DEMONSTRATION OF ADVANCED CONCEPTS FOR NUCLEAR TEST MONITORING APPLIED TO THE NUCLEAR TEST SITE AT LOP NOR, CHINA

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ABSTRACT

Starting in October 2001 the Center for Monitoring Research (CMR) engaged in an advanced concept demonstration (ACD) to improve nuclear-explosion monitoring capability, focused on the Chinese test site at Lop Nor. A demonstration prototype system was developed by integrating innovative techniques gleaned from recent research and development advances. Emphasis was in the areas of detection, location and identification of underground nuclear explosions with particular attention to techniques applicable to regional seismology in and around the Chinese test site.

The demonstration prototype system was tested against a very large uniform and calibrated database of seismic recordings from over 200 explosions and earthquakes in the vicinity of Lop Nor. The data set, which was assembled from approximately 100,000 event recordings (~ 100 GB) from some 60 different seismic stations sampling the near-regional to teleseismic distance range, provides an unprecedented data resource that can be used to conduct appropriate and meaningful scale tests to quantitatively assess new monitoring techniques for this region.

The above referenced data were supplemented by theoretically scaling selected event recordings of historical nuclear explosions and earthquakes down to levels of m_b = 3.5, m_b = 3.0 and m_b = 2.5. This permitted, for the first time, realistic assessments of frequency dependent event detection and identification capability at low thresholds. The scaled waveforms were embedded in actual background noise and integrated into a database specifically designed for processing with a standard automated and interactive analysis pipeline compatible with those currently employed by the International Data Centre (IDC) and the United States National Data Center.

With respect to the final version of the processing and analysis tools delivered to the IDC by CMR, innovations in the ACD demonstration prototype system include site-specific threshold monitoring and the F-statistic detector to facilitate automated detection. Origin information and waveform data from the underground nuclear explosions historically conducted at Lop Nor were assembled and used to facilitate improved location, including:

- Development of static travel-time test-site corrections
- Calibration of regional travel times, i.e. Site-Specific Stations Correction (SSSCs) developed by the Defense Threat Reduction Agency (DTRA) Group 1 and Group 2 calibration consortia and integrated into the ACD
- Development of a waveform cross-correlation tool, used for making very accurate arrival picks
- Master event and joint hypocenter determination (JHD) relocation algorithms
- Non-gaussian confidence area visualization

To extend the applicability of the mb:Ms discriminant to low thresholds, phase-matched filtered-surface wave detection was integrated into the ACD demonstration prototype system. In the area of depth phase utilization, a number of innovations were integrated, including depth phase stacking and the use of F-statistic and probability traces. Regional 3-component amplitude ratios were calibrated specifically for the Lop Nor area and fused with other discriminants (depth, mb:Ms) to form event identifications based on multivariate syntheses.

The tuned ACD demonstration prototype system was applied to the systematic analysis of the events in the Lop Nor data sets. The results have confirmed that significant improvements in detection, location and identification capability in this region are achievable as a result of this effort.

OBJECTIVES

General Approach

To assess the potential applicability of recent research results to the overall objective of improving nuclear test monitoring capability, the Center for Monitoring Research (CMR) has been developing a test environment and approach, within which promising results and developments can be evaluated in the context of a broader nuclear test data processing and analysis system. Promising advanced concepts such as site-specific threshold monitoring (Kværna *et al*, 2001), high precision location through waveform cross-correlation and master event location (Fisk, 2002) and regional surface wave detection through phase matched filtering (Stevens *et al*, 2001) have shown great potential for improving detection, location and identification capabilities. These and many other similarly promising advanced concepts have been demonstrated within the realm of the individual research projects, limited in terms of the scope and resources of a basic research and development (R&D) project.

The CMR offers an open and flexible environment that is ideally suited to perform intensive, broadly scoped projects on short time scales specifically geared to assessing improvements to nuclear test monitoring capabilities. We have developed an approach termed an Advanced Concept Demonstration (ACD) that facilitates the rapid assessment and demonstration of realizable capability gains through appropriate scale testing, focused on a specific nuclear test monitoring problem. The approach we have developed leverages a wide range of resources that are not typically available to individual researchers, that are on the other hand available at the CMR. These include

- Database and extensive archive of International Monitoring System (IMS) waveform data
- Numerous specialized data sets (e.g. explosion and ground truth databases)
- System software i.e. the core of the data processing and analysis system used by both the International Data Centre (IDC) and the United States National Data Center (USNDC)
- Computer infrastructure, in particular numerous data processing servers and analysis workstations
- Software development team, well suited to rapid prototyping and integrating tools based on R&D efforts
- Operational test and evaluation experience; in particular, scientists and analysts familiar with the real-world challenges of processing and analyzing large volumes of data

As mentioned above, an ACD facilitates appropriate scale testing within the context of a broader nuclear test data processing and analysis system. We integrate and apply new prototype tools and R&D results at the appropriate point within the full range of processing and analysis steps going from signal detection, all the way through event identification. This has the benefit of assessing the performance of the advanced concepts under realistic conditions.

