measured S wave velocities in soils are commonly as low as 200 m/s (less than the sound speed in air). This makes the soil horizon in most areas of the land the most drastic waveguide on earth. This "layer", however, is also highly irregular. We are seeing increasing evidence that this leads to very strong scattering of high-frequency seismic waves when they interact with this highly irregular "layer".

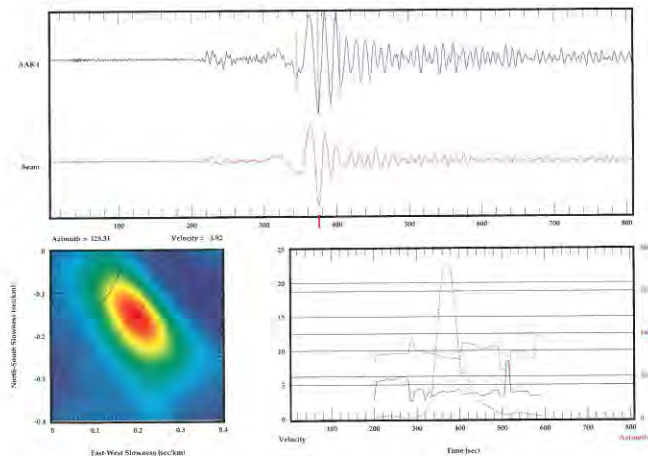


**Figure 4.** Array analysis of early Love wave packet for the Tibet event (see Figure 3). Seismograms have been rotated into the transverse component, and the analysis window is 60 s long.

A final, preliminary observation is shown in Figure 7. This figure shows time-domain polarization analysis of the beam seismograms produced by stacking at the measured phase velocity of the P wave signal. We then resolve the particle motion into ray coordinates (longitudinal, SH, and SV). Figure 7 shows the projection of the particle motion in the longitudinal-SH plane. This shows that the particle motion is nicely linearly polarized, but the particle motion defined by the beam is skewed by  $5^\circ$  in the longitudinal-SH plane. An intriguing possibility is that this particle motion is an indication of

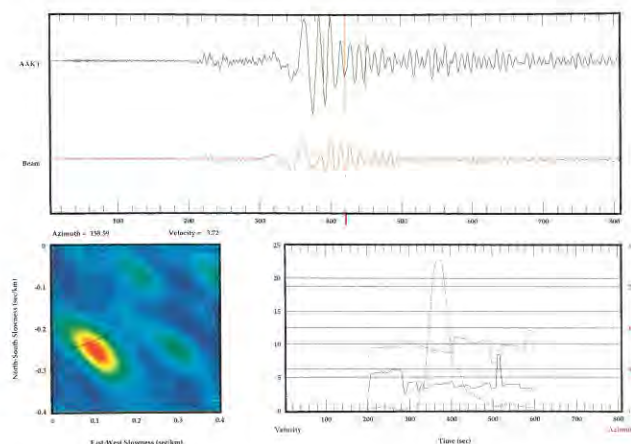


**Figure 5.** Love wave multipathing revealed by array processing of KNET. This figure is identical to Figure 4 except here we focus on a later section of the Love wave packet. Note the drastic difference in the location of the f-k analysis peak. The emergence of this secondary peak is shown by the azimuth estimates in the lower right panel. Between the times in Figures 4 and 5, this secondary peak grows and by 420 s (shown here) it becomes totally dominant.

anisotropic wave propagation. That is, in an anisotropic medium P wave particle motions will not, in general, lie perpendicular to a wavefront (measured here by f-k analysis of phase velocity). This is a unique measurement that can be made with a three-component seismic array, and demonstrates a potentially important application for three-component arrays at a variety of scales.

### Scientific Benefits of Three-component Arrays

We have attempted to show a sampling of important scientific benefits that can come from careful analysis of data from three-component, broadband arrays. These arrays provide measurements fundamentally different from a single seismic station. The issue of scale, however, is absolutely fundamental to arrays in a way that is easily misunderstood. To achieve "broadband" recording in time, all we need to do in the modern era is buy the right sensor. To achieve "broadband" recording in wavenumber, however, requires sensors to be distributed over the planet at a mix of scales. KNET and the Geyocha array demonstrate two endmembers. KNET is very useful array in the conventional long-period band. We have demonstrated one example of this type of analysis, but many others are waiting to be exploited. Furthermore, we would argue that the large number of vertical, short-period, analog telemetry, seismic stations now running in this country could revolutionize our knowledge of earth structure if a large fraction of them were upgraded to digital, broadband, three-component stations.

The Geyocha array operates on a drastically different frequency-wavenumber scale than an array like KNET. The data being gathered by this array contains a wealth of information on high-frequency wave propagation and microearthquake source properties. We demonstrate one example here that

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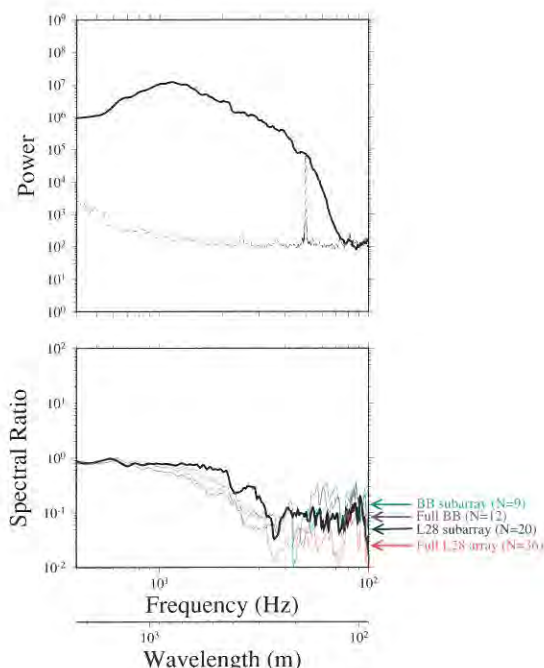


**Figure 6.** High-frequency stacking analysis of the P wave of a local event at Geyocha. The top panel shows the median of power spectral estimates from all 36 stations equipped with geophone strings relative to the median noise floor. The lower panel shows power spectral ratios of beams constructed from different subarrays. The labeled arrows show the expected levels if we stacked pure noise. The "Wavelength" axis corresponds to an apparent velocity of 9 km/s obtained from f-k analysis of the P wave signal.

suggests three-component arrays could be used in a new way to measure anisotropy. In addition, these data are proving invaluable in providing sampling of all three components of the wavefield generated by earthquake sources at finer scales than ever attempted before. These data will help improve our understanding of near-surface scattering and site effects. •

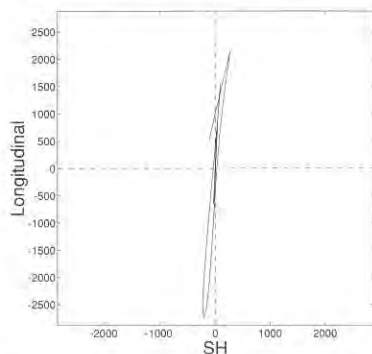


**Figure 7.** Polarization anomalies observed with Geyocha array for the P wave of the same event analyzed in Figure 6. The particle motion of the beam is constructed by stacking at the slowness defined by f-k maximum determined from the vertical component of the P wave. This figure is the projection of the particle motion of the P wave onto the longitudinal-SH plane.

## Investigations of Lithosphere Architecture and Development (ILIAD)

### Lithospheric Science Workshop

A workshop on the continental lithosphere will be held in Taos, New Mexico, from November 5-9, 1994. The workshop is designed to encourage scientific exchange between seismologists and other Earth scientists engaged in fundamental research on the structure and evolution of the continental lithosphere. We will emphasize both integrated Earth science approaches and integrated multi-scale seismic experiments for understanding lithospheric structure and processes. The workshop will include three half day sessions of invited and contributed talks, followed by poster sessions and working group meetings on science planning, experiment design, instrumentation needs, and community organization.

The workshop is intended to assess the technical and organizational resources necessary to undertake the scientific investigations described in the report: "A National Program for Research in Continental Dynamics CD/2020" and to develop community-wide scientific consensus on instrumentation needs for lithospheric seismology. Workshop attendees will develop a science plan to complement and support the technical plan for seismic instrumentation developed by IRIS.