Aside from slight variations in approach due to the specifics of a particular focus area, all ACDs invoke a common process and summarized in the following six steps:

1. Use customer focus and technical challenges to define scope of the specific monitoring problem being addressed by the ACD
2. Identify relevant R&D results
3. Rapid prototype new tools based on research results
4. Integrate prototype tools and/or research contributions into a prototype demonstration system compatible with the core system software of the IDC and USNDC
5. Apply core system and ACD tools and against a variety of very large data sets
    a. Historical data for validation of techniques
    b. Scaled or synthetic data to allow testing at thresholds of interest for US monitoring objectives
6. Conduct performance evaluation

While the content and structure of the data sets are motivated by the specific requirements of the ACDs, it is recognized that these may have significant value to the R&D community at large. As a result the data sets are transitioned to the Research and Development Support System (RDSS) function of the CMR (Woodward and North, 2002), through which the data and some portion of processing and analysis results are made available to researchers.

In this paper we present the results of having conducted an ACD focused on assessing potential improvements to the capability to detect, locate and identify events in and around the nuclear test site at Lop Nor, China.

Lop Nor ACD Goals

The Chinese nuclear test site at Lop Nor (alternately referred to as Lop Nur in some publications) is of considerable interest and is a particularly attractive ACD focus area for a number of reasons. Commercial satellite imagery obtained by the CMR (Skov *et al*, 2002) shows evidence of continued activity of unknown purpose at the test site. The 45 historical nuclear explosions of which 23 were underground detonations (Yang *et al*, 2000) provide an excellent source of data for calibration and evaluation purposes, particularly since high quality ground truth locations are now available from Fisk (2002) for the most recent explosions with extensive waveform recordings. Finally capability for monitoring of Lop Nor has dramatically improved with the deployment of the seismic array at Makanchi, Kazakhstan.

A potential technical challenge to monitoring of the Lop Nor site is posed by the fact that the area is seismically active. Since 1964 the ISC reported some 370 earthquakes within the geographical area of 37° – 44° north latitude, 84° – 94° east longitude, most of which are at m_b 4 or larger. Figure 1 shows the ISC locations of earthquakes (orange circles) and underground nuclear explosions (red stars). The Harvard CMT solutions are also shown (beach balls) when available. It is clear that earthquakes occur within the test site area itself. In fact two moderate earthquakes (January 27 and 30, 1999) occurred within about 15 km of historical nuclear tests. As detection capability improves it can be expected that the number of small events detected within the historical test site will significantly increase. The challenge will be to supplement the capabilities of the Makanchi array and accurately locate and identify numerous small ($< m_b$ 3.0) events using regional seismic data.

Our baseline for assessing improvements obtained through the execution of the ACD was derived from the performance of the GSETT-3 and IMS network. This is embodied in the reviewed event bulletin (REB) of the Prototype International Data Center (PIDC) from 1995 – 2000, followed by the REB produced by the IDC after Feb. 20, 2000. An analysis of these bulletins reveals historical capability at Lop Nor as follows:

- Three-station 90% confidence detection threshold: m_b 3.6
- Location – 90% confidence coverage ellipse area: 3000 km^2 for m_b 3.5 events
- Event identification threshold: m_b 4.5

RESEARCH ACCOMPLISHED

The main effort of the Lop Nor ACD took place in the seven months between October 2001 and April 2002 involving numerous scientists and engineers. Rather than present the full scope of the accomplishments, in this paper we present a high-level summary of the results, and overviews of the data sets and integration activities.

Using metrics analogous to those presented in the "Objectives" section of this report, we summarize the accomplishments of the ACD as follows: it was demonstrated that by integrating a number of advanced concepts gleaned from recent research endeavors, significant improvements in detection, location and identification capability were achieved. As specifically applied to the Lop Nor test site, these improvements are:

- Detection – three-station 90% confidence detection threshold:
    - m_b 2.8, as validated through a combination of real and scaled explosion waveform data sets
    - m_b 2.5, expected as more experience is obtained with the Makanchi array (MKAR) allowing a robust single or two-station event definition criteria
- Location – 90% confidence coverage ellipse area:
    - 1200 km^2 for m_b 3.5 events, based on individual event locations using calibrated travel times
    - 40 km^2 for m_b 3.5 events that are within 20 km of historical explosions and exhibiting a high degree of waveform cross-correlation, based on a master event and/or JHD algorithms
- Location – mislocation of explosions:
    - Application of the waveform cross-correlation/master event location technique to explosions since 1990 and to the scaled explosion data showed that the median mislocation was reduced from 7.6 km to 0.4 km. For the same set of explosions, the median error ellipse area was reduced from 700 km^2 to 11 km^2. This indicates that with the ACD station set and tools, we can locate explosions at the test site to within 2 km of ground truth, even events as small as m_b 3 – 3.5.
- Event identification threshold: m_b 3.0, based on application to 162 earthquakes, actual nuclear explosions, and the scaled explosion waveform data sets