The workshop is open to all lithospheric scientists; travel support is available for 40 participants. We particularly encourage scientists involved in active tectonics and continental margin studies to apply. Interested parties should send by email a letter of application to Liz McDowell (liz@iris.edu).

The workshop is sponsored by the National Science Foundation, Geophysics and Continental Dynamics Programs, and the Mathematics and Geophysics Directorate of the Air Force Office of Scientific Research.

**Workshop Organizing Committee:** Alan Levander (Rice University); Larry Brown (Cornell University); Walter Mooney (USGS); and Gene Humphreys (University of Oregon).

**Workshop Advisory Committee:** Nik Christensen (Purdue University); Ron Clowes (UBC; Lithoprobe liaison); Kevin Furlong (Penn State University); Bob Hatcher (University of Tennessee); Steve Hickman (USGS; Deep Continental Drilling liaison); Art Lerner-Lam (Lamont-Doherty; CSEDI liaison); Jill McCarthy (USGS); Anne Meltzer (Lehigh University); Jinny Sisson (Rice University); and George Zandt (Lawrence Livermore). •

# Analysis of Multidimensional JSP Data

Gregory S. Wagner, University of South Carolina

Analysis of multidimensional seismic data provides one of the keys to our understanding of earth structure and composition. Many multidimensional data analysis approaches involve the assumption that the noise is random in nature. The important implication in this assumption is that the energy associated with the noise is distributed isotropically in space and is channel-wise incoherent. A signal's energy, on the other hand, is distributed anisotropically in space and exhibits varying degrees of channel-wise coherence. The goal in multidimensional analysis is, therefore, to find the direction in space in which the data exhibits the greatest variance. The information provided by the solution to this problem allows us to estimate the signal's propagation direction, propagation velocity, and polarization characteristics. Whether the data are from a three-component sensor, a single-component array, or a three-component array, analysis presents the same basic problem and can be carried out using numerous approaches. In this article we will discuss the use of eigen-structure routines in the analysis of single three-component sensor, single component array, and three-component array data. The focus will be on signal detection, bearing estimation, and waveform enhancement for events at regional distances. The data we will

use were collected as part of the IRIS Joint Seismic Program at Piñon Flat, California (PFO) (Al-Shukri *et al.*, 1992) and Geyöcha, Turkmenistan (GCH) (Pavlis *et al.*, 1993).

## Multichannel Eigen-Analysis

In this article we demonstrate the application of a class of spectral estimates that focus on the eigen-structure of the sample covariance matrix (Pisarenko, 1972); the reader is referred to papers in the references for specific details regarding any of the approaches (Gething, 1971; Pisarenko, 1972; Schmidt, 1979; Samson, 1983). The diagonal elements of the covariance matrix provide a measure of the observed power flux density, while the off-diagonal elements provide a measure of the channel-wise coherency. The covariance matrix eigen-decomposition is simply a linear transformation to a natural basis that provides an appealing approach to the analysis of the structure of the covariance matrix because of the physical insight that can be gleaned from a simple examination and interpretation of the information provided by the eigenvalues and eigenvectors. We can think of the eigen-decomposition change of basis as allowing us to view the multidimensional space from the signals' point of view as opposed to the sensors' point of view. The eigenvectors parameterize the new coordinate axes in terms of the original coordinate axes and provide specific information regarding the energy distribution in the multidimensional space. The eigenvalues indicate how the energy is partitioned between the new coordinate axes and provide general information concerning the spatial distribution of the energy. If there are no signals present, the energy should be distributed isotropically in space and all of the eigenvalues should be approximately equal. If a signal(s) is present, the energy distribution will be anisotropic and one or more of the eigenvalues will be considerably greater than the others. The multidimensional space spanned by the data can be partitioned into signal and noise subspaces based on the magnitude of the eigenvalues. The eigenvectors associated with the larger eigenvalues span the signal subspace, while the eigenvectors associated with the smaller eigenvalues span the noise subspace (Schmidt, 1979). For the case where one signal is present, the components of the eigenvectors computed using data from a three-component sensor, a single component array, or a three-component array reflect component-wise amplitude, sensor-wise phase, or the product of component-wise amplitude and sensor-wise phase relations, respectively. When multiple signals are present, the individual eigenvectors do not necessarily correspond to individual signals and it may no longer be feasible to interpret the information provided by the eigenvectors in this manner.

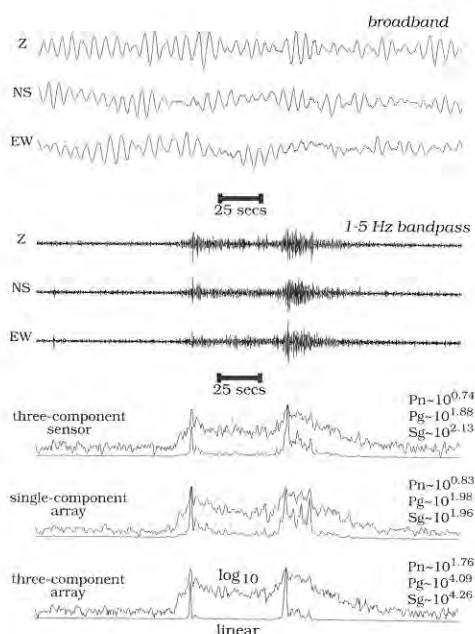


Figure 1. Broadband and bandpass filtered three-component data, and the corresponding principal component eigenvalues ( $\lambda_0$ ) for a  $M_L$  2.8 event that occurred approximately 500 km NNE of PFO. The  $\lambda_0$  were computed using (top to bottom) single three-component sensor, single-component array, and three-component array data. The  $\lambda_0$  magnitudes are displayed using both linear and  $\log_{10}$  scaling. The SNR of the Pn, Pg, and Sg phases are listed to the right.

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### Signal Detection

Three-component data should prove advantageous in the detection of events at regional distances because the crustal phases associated with these events are commonly observed on both the vertical and horizontal components. A popular approach to signal detection using three-component data involves the use of polarization filters to help enhance signals based on their polarization characteristics. Particle motion polarization estimates can be computed using simple ratios of the eigenvalues of the covariance matrix. Because the eigenvalues provide estimates of how the energy is partitioned between the signal and noise subspaces, these eigenvalue ratios are essentially measures of the signal-to-noise ratio (SNR); therein lies the problem. Regardless of the actual polarization characteristics of the signal, low SNR data will not exhibit the high degree of apparent polarization needed to enhance and detect signals.

A slightly more robust approach to signal detection in high-frequency, low SNR data is simply to use the magnitude of the principal component eigenvalue  $\lambda_0$  which provides an estimate

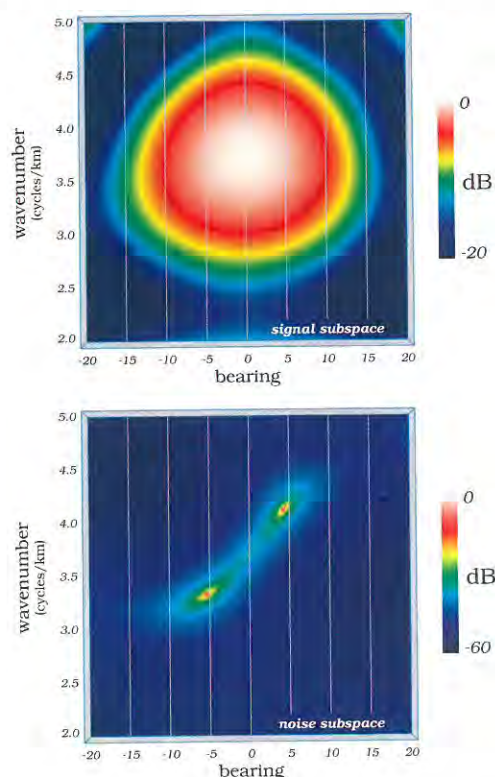


**Figure 2.** Broadband eigen-analysis bearing estimates computed using the signal and noise subspaces for superimposed, synthetic *P* and *S* waves. The signals are 10 dB above spatially and temporally white noise, and have bearings, velocities, and peak frequencies and wavenumbers of 5°, 5.5 km/sec, 23 Hz, 4.18 cyc/km, and -5°, 3.25 km/sec, 11 Hz, 3.38 cyc/km, respectively. The array consisted of three elements in a triangular geometry.

of the absolute level of component-wise coherent energy (Wagner and Owens, 1994a). The premise that multidimensional analysis presents the same basic problem regardless of the data type is demonstrated by the fact that this approach, and in fact the very same algorithm, can be used with single sensor three-component, single component array, or three-component array data. When used with array data, the eigenvalue approach circumvents the need to compute beams. Figure 1 shows broadband and bandpass filtered three-component data, and the magnitude of the principal component eigenvalue as a function of time computed using three-component sensor, single-component array, and three-component array, 1-5 Hz bandpass filtered data for a  $M_L$  2.8 event that occurred approximately 500 km NNE of PFO. The eigenvalue magnitudes are displayed using both linear and  $\log_{10}$  scaling. The SNR of the  $P_n$ ,  $P_g$ , and  $S_g$  phases are listed to the right. All three approaches are capable of detecting both the high SNR  $P_n$  and  $P_g$  arrivals, and numerous direct and scattered arrivals in the low SNR *P* and *S* coda. Using more information/channels clearly provides greater SNR gains and a more complete picture of the entire wavefield.

### Bearing Estimation

Measurements provided by an array of sensors will always contain noise. The subspaces defined by the covariance matrix's eigenvectors should, more concisely, be referred to as the signal-plus-noise and noise subspaces. Because the signal subspace is never noise-free, searching the signal subspace for an ideal plane wave will always provide less than optimal results. We can, alternatively, take advantage of the orthogonality of the signal and noise subspaces and look for minima when the signal-only mode vectors are projected onto the noise subspace rather than for maxima when the signal-only mode vectors are projected onto the signal subspace. This approach provides both sharper bearing estimates and superior resolution of multiple signals (Schmidt, 1979). While this approach could be used with single sensor three-component data, it has been used almost exclusively with single or multicomponent array data.

Figure 2 illustrates the application of broadband eigen-analysis signal and noise subspace approaches to superimposed synthetic *P* and *S* waveforms for a single component, three-sensor array. The result obtained using the signal subspace is nearly identical to that obtained using standard beamforming; neither is capable of resolving the two signals. The noise subspace approach is, however, capable of resolving the signals in both bearing and wavenumber. Figure 3 shows a bearing-time record (BTR) computed using a broadband, multicomponent eigen-analysis approach (Wagner and Owens, 1993b) with 0.75 Hz highpass filtered three-component array data from a  $M_L$  2.8 event that occurred 500 km NNE (335°) of PFO. The information provided by this type of analysis can be used to guide narrowband processing, and to study elastic wave propagation and scattering (Wagner and Owens, 1993a).

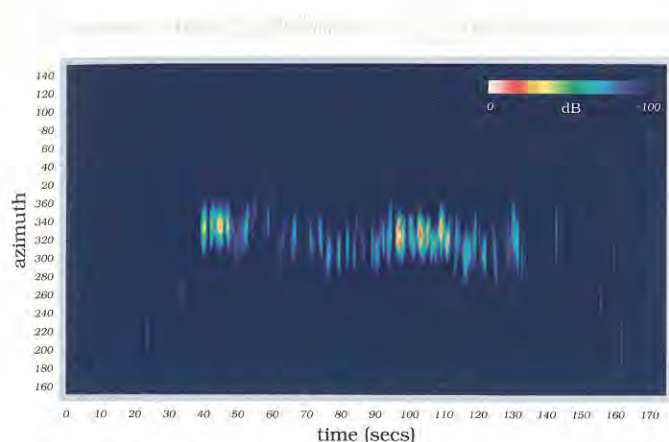


**Figure 3. Broadband eigen-analysis bearing-time record (BTR) for a  $M_L$  2.8 event that occurred approximately 500 km NNE ( $335^\circ$ ) of PFO. This BTR was computed using 0.75 Hz highpass filtered three-component array data and displays the linearly polarized component of the signal. The 0.75 Hz highpass filtered trace above the BTR is the vertical component from the array's center sensor.**

### Waveform Enhancement

Implicit in the multichannel analysis assumption that the observations are the result of a linear combination of signals and noise, is that the signals and noise can be reconstructed by a linear combination of the observations (Gething, 1971). This can be accomplished using the information provided by the eigenvalues and eigenvectors of the covariance matrix (Wagner and Owens, 1993c). This approach differs from standard beamforming approaches in that it uses information provided directly by the data instead of that appropriate for a, in some sense, best fit to an idealized model. The eigen-structure approach involves no assumptions of plane wave propagation or, for the three-component array case, consistent polarization characteristics across the array. This feature is particularly advantageous in the analysis of high-frequency data because of their sensitivity to small scale heterogeneities which commonly result in arbitrary amplitude and phase variations across the wavefront that cause the signal to depart from the ideal scenario assumed in most array analysis approaches.

Figure 4 compares the application of the eigen-structure approach to standard beamforming for a  $P$ -wave from a  $M_b$  4.0 event in south-west Iran recorded at the GCH array. All signal estimates were computed using 0.5 Hz highpass filtered vertical component data from nine Streisen STS-2 sensors; Figure 4 shows the waveform from the array's center site and the power spectra for the nine STS-2's. The slant-stack waveform was computed using the known back-azimuth and apparent velocity for a source at a distance of  $10.1^\circ$ . As with the signal detection problem, no beamforming (*ie* search to find the 'best' beam) is required to compute the eigen-structure waveform estimate; the observed data are simply projected onto the signal subspace defined by the eigenvectors of numerous narrowband covariance matrices. The extreme SNR gain result from the fact that in addition to frequency domain stacking of the input channels,

which should produce a SNR gain similar to that provided by standard beamforming, the signal has essentially been passed through an adaptive filter whose structure is determined by the degree of signal coherency at each frequency. Because this signal is coherent over a narrow frequency band, the filter is narrowband resulting in a 'ringing' output.

### Summary

The eigen-structure approach is only one of the numerous approaches available to unlock the abundance of information contained in multidimensional data. The information provided the eigenvalues and eigenvectors of the multichannel covariance matrix can be combined or used separately, depending on the problem at hand. One of the main advantages of the eigen-structure approach is the relative ease of handling three-component array data which is crucial to a better understanding of elastic wave propagation, particularly at higher frequencies. •

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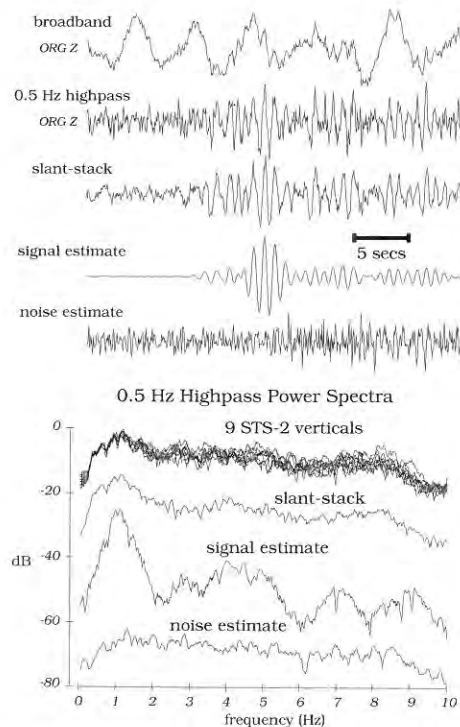


**Figure 4. Broadband and 0.5 Hz highpass data, signal and noise waveform estimates, and power spectrum estimates computed using standard beamforming and an eigen-structure approach for the  $P$  wave from a  $m_b$  4.0 event that occurred in south-west Iran approximately 1,000 km from the GCH array.**

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## GSN Update

IRIS/IDA has installed a new GSN station at Warramunga Array, Tennant Creek, Northern Territory, Australia (WRAB). The station has a 24-bit IRIS-3 data acquisition system recording a Teledyne KS54000 broadband borehole seismometer and a Streckeisen STS-2 seismometer.