It should be noted that these improvements are based on the processing and analysis using a demonstration prototype system. It would take additional engineering effort to promote this functionality to the point where it could be integrated into the system of a monitoring agency such as the USNDC or the IDC. Further, capabilities are highly dependent on the particulars of the sensor network providing data. It is therefore expected that upon implementation of these advanced concepts in an actual monitoring environment, the capabilities could well be better than those listed above, depending on particular contributions of additional stations not considered in this ACD.

Development of Data Sets

A key element of the Lop Nor ACD was the assembly of data sets for the purpose of developing, testing, calibrating and ultimately validating the advanced concepts.

Station Set

In selecting the stations contributing to the data sets, we first chose to include all stations at regional distances to Lop Nor for which an appreciable amount of historical waveform data were available. Second we chose to include those teleseismic stations from either the GSETT-3 or IMS station networks that had excellent signal detection characteristics as determined from the recordings of historical Lop Nor explosions. This resulted in a network of approximately 60 stations as shown in Figure 2. It should be noted that the stations of the Chinese Digital Seismic Network (CDSN) were included in the ACD station set despite the fact that only one waveform record of a Lop Nor explosion is available from those stations. Because our capability assessments were largely based on the processing of scaled nuclear explosion data, our overall conclusions implicitly exclude the CDSN stations.

Figure 3 shows the relative performance of all the stations in the set. It clearly shows how the Makanchi array (MKAR) is the most important station for detection of events in and around Lop Nor. Other key sites are the regional three-component stations TKM2 and ULHL that are part of the Kirghiz network. The best performing teleseismic arrays are CMAR, NORES, ILAR and YKA.

Reference Data Set

The event based reference data set was assembled by first pulling together bulletin information from available open sources (ISC, PIDC, IDC) and then supplementing that with the Annual Bulletin of Chinese Earthquakes (ABCE) (Richards et. al, 2002). This produced the master list of events used to obtain waveform data from a variety of sources including the CMR archive, AFTAC, NORSAR, Blacknest, and the data management center at IRIS. The data set included 21 underground nuclear explosions and 51 events published in the PIDC or IDC REB since 1995 and 101 events published only in the ABCE during 1995 - 1999, all within the study area of 39° - 44° north latitude, 86° - 92° east longitude. More information about the reference data set is reported by Woodward and North (2002).

Fixed Data Set

To supplement the event based reference data set, we assembled a fixed data set consisting of 10 days of continuous waveform data for the period August 2 – 11, 2001. This data set was used for a variety of assessments, including determining background noise levels and false alarm rates. Further the fixed data set was processed with an objective of detecting and locating events not published in any bulletin. Three small events within the Lop Nor study area of 39° - 44° north latitude, 86° - 92° east longitude were detected and located by multiple stations using the ACD demonstration prototype system. Additionally several dozen small events from within the study area were detected by the Makanchi array only, however without further constraints they were not well located.

Scaled explosion waveforms

In order to assess monitoring capability with respect to the smallest explosions of current interest at Lop Nor, it is necessary to have access to broadband regional waveforms corresponding to explosions associated with the magnitude range from about $m_b = 2.5$ to $m_b = 3.5$, which encompasses the values expected from very small subkiloton tamped explosions, as well as from fully decoupled cavity explosions with yields greater than about 1 kt. However, at the present time, we have no observations available from Lop Nor explosions in this magnitude range, so it was necessary to theoretically scale data observed from larger explosions to obtain approximations to the signals expected from the smaller or decoupled explosions in order to quantitatively evaluate the applicability of various proposed monitoring strategies and algorithms. In the past, for applications to traditional short-period teleseismic data, such scaling has generally been accomplished by simply multiplying the observed narrowband waveforms by a frequency independent constant factor taken to be consistent with the difference in m_b values between the observed and hypothetical explosions. However, this approach is not appropriate for broadband regional data and, consequently, in the present study we have employed the more sophisticated frequency dependent scaling methodology which is summarized as follows.

The expected ground motion time history for a small explosion can be determined from the observed ground motion from a large explosion at the same station if the spectral ratio of the two seismic source functions can be estimated. For the present application, we have approximated this source spectral ratio using the well-documented Mueller/Murphy explosion source model (Mueller and Murphy, 1971). In this case the scaled seismogram $Z_2(t)$ of a particular component of motion recorded at a fixed station can be derived from the recorded waveform by

$$Z_2(t) = \int Z_1(t)\, S(t - \tau)\, d\tau$$

Where $Z_1(t)$ is the original seismogram and S(t) is the explosion source scaling operator (i.e. the inverse transform of spectral ratio from the Mueller/Murphy explosion source model).

The procedure described above has been used to scale seismic data from the Lop Nor reference explosions of May 15, 1995 and July 29, 1996 down to the lower equivalent explosion yields of interest in the assessment of monitoring capability at that test site. As a test of the applicability of this methodology to Lop Nor explosions, we first theoretically scaled selected observed regional data from the larger of the two reference explosions (i.e. May 15, 1995, m_b(REB) = 5.73) to the source conditions of the smaller reference explosion (i.e. July 29, 1996, m_b(REB) = 4.71) and compared the resulting synthetics with the corresponding observed data from the smaller explosion. The results for station MAK ($\Delta \approx 7°$) are shown in Figure 4, where it can be seen that the theoretical scaling very accurately accounts for the observed frequency dependent changes in waveform characteristics, as evidenced by the pronounced change in the L_g/P amplitude ratio between the larger and smaller explosions. In this case, because the two explosions are not collocated, some differences are evident in detailed waveform characteristics and amplitude level between the scaled and observed data, with the theoretically scaled having a broadband peak amplitude level which is about a factor of 2 smaller than the observed at this station.

Integration of R&D elements and prototype into a demonstration system

Table 1 presents a listing of the key R&D elements, rapid prototyped tools, calibration and tuning results synthesized into a demonstration prototype system as part of this ACD. Our approach to integrating these elements was to use as a baseline, the monitoring system software that defines the core of both the IDC Release 3 upgrade delivery and the USNDC Phase 2 system.

We made numerous significant upgrades to many of the key elements of the core system, including the detection and feature extraction software (DFX) and the interactive analysis suite (ARS). When R&D elements or advanced concepts were implemented through direct changes to the core part of the system software they are categorized in Table 1 as “Software”. Some of the advanced concepts required implementation in the form of a new tool or component. In that case they are flagged in Table 1 as “Prototype software”. Finally a number of the changes were the result of tuning, calibration or reconfiguration. There were typically implemented by updates to existing parameter or configuration files, for example, detection recipes, SSSCs and magnitude correction files.

Table 1: R&D elements, prototype tools, calibration and tuning results integrated into a demonstration prototype system as part of the Lop Nor Advanced Concept Demonstration (ACD)

Monitoring Category	Element Type	Description
Detection	Tuning	Tuned recipes for sta/lta detector for the Makanchi array (MKAR)
	Software + Tuning	Implemented and integrated the F-statistic detector, developed and tuned recipes for regional and teleseismic arrays
	Software + Tuning	Implemented and integrated site-specific threshold monitoring (SSTM) focused on Lop Nor, using MKAR, key teleseismic arrays + selected regional 3-C stations, derived from Kværna *et al* (2001).
	Prototype software	Implemented event detection by triggering off of deviations of SSTM trace
	Tuning	Adapted global association algorithm (GA) to regional association, using fine regional grid and tuned phase association rules
	Prototype software	Developed and integrated a tool to facilitate tip-off based review of scrolling real-time waveform data, including beams, SNR and other traces
Location	Software	Upgraded system software to allow user selection between SSSCs
	Software	Upgraded system software to support a variety of location algorithms: single event technique (LocSAT), master event location or JHD
	Software	Upgraded system software to allow simultaneous analysis of numerous association, phase picking and location hypothesis of the same event
	Calibration	Incorporated SSSCs based on CUB1.0 model (McLaughlin et. al, 2002)
	Calibration	Incorporated kriged SSSCs based empirical data (Richards et. al, 2002)
	Calibration	Developed test site corrections based on ground truth (Fisk, 2002)
	Prototype software	Developed tool to allow phase retiming and master event locations based on waveform cross-correlation
	Prototype software	Developed tool to allow visualization of confidence regions based on non-gaussian error models (based on Rodi and Toksoz, 2001)
	Software	Upgraded system map display capability and incorporated commercial satellite imagery (including 1 meter IKONOS imagery)
Identification: depth	Prototype software	Developed and integrated depth phase stacking tool (Murphy *et al*, 2000)
	Prototype software	Developed and integrated display to facilitate interactive review of depth phase move-out
	Software	Upgraded interactive analysis suite to facilitate use of F-statistic and probability traces in picking and timing of depth phases
Identification mb:Ms	Prototype software	Integrated software (MaxPMF) to perform low threshold regional surface wave detection using phase matched filtering (Stevens *et al*, 2001)
	Software	Upgraded analysis suite to support interactive review of phase matched filtering results, including noise amplitude measurements
	Prototype software	Developed and integrated display to facilitate interactive review of mb:Ms discrimination results
	Prototype software	Developed and integrated software to compute and display RAMP results (Pearce *et al* 1988)
	Calibration	Recalibrated test site m_b, and Ms station magnitude corrections
Identification: regional amplitude ratios	Software	Upgraded system software to compute regional amplitudes using 3-component broad-band channels
	Calibration	Recalibrated regional amplitude ratio discriminant based on historical Lop Nor explosions and earthquakes
	Prototype software	Developed and integrated tools to facilitate interactive review and display of regional amplitude ratios and discriminant
Identification: summary	Prototype software	Developed and integrated tools to compute and display multi-variate event identification, combining depth, mb:Ms, and regional amplitude ratios