MSVF, Monasavu, Fiji — a new borehole GSN station installed by IRIS/IDA — is now operational. •

# The Caucasus Network

Geoffrey A. Abers, Lamont-Doherty Earth Observatory

In 1990 an opportunity presented itself to IRIS for a cooperative effort with Soviet scientists to install seismographs in the Caucasus mountains. The 1988 Spitak, Armenia earthquake had illustrated the high seismic exposure of the region, and cooperation with IRIS and the USGS in regional monitoring was an important aspect of Soviet participation in the JSP. The opportunities were wide, and Lamont scientists (led by David Simpson) made contacts or set up sites in Georgia, Armenia, and southern Russia. The OME research station at Bourgostan (Kislovodsk, home of IRIS/IDA station KIV) was a natural base. The first instruments were brought over in August 1990, and telemetry was first installed in April 1991. The network reached steady-state configuration in November 1991.

The ensuing rapid evolution of the region led to several major changes in both the way the program could be carried out and its motivation. Access within new republics south of Russia became curtailed. Nowhere was this more evident than in May, 1991, when an aftershock deployment was conducted following the destructive April 29 Racha-Dzhava earthquake ( $M_s$  7.3). Lamont and OME scientists deployed PASSCAL instruments in Russia and in the Ossetian part of Georgia (then an autonomous region of the U.S.S.R.) while French, English, and USGS scientists operated in the rest of

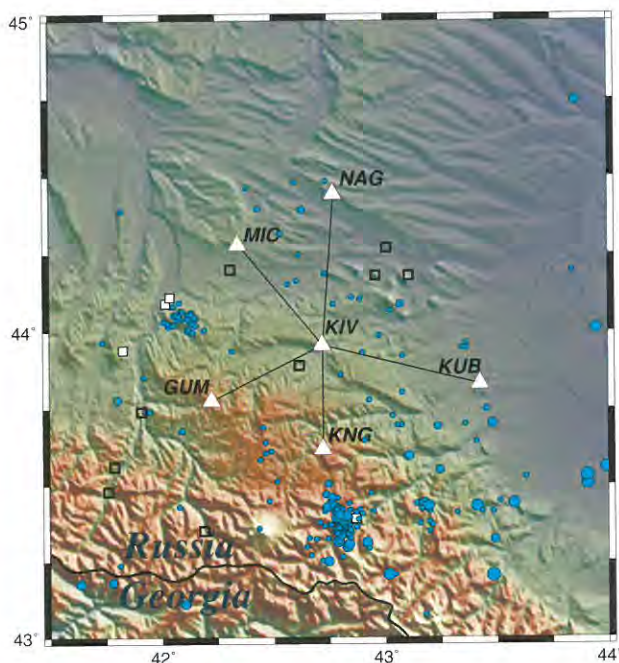


**Figure 1. The Caucasus Network.** Stations are shown by red triangles, filled white where telemetered. Black lines show telemetry links. Squares show known quarries, filled white where associated with seismicity. Blue-green circles show events from 1992 (January 1 - November 9). Topography, colored, extends from near sea level on the Russian Platform to 5600 m at the summit of Mt. Elbruz (the highest point in Europe).

Georgia (*IRIS Newsletter*, 10(2), 1991). Even though the two groups had sensors within a kilometer or two of each other, at the center of the aftershock zone, communication was only possible by relaying messages back through Moscow because regional conflicts blocked direct access. The current network (Figure 1) reflects this new world order by hugging the southern border of Russia, along the northern flanks of the Greater Caucasus.

As global nonproliferation became a major concern, the Caucasus Network (like the other JSP facilities) found itself well situated to record earthquakes from a number

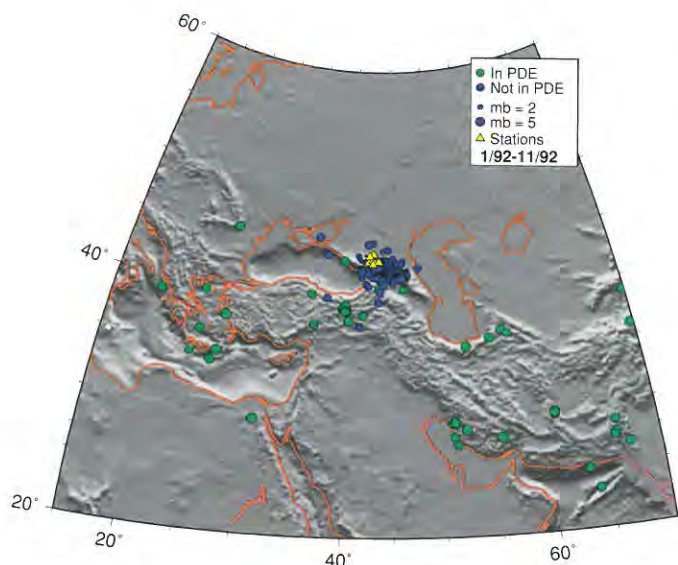


**Figure 2. Regional events recorded by the Caucasus Network triggered data stream. Events are from the JSPC information product covering January 1 - November 9, 1992.**

of regions of growing interest. The Middle East, Iran, southern Russia, and Ukraine are all within  $20^\circ$  from the network (Figure 2). Digital waveforms from the network stations provide new evidence on wave propagation beneath the Caucasus in particular and eastern Asia in general. Extreme attenuation effects, previously known from WWSSN stations south of the Caucasus, are now well sampled and are an important consideration in many verification scenarios.

The network has proved to be a valuable source of high-frequency signals from small events, both natural and manmade (Figure 3). Within a degree of the center of the network, over half of the events recorded can be associated with active quarries (Figure 1), or roughly 150 events per year. These data are useful for characterizing discriminants of chemical explosions from earthquakes, a critical issue facing any test ban treaty. For example, waveforms (Figure 3) show different spectral character than cratonic paths, where most work has been done on discriminants.

The current network consists of six stations. Five remote stations telemeter digital data to a central recording site and station at the Bourgostan Seismic Observatory (KIV). Signals are recorded on a three-component set of passive intermediate-period sensors (Kinometrics SV1/SH1). The sensors are situated in Russian vaults, 3-4 m below the ground surface. Signals are digitized on site by a Nanometrics RD-3 digitizer with 16 bit resolution and additional 10-100x gain ranging, which after FIR filtering provide a 60 samples per second data stream. Digital signals are transmitted via a one-way VHF telemetry link to Bourgostan, where they are decoded, demultiplexed, time stamped, compressed, and stored in a ring buffer on a central OS/2-based computer. A triggering algorithm

generates a data stream which is used by local analysts and written to DAT tape. Since September, 1993 a continuous stream is also written. Tapes are sent to Obninsk, where the OME group copies and analyzes data, and are sent on to Lamont for quality control and reformatting. Processed SEED volumes are delivered to the JSPC and DMC. The system is occasionally accessed directly via electronic link, to troubleshoot with the local operators and manipulate system parameters.