CONCLUSIONS AND RECOMMENDATIONS

During the Lop Nor ACD a very wide variety of techniques contributed at various levels. The following conclusions can be drawn as to the relative contributions of various tested concepts. With regard to detection capability, a number of conclusions are as follows:

- The main driver for improving detection at Lop Nor was clearly the tuned sta/lta detector running against the Makanchi array. To support a three station event definition criteria using stations outside China, the stations of the Kirghiz network (KNET), in particular TKM2 and ULHL were critical.
- The tuned F-statistic detector was a major element in increasing the teleseismic association rate particularly for events in the magnitude range 3.0 – 3.5.
- Site-specific threshold monitoring (SSTM) provided a robust method for assessing that no significant events had escaped detection. As an event detector, SSTM was robust with an extremely low false alarm rate, however it did not offer the low threshold capability of the tuned regional association (regional GA).

With regard to location, the conclusions are:

- Some improvements in location capability were obtained though calibration, specifically the use of SSSCs or test site corrections. The improvements were primarily in the form of better confidence area estimates. However the large measurement errors associated with small events will be the major driver.
- The most striking improvements came from the joint use of waveform cross-correlations to retime arrivals, coupled with master event location algorithms illustrated in Figures 5 and 6. The waveform cross-correlation method was applicable to events within about 20 km of one another, including in some cases the cross-correlations between the P arrivals of earthquakes and historical explosions, even for small events.

Finally with regard to identification,

- Some improvements were made in the identification of depth phases recorded teleseismically from moderate sized earthquakes. In particular 30 of 162 events (18.5%) were determined to be confidently deeper than 10 km using the new ACD depth tools. Teleseismic depth determination does contribute significantly as a robust discriminant for small events ($< m_b$ 3.5) occurring around Lop Nor. Research into regional depth determination will be required if depth is to be a robust discriminant at low thresholds.
- The detection of surface waves using phase matched filtering shows some promise in facilitating the extension of the mb:Ms discriminant down to events that are only recorded regionally.
- By far the most robust discrimination method for events around Lop Nor is through the use of regional 3-component amplitude ratios. It has been demonstrated for a very large variety of events including numerous small earthquakes and the scaled nuclear explosions indicating applicability to small events just above the detection threshold.

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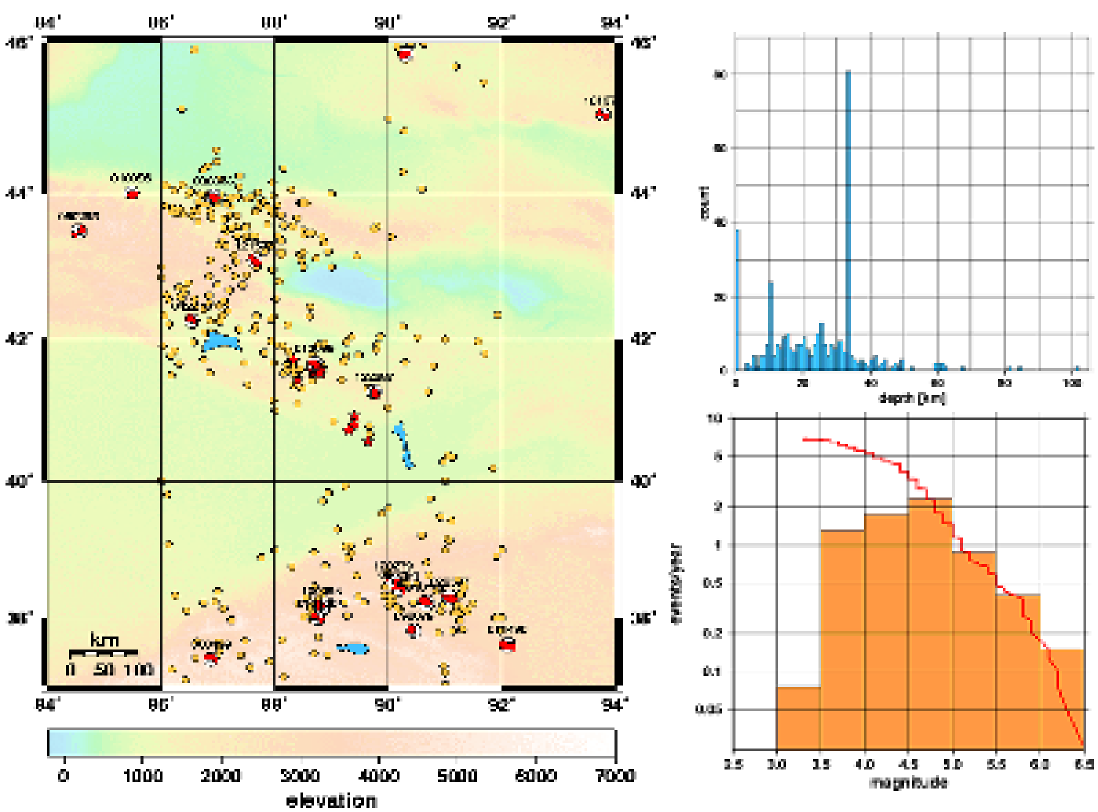