A JSP Center Information Product for the first ten months of data in 1992 is now available through the IRIS DMC. We encourage the community to explore this data product. •

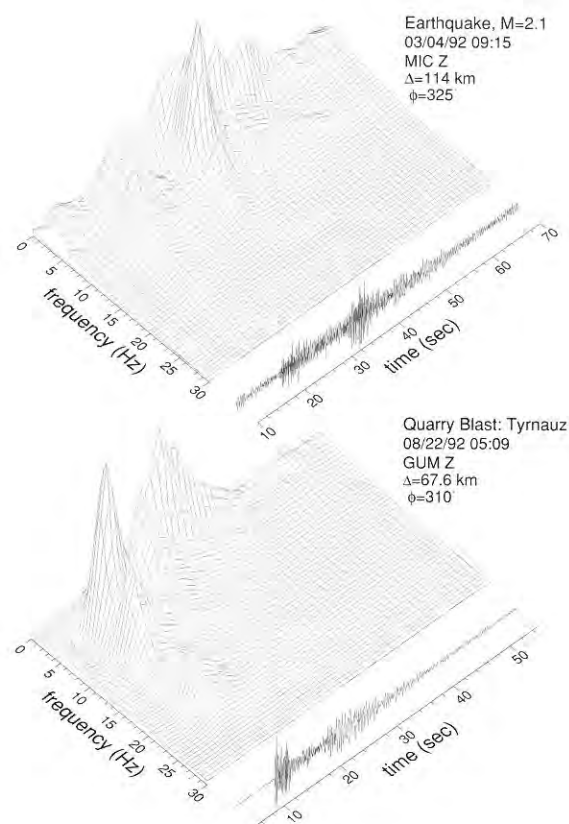


**Figure 3. A comparison of vertical-component regional seismic signals from an earthquake recorded at station MIC ( $\Delta \approx 114$  km) and from an underground multiple-hole instantaneous quarry blast (8/22/93 05h 09m) recorded at GUM ( $\Delta = 68$  km) and corresponding spectrograms. Spectrogram of the earthquake record (upper panel) shows random distribution of seismic wave energy in frequency with strong S waves up to about 15 Hz, while the spectrogram of the quarry blast record (lower panel) shows strong P waves at high frequencies (up to 20 Hz), but weaker S wave at this band. This clear difference in frequency content between P and S waves from earthquakes and explosions can be used to discriminate these events using P/S or  $P_g/L_g$  spectral amplitude ratios. Figure courtesy W.-Y. Kim.**

## A Broadband Seismic Profile of the Non-Proliferation Experiment

Terry C. Wallace and NPE Team<sup>1</sup>, Southern Arizona Seismic Observatory, University of Arizona

Early on the morning of September 22, 1993 (one minute after midnight, Pacific Daylight time) the Department of Energy (DOE) detonated a large chemical explosion at the Nevada Test Site (NTS). The explosion, code named the Non-Proliferation Experiment (NPE), was conducted to investigate the various physical signatures of a large, buried chemical explosion. Industrial explosions for mining, quarrying, and engineering are considered to be a crucial verification issue for renewal of the Non-Proliferation Treaty (NPT) or a future Comprehensive Test Ban Treaty (CTBT). DOE and cooperating organizations made a comprehensive suite of measurements (stress, particle velocity, electromagnetic, local and regional seismic, to name just a few). The University of Arizona deployed a temporary profile of ten portable broadband IRIS-PASSCAL seismometers along an east-west profile between NTS and the Lawrence Livermore National Laboratory station KNB (Kanab, Utah). The primary objective of the deployment was to investigate the development of regional seismic phases  $P_n$ ,  $P_g$ ,  $S_n$ ,  $S_g$ ,  $L_g$ , and  $R_g$ .

NPE was detonated within Rainier Mesa, located in the northwestern part of NTS. 1.3 million kg of blasting agent, composed of ammonia nitrate, fuel oil, and epoxy, were placed in a cylindrical cavity, known as the "tuna can" (see Figure 1). The chamber was 15 m in diameter and 5.5 m high and was located 390 m below the surface of the mesa. The explosion produced regional and teleseismic seismic signals that gave a magnitude of  $m_b = 4.1$ . Various estimates have put the energy release of NPE to be between 1.5 and 1.9 kt. NPE produced a remarkable seismic data set that could be compared with data from nearby nuclear detonations. Hunter's Trophy (September



Figure 1. The explosive chamber, known as the "tuna can," which was filled with a blasting agent for NPE. The cavity was filled with nearly 1.3 million kg of the agent and produced a seismic signal which had a magnitude of 4.1. Photo courtesy of Jay Zucca, Lawrence Livermore National Laboratory.

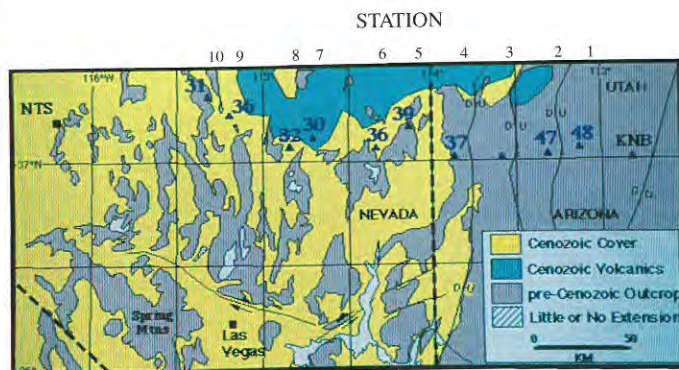


Figure 2. Location of the University of Arizona profile (stations shown with triangles). NPE was located at NTS. The stations span the Basin and Range–Colorado Plateau transition. Numbers next to each of the stations give the crustal thickness determined from receiver function analysis.

16, 1992, the second to last U.S. nuclear test) had a similar yield to NPE and was located only 500 m away. There was some expectation that the seismic wavefield from a contained chemical explosion would differ from that of a nuclear event, although preliminary analysis indicates that NPE "looked" very similar to a nuclear test.

The University of Arizona profile made use of the IRIS RAMP (Rapid Array Mobilization Program) PASSCAL instruments. Figure 2 shows the location of the ten stations and the geology of the eastern Basin and Range–western Colorado Plateau transition. The closest station is approximately 73 km from NPE, and the station spacing along the profile was approximately 20 km. The close station spacing was essential to track phase development without spatial aliasing. The Reftek data loggers were attached to very broadband seismometers (STS-2). We installed the equipment in "RAMP mode," meaning we deployed it very rapidly. Although RAMP was originally developed for aftershock studies, it can also be used for other scientific targets of opportunity (for example, the monitoring of a site suspected of nuclear testing activities). The broadband seismometers require considerable care in installation to achieve the full frequency band width, so sites were selected which were on bedrock and well insulated (see Figure 3).

<sup>1</sup> George Zandt, Steven Meyers, Mark Tinker, Jennifer Swenson, Richard Brazier, Guangwei Fan, and Robert Busby (from the PASSCAL Instrument Center).

The seismic wavefield was sampled at 100 and 20 sps. Figure 4 shows a reduced seismic section for the profile. Crossover between  $P_g$  and  $P_n$  being the first arrival occurs between station 7 and 6; there also was a significant change in character of the seismic signature between stations 5 and 4. This also corresponds to the boundary between the Colorado Plateau and the Basin and Range.

Several days prior to NPE, just after the profile was installed, an earthquake located near Chiapas, Mexico ( $D \approx 29^\circ$ ) was recorded by nine of the profile stations. Zandt et al. (1994) used the teleseismic P-waves from this event to determine the receiver function beneath the stations and estimate the crustal thickness. There is a thickening from the Basin and Range to the Colorado Plateau of approximately 17 km, although the thickening is not uniform (the crustal thicknesses are shown in Figure 2). The gross variations in crustal thicknesses, translated into undulations of the Moho, seem to explain the variations in the P-wave amplitudes. Note that the  $P_n$  amplitude at station 5 is more than five times larger than that observed at stations 4 or 6. This type of variability of  $P_n$  is a fairly common observation within the Basin and Range. A possible explanation for this behavior is that significant Moho topography can produce localized zones of rapid amplitude variations due to focusing/defocusing. Tracing rays through a simple Earth

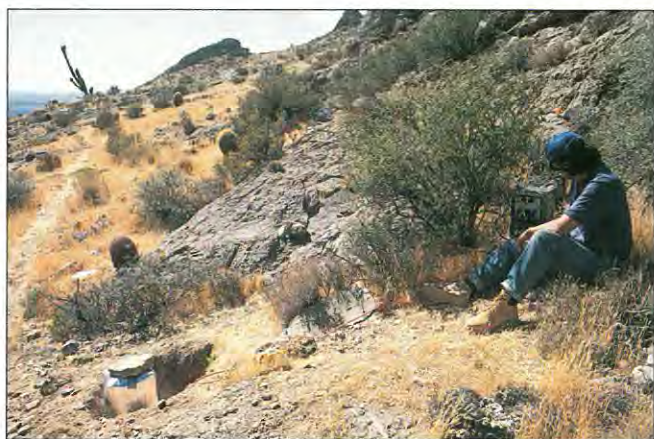


**Figure 3. Installation of station 5 on limestone bedrock. George Zandt programs the Reftek data logger.**

model incorporating the variations in receiver functions produces a zone of pronounced focusing at about 200 km. The receiver function analysis is a testament to the advantages of using broadband instrumentation for temporary seismic deployments. The "chance" recording of a distant earthquake provided significant structural constraints which improved the analysis of the NPE data.