Figure 1: Left: seismicity of the Lop Nor region based on the ISC bulletin. Nuclear explosions are shown as red stars and the Harvard CMT solutions are shown as beach balls. Upper right: earthquake depth distribution in the ISC bulletin. Lower right: m_b recurrence distribution derived from the ISC bulletin.

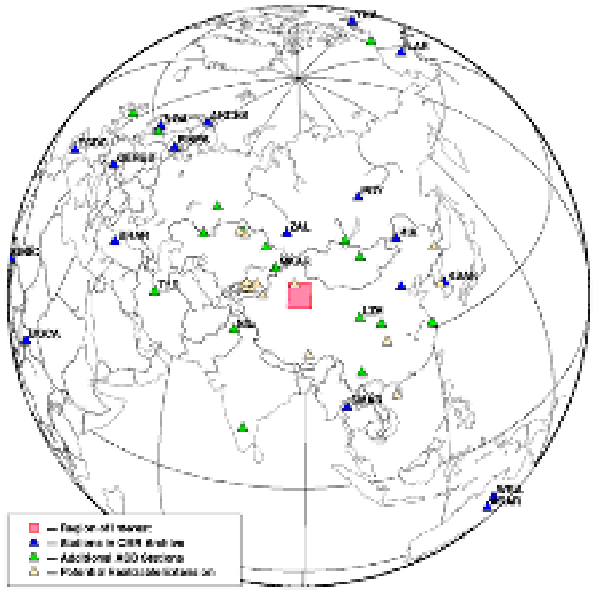

Figure 2: Stations contributing to the ACD data sets. Stations in blue are actual or surrogate IMS primary seismic stations as of June 2001. The green triangles are actual or future IMS auxiliary sites, while the tan symbols are non-IMS sites.

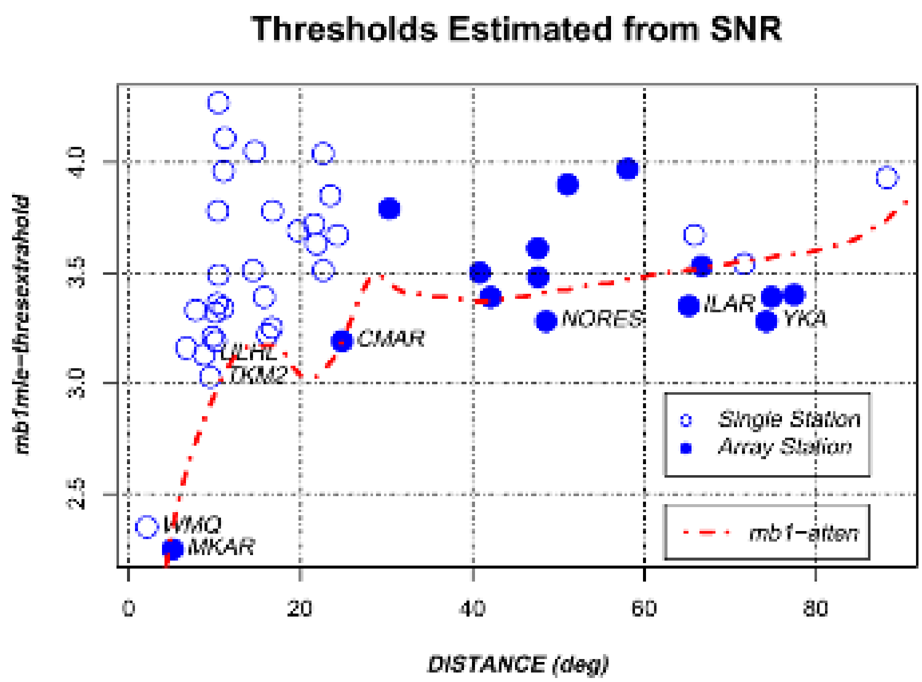

Figure 3: mb1mle station thresholds as a function of distance.