Most schemes for discriminating nuclear explosions from earthquakes are based on differences in frequency content of the radiated seismic waves. Earthquakes are enhanced at the long-period end of the spectra compared to explosions. One of the best discriminants is the spectral ratio of a given seismic

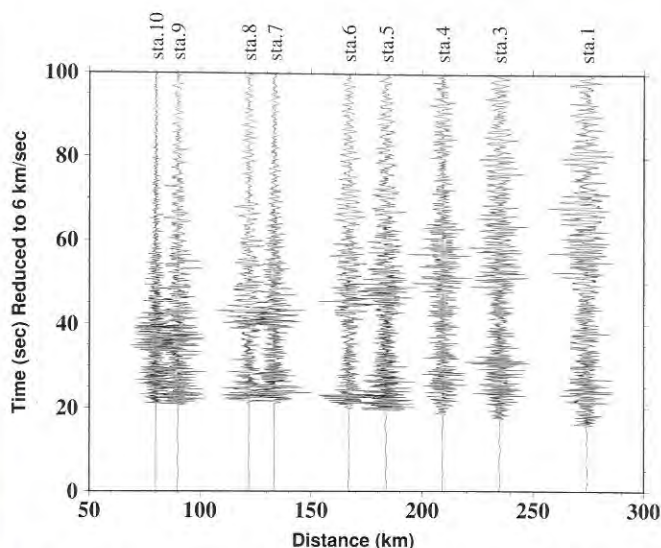


**Figure 4. A reduced seismic section for NPE. Crossover from  $P_g$  to  $P_n$  is at approximately 150 km.**

phase at two different frequencies (typically 1–2 Hz and 6–8 Hz). The spectral ratios for NPE indicate that it looked very much like a nuclear explosion. In fact, preliminary analysis indicates that the physical signatures of NPE were very similar to a nuclear explosion except for the electromagnetic pulse (EMP) produced. The similarity suggests that chemical explosions can be used to seismically calibrate suspect regions. The character of regional distance seismograms is strongly dependent on the geologic structure along the travel path between the source and receiver. It is likely that if there is an extension of the NPT or implementation of a CTBT, monitoring will concentrate on clandestine tests. Such an explosion, designed to skirt a treaty, would likely be a "first and only" test conducted in a region for which there are no historic seismic data available. Thus, chemical explosions and portable seismic instrumentation will undoubtedly play an important role in the future for investigating diverse geologic environments.

Seismic data collected for NPE are available through the IRIS DMC and anonymous ftp. The data are organized in sub-directories based on distance: local, near and far regional. •

## IRIS DMC Installs MOSAIC Server

A NCSA Mosaic Information Server was recently installed at the IRIS DMC. Individuals knowledgeable about MOSAIC can access the home page of the DMC by opening <http://www.iris.washington.edu/>.

Client versions of MOSAIC can be obtained from anonymous ftp from NCSA through address <ftp.ncsa.uiuc.edu>.

Versions of the MOSAIC client exist for X windows, Macintosh, and PC computers running Windows. •

# The Canadian National Seismograph Network

*Bob North and Ken Beverley, Geological Survey of Canada*

The Geological Survey of Canada (GSC), through the Geophysics Division in Ottawa, Ontario and the Pacific Geoscience Centre in Sidney, British Columbia, has the sole responsibility for monitoring and studying earthquake activity in Canada. With the exception of three small networks in southern Ontario, southern Saskatchewan, and southwestern British Columbia, the GSC operates all the seismograph stations in the country. In the 1960s the Geophysics Division (then known as the Earth Physics Branch) installed the Canadian Standard Station Network of 24 stations almost identical in characteristics to the WWSSN, with three-component short- and long-period seismometers and photographic recording. Starting in the late 1970s, digital telemetered networks were installed in southeastern and southwestern Canada as the Eastern (ECTN) and Western Canada Telemetered Networks (WCTN). Over the last decade, standard stations have been closed in response to declining budgets and increasing costs. The 1988 Saguenay, Quebec earthquake provided the impetus for the funding of a complete modernization of GSC seismograph stations. The Canadian National Seismograph Network (CNSN) replaces the standard and regional (short-period vertical) analogue networks, as well as incorporating and upgrading the ECTN and WCTN.

## CNSN Objectives and Siting

The resources available for seismology in Canada are limited and the CNSN has to satisfy a number of needs that, in order of priority for the Geological Survey of Canada (GSC), are as follows:

- monitor national seismicity in near-real time
- provide data for research into the nature and causes of earthquakes in Canada
- contribute to the assessment of global seismic activity
- provide the Canadian contribution to nuclear test ban monitoring experiments
- produce data from Canadian stations for seismological research worldwide
- contribute continuous data to the Federation of Digital Seismograph Networks

These objectives are not always compatible and some compromises have had to be made - for example, current so-called Very Broad Band (VBB) systems are biased towards low frequencies. As such, they do not cover the full range of frequencies necessary for local and regional seismicity, or for test ban monitoring, but with the resources available it has not yet been possible to equip VBB stations with supplementary high frequency sensors.

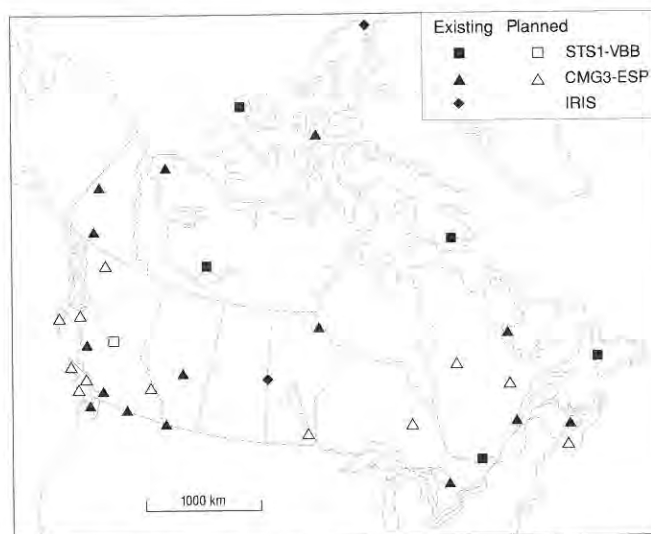


**Figure 1. Locations of CNSN VBB (squares) and BB (triangles) stations, and the two IRIS VBB sites (diamonds) in Canada.**

The locations of the CNSN VBB and broad band (BB) sites are shown in figure 1. The five VBB sites have been installed with an average spacing of about 1500 km, taking into account the two IRIS VBB stations in Canada. They are equipped with Wielandt-Streckeisen STS-1VBB seismometers. The thirty BB sites, based on Guralp CMG-3ESP and CMG-3T seismometers, have generally national coverage and roughly 500 km spacing, with some concentration in the seismically active areas of western Canada. Not shown are the much denser short period (SP) networks in southeastern and southwestern Canada. The former are distributed throughout southern Quebec and the adjacent provinces, with a spacing of a few hundred km, and the latter are concentrated on Vancouver Island, with an average spacing of less than 100 km. Most of the SP stations are vertical component only.

All sites are provided with 24-bit digitizers and real-time continuous data telemetry. There is no local recording of the data, other than in a short-term RAM buffer. A battery-backed Uninterruptible Power System (UPS) that will run the seismograph and telemetry systems for up to 6 hours, is provided at each location.

## Digitizers

The GSC Instrumentation Laboratory has developed two new digitizers for the CNSN. The Geophysical Digitizer (GD) is used at the VBB and BB sites, and the Short Period Digitizer (SPD) at the SP sites. Each generates time-tagged packets containing 6 seconds of data in a format employing a data

compression scheme that encodes second differences at the bit level. Concentration software that produces a packetwise continuous data stream from several inputs - multiple sensors at one site, or telemetered by radio into a central location - has also been developed.