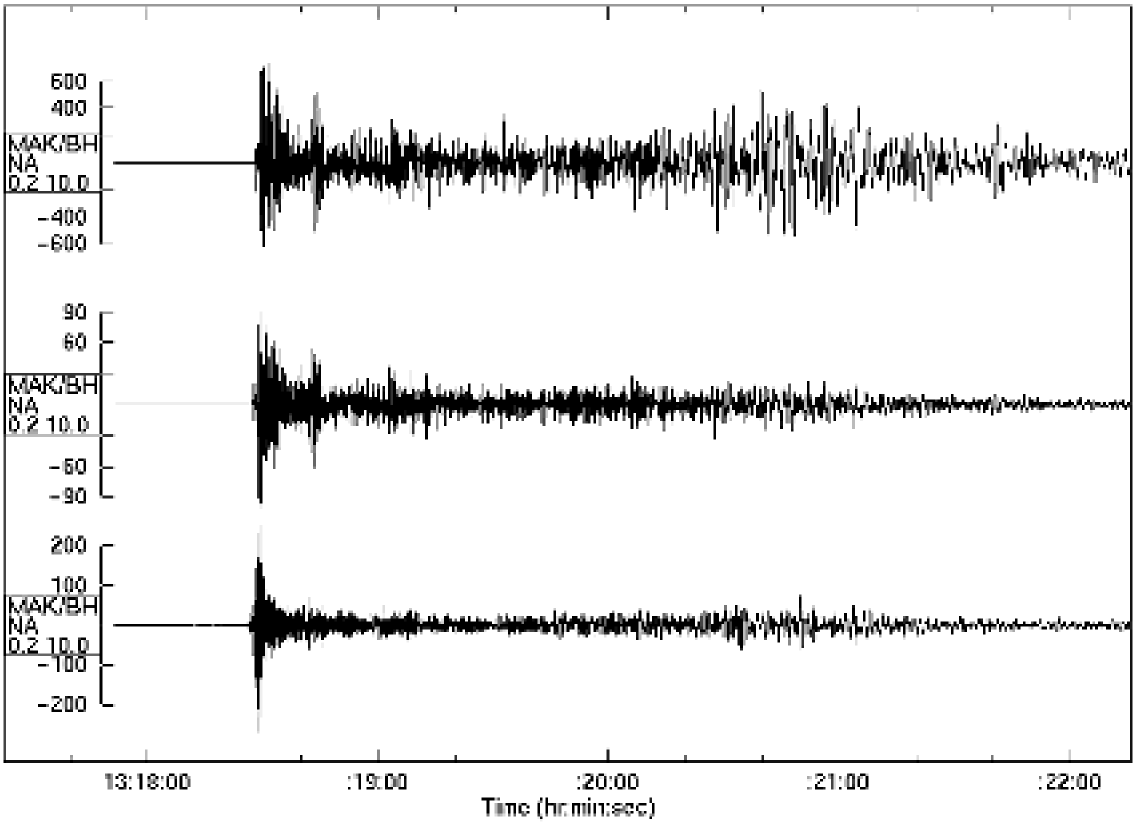

Figure 4: Comparison of the station MAK seismogram obtained by scaling the observed data from the larger May 15, 1995, (m_b = 5.73) reference Lop Nor explosion (top) to the source conditions of the smaller July 29, 1996, (m_b = 4.71) reference Lop Nor explosion (center) with the corresponding observed July 29, 1996, data (bottom).