The GD has three seismic input channels, a single (16-bit) calibration channel, and a clock. Each seismic input channel has a continuously-calibrated, 10-bit programmable-gain amplifier (PGA) which feeds into an oversampled, 16-bit analog-to-digital converter (ADC). A 32-bit, floating-point, digital signal processor (DSP) is used to correct the PGA errors on a sample-by-sample basis. It also digitally filters (3-stage FIR filter with 297, 73 and 391 coefficients, -140dB stopband) and decimates each of the three channels of data, from 15,000 Hz down to the output sample rate of 40 Hz. The resulting 32-bit (mantissa only) samples are compressed, time-tagged, and formatted into CNSN data packets by a 16-bit auxiliary processor. Up to 12 Mbytes (about 24 hours) of data packet storage capacity can be provided in RAM - most sites will be equipped with 4 Mbytes.

The SPD has a single seismic input channel, a 12-bit calibration channel, and a clock. The seismic input channel has a continuously-calibrated, 8-bit PGA which feeds into an oversampled 16-bit ADC. A 16-bit microprocessor is used to correct the PGA errors and digitally filters (2-stage FIR filter with 59 and 115 coefficients, -128dB stopband) and decimates the data from 1,000 Hz down to the output sample rate of 100 Hz. It also compresses the resulting 32-bit samples, time-tags them, and formats them into CNSN data packets. A total of 112 Kbytes (about 15 minutes) of data packet storage capacity is provided.

In both the GD and SPD, timing is synchronized, by a phase-locked loop, to a GPS or Omega clock module which is an integral part of each digitizer. Data packets are transmitted every 6 seconds over an RS-232 serial link. Typical data rates from quiet sites are 1400 bit/s for three channels of BB data from the GD,

and 1200 bit/s for single channel SP data. The salient specifications of the two digitizers are given in the table. Figure 2 summarizes the generalized response of the three classes of seismograph stations presently operated in the CNSN.

### Telemetry

At most locations, Very Small Aperture Terminal (VSAT) satellite links are used to relay the continuous data to the network data acquisition systems. Satellite links are usually cheaper than dedicated telephone links over distances greater than about 200 km and are the only viable means of communication to many of the more remote areas of Canada. All communications links are provided with a capacity sufficient to transfer two bytes per data sample (note that these two bytes are for the compressed differences, and thus easily

accommodate actual data values approaching 27 bits). A 2400 baud link suffices for a three-component, 40 sample/sec BB or VBB site. The SP stations use a mixture of radio, microwave, dedicated telephone, and satellite links; in many cases data from several sites are telemetered by radio to a concentration point and then transferred to a satellite link. As shown in figure 3, data from the VSAT-linked sites are received at a Master Earth Station (MES) in Toronto, where they are concentrated and sent over separate high-speed (128 Kbaud) satellite links to both Ottawa and Sidney. The satellites (ANIK-E) and MES are operated by Telesat Canada.

### Data Acquisition, Processing and Archiving

Twin Network Acquisition Systems (NAQS) in Ottawa, Ontario and in Sidney, British Columbia acquire the

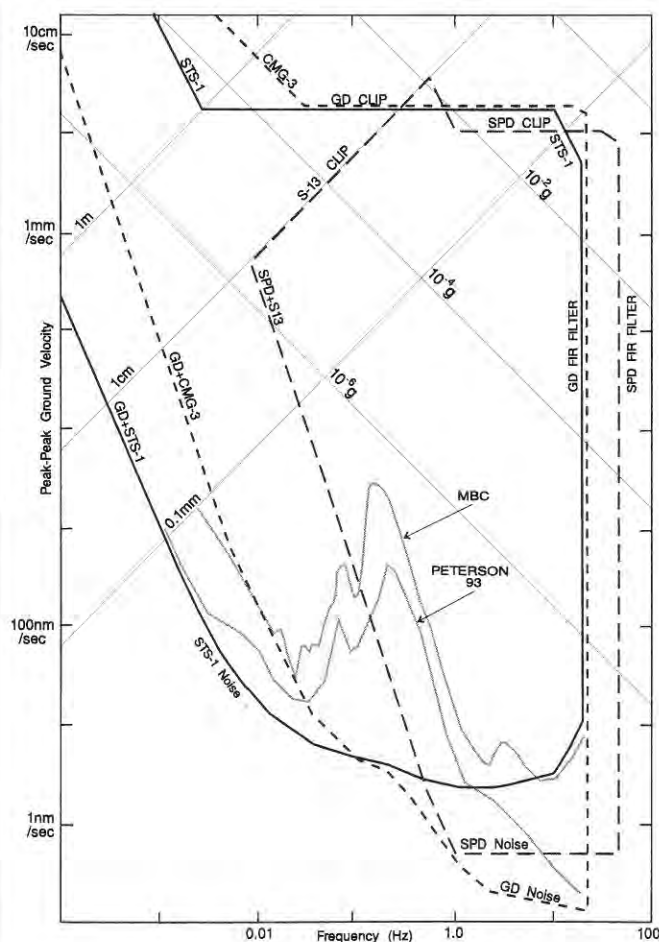


Figure 2. Operating ranges of the three types of seismograph stations in the CNSN. The characteristics of each are limited by the noise characteristics of the digitizers and seismometers at low frequencies and at low amplitudes, and by the clipping and FIR filter characteristics of the seismometers and digitizers at high frequencies and high amplitudes. Also shown are two noise spectra - the revised (1993) Low Noise Model of Peterson and from data recorded at Mould Bay (MBC), North West Territories. The seismometer at MBC is an STS-1 VBB, and at this quiet site the observed levels at frequencies greater than about 3 Hz arise from the seismometer, rather than from background earth noise.

Continued from page 21

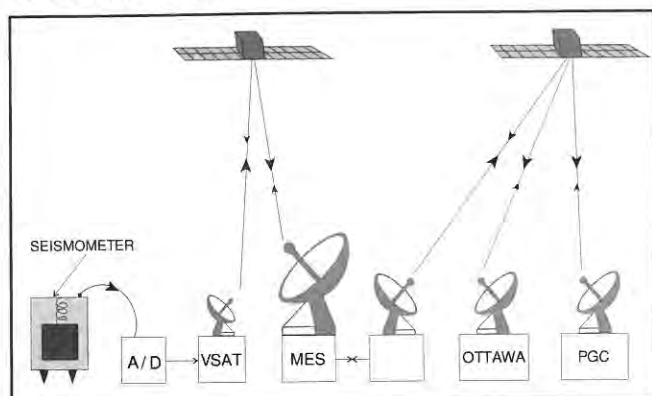


Figure 3. Schematic of CNSN satellite telemetry.

are processed and archived at both locations, providing enhanced overall CNSN reliability. If a data packet or packets are garbled or missing, the remote site is requested to retransmit the packets in question. Some SP stations with radio or telephone telemetry only are received by just one of the two NAQS, but all VBB and BB data are acquired at both locations. Both NAQS are provided with UPS systems, supplemented by a diesel generator. The NAQSs carry out signal detection and subsequent automatic location processing, and archive the continuous data on optical disk. They also maintain a 3-4 day ring buffer on magnetic disk, in order to satisfy requests for recent data as rapidly as possible. The continuous data from the whole network are archived in half-hour SEED volumes on Sony 12-inch WORM (Write Once - Read Many) platters that have a capacity of 6.4 Gbytes. At present each half-hour file is approximately 12 Mbytes and when the CNSN has been completed the anticipated daily archive volume is expected to be between 1.5 and 2 Gbytes. At the end of each data day, long period data streams sampled once per second are filtered from the BB and VBB data, and also archived on optical disk as network day SEED volumes. A separate archive is maintained for waveform data segments from events in and near Canada.

### Implementation Status

The filled symbols on figure 1 show the currently operating stations, the oldest of which date back to late 1992. All but one of the VBB sites, and over half of the planned BB stations, have already been installed. Only a few of the SP stations are operational, though most of the remainder are part of the existing digital WCTN and ECTN systems that now save only detected waveform segments. Problems have been experienced with station timing (mostly Omega signal reception, being corrected with replacement by GPS systems), occasional telemetry outages, and poor overall reliability of the data acquisition systems. These are slowly being resolved, and it is expected that the network will be completed by the end of 1995.

### Data Access

Access to CNSN data in the on-line magnetic disk buffer (most recent 72 hours) is provided through an Internet mail-based system that is basically identical to the AutoDRM method developed in Switzerland (Kradolfer, 1993) that has been adopted as a standard by the FDSN. Requested waveform data is provided either as returned mail messages in the (ASCII) so-called GSE format or, via an anonymous ftp option, in SEED format. To learn how to use this method, send an internet mail message containing the following text lines:

```
BEGIN
GUIDE
EMAIL youraddress@yourplace
STOP
```

to [autodrm@seismo.emr.ca](mailto:autodrm@seismo.emr.ca), and the user guide will be mailed back to you.

Since April 1993, data from the VBB sites (site codes GAC, YKW3, MBC, FRB and DRLN) have been sent on Exabyte

|                                                                         | <u>GD</u>       | <u>SPD</u>  |
|-------------------------------------------------------------------------|-----------------|-------------|
| Output sample rate (samples/s)                                          | 40              | 100         |
| Frequency response (Hz) (-3dB)                                          | 0 - 18.3        | 0.51 - 40.9 |
| Max. input signal (cm/s)                                                | 1.67(STS-1 VBB) | 1.0 (S-13)  |
| Total noise (peak-peak)                                                 | -145 dB         | -127 dB     |
| Noise power spectral density<br>(6 * RMS/(root Hz), 1/3 octave average) | -160 dB         | -145 dB     |
| Linearity (worst harmonic with a<br>full-scale input signal)            | -100 dB         | -100 dB     |

Table. Specifications of the two digitizers used in the CNSN.

tape in SEED format to the FDSN archive at the IRIS Data Management Centre in Seattle, Washington, about one month after being recorded. Copies of the archive files (30-minute SEED volumes for the entire network; LP network day SEED volumes) can be obtained upon request from the Ottawa data laboratory manager ([shannon@seismo.emr.ca](mailto:shannon@seismo.emr.ca)). Requestors are reminded that the chief function of the CNSN is the monitoring of Canadian seismicity, not the provision of data for research, and that staff shortages may result in some delays. •

### New Information Server Installed

A new email based information server has been installed at the IRIS DMC. To obtain information on how to use this server send email to:

[info@dmc.iris.washington.edu](mailto:info@dmc.iris.washington.edu)

and in the subject line enter the word help. Instructions on how to use this system will be mailed back to you. •

# Evaluation of Instrument Responses Made (Relatively) Simple!

*Bob Woodward, Albuquerque Seismological Laboratory*

In recent years there has been a dramatic increase in both the quantity and complexity of seismic instrument responses which seismologists must deal with. For example, the data of the IRIS Global Seismographic Network for a single event might involve well over one hundred unique instrument responses. Adding to the complexity, many of these instrument responses are specified as a series of stages. A typical long-period channel, for example, would be specified by an analog seismometer stage (specified by poles and zeros) followed by several Finite Impulse Response (FIR) digital filter stages (specified by digital filter coefficients).

Recently, a new software product, EVALRESP, has been written to make evaluating instrument responses easier. This new software provides C and FORTRAN callable functions which will evaluate a given instrument response at a specified frequency. This software was commissioned by the IRIS DMC and was written by Jean-Francois Fels of the IDA group at Scripps Institution of Oceanography, University of California, San Diego. A companion program to EVALRESP, called RELISH, has been produced by Tom McSweeney at the University of Washington and provides a MATLAB interface to the EVALRESP software. Both EVALRESP and RELISH are available from the IRIS DMC. EVALRESP was written and tested in the Sun UNIX environment, but it should be easily portable to other UNIX environments (an early version was successfully ported to and tested in a VMS environment).

EVALRESP was designed to meet two basic goals. The first goal was that the code should be able to compute the instrument response for any data stream written in SEED format. The

second goal is that it should be easy to add or update the instrument responses that EVALRESP can compute, and changing the responses should not necessitate changing the software.

In practice, the data user who wishes to evaluate an instrument response would proceed through the following steps.

1. Compile and link the EVALRESP code with your own software. The software comes with several sample programs which demonstrate how to call the response evaluation function from either C or FORTRAN. While the overall response evaluation software has the name EVALRESP, the actual function called from within a user's code is called EVRESP.

2. Run the program RDSEED on a SEED volume (or a dataless SEED volume). RDSEED is available from the DMC. Use the "r" option of RDSEED to extract "response" files (alternatively, if you are also reading data from the volume then simply answer "Y" to the final question which asks if you want responses). RDSEED will create ASCII files containing all the information necessary to evaluate the response of a given station-channel. These response files have the naming convention "RESP.STA.CHAN" — for example the response file for the broadband vertical channel at ANMO would be named RESP.ANMO.BHZ.

3. Define an environment variable which points to the directory containing the "RESP" files, for example:

```
setenv SEEDRESP /users/data/responses
```

4. Run your own software and call the EVRESP function. In the call to EVRESP you would specify the station name, channel name, data date, frequency at which you wish the instrument response evaluated, the units you desire (*i.e.* response to ground displacement, velocity, or acceleration), as well as some other options. The EVALRESP function will return the complex valued instrument response at the specified frequency. It is necessary to specify the date, as a particular station-channel may undergo changes (seismometer replacement, etc.) which will result in different instrument responses for different time periods. For a given station-channel-date the code will read and load into memory the information from the appropriate "RESP" file residing on disk. In typical usage, you would loop over a number of frequencies for a given station-channel-date — thus the response information would only need to be read from disk when the station-channel-date information changes.

*Continued on page 24*



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The IRIS Newsletter welcomes contributed articles. Articles should be less than 1000 words and four figures. Please send articles or requests for details on submission of articles to the address listed above. Electronic submission is encouraged.

Executive Editor: David Simpson (simpson@iris.edu)  
Production Editor: Denise Dillman Crump (denise@iris.edu)

## CALENDAR

### JULY

20-22 HPCC Workshop,  
Boulder, Colorado

### SEPTEMBER

27-29 EXECOM Meeting,  
Snowbird, Utah

### OCTOBER

17-18 ESSSA Meeting  
Columbia, South  
Carolina

24-27 GSA Meeting,  
Seattle, Washington

### NOVEMBER

5-9 ILIAD Workshop,  
Taos, New Mexico

### New Members

IRIS welcomes as new member institutions Auburn University, Lorraine Wolf, representative; and Florida International University, Dean Whitman, representative. IRIS also welcomes Utrecht University as a foreign affiliate, Roel Snieder, representative. •

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In a departmental computing environment one could easily maintain a single common directory containing many different "RESP" files and this directory would be accessible to many users (each user could set their "SEEDRESP" environment variable to point to this directory). In addition, EVALRESP is also available in a version which reads directly from a SEED volume, without the intermediate step of using RDSEED to create the "RESP" files. Note that it is a good practice to update the "RESP" files any time a new SEED volume is obtained, as the instrument response information may have changed, been corrected, etc.. So-called "dataless" SEED volumes are produced by the Data Collection Centers and are available from the DMC for the express purpose of providing the latest information about stations. These dataless SEED volumes are regularly updated.

Note that the "RESP" files can also be obtained in several other ways besides reading SEED or dataless SEED volumes, such as:

1. using the bulletin board at the IRIS DMC — use the "s" menu option and the "r" sub-option.
2. using the anonymous FTP at the IRIS DMC and going into the directories:  
pub/RESPONSES/IU pub/RESPONSES/II, etc..
3. from xmosaic, in the IRIS DMC home page, select:  
Station RESPONSE INFORMATION
4. use the IRIS DMC information server: email to [info@dmc.iris.washington.edu](mailto:info@dmc.iris.washington.edu) with a subject of:

response

and the body of the email with text entries such as:

ANMO IU BHZ  
PAS TS BHN  
AAK II BHE

(note that the IU, TS, II indicate the network: IRIS/USGS, TERRAscope, and IRIS/IDA, respectively).

For instructions on how to obtain EVALRESP or RELISH use the bulletin board at the IRIS DMC (select menu option "p"). The software comes with manual pages which provide detailed information on its use. For further information about the evaluation of instrument responses, see Appendix C of the SEED manual. •



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