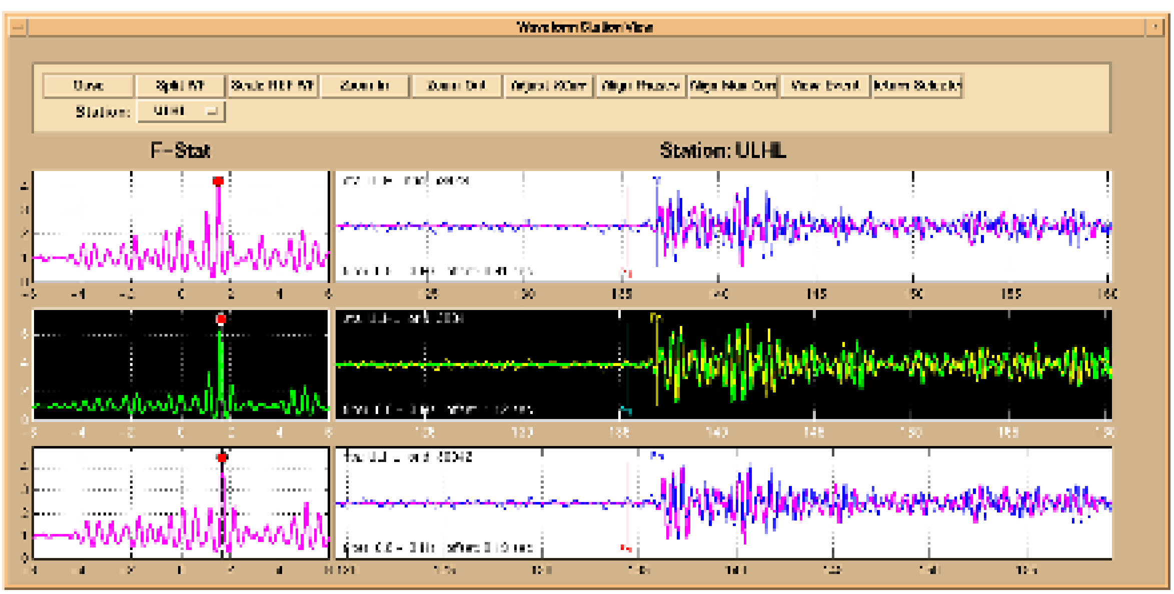

Figure 5: Illustration of the prototype waveform cross-correlation tool developed for the ACD to facilitate consistent arrival time picks. The right three panels show the waveforms scaled to the level of an m_b 3.0 nuclear explosion overlain on the records from historical explosions. The left three panels show the level of correlation displayed as an F-statistic. The analyst has the option to retime according to the maximum correlation and feed the resulting picks to a master event location (see Figure 6).

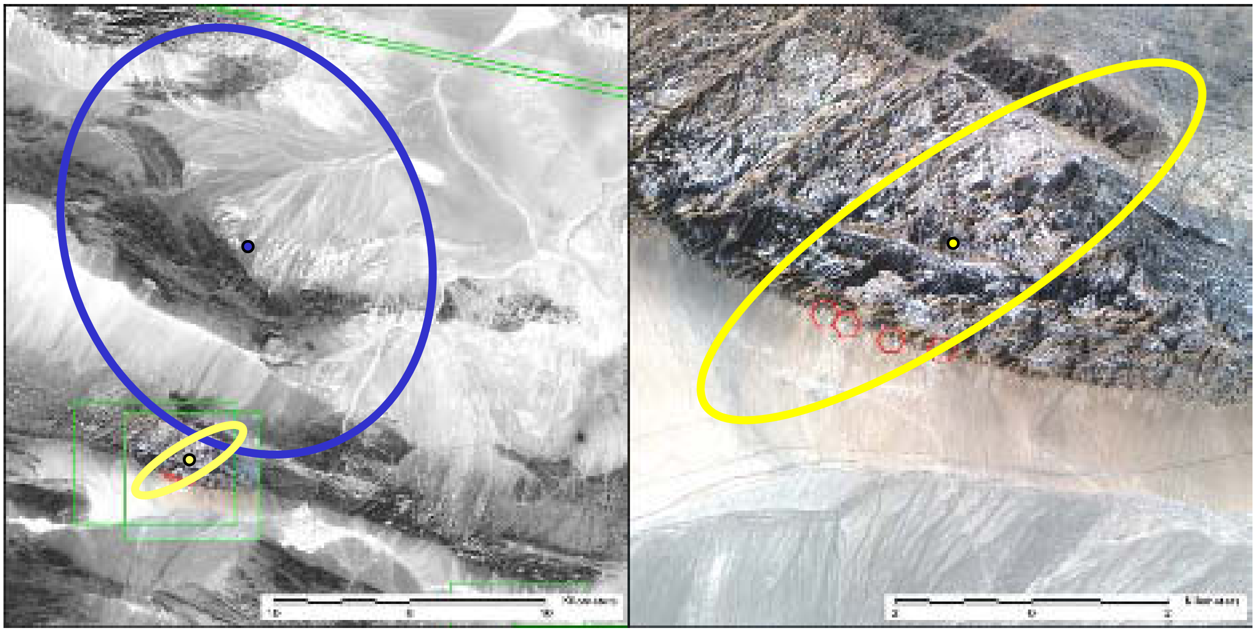

Figure 6: Comparison of locations obtained by processing and analyzing the waveforms from a known nuclear explosion scaled to m_b 3.0. The location depicted in blue in the left panel was obtained by using the calibrated travel times and a traditional single event location algorithm (LocSAT). The solution depicted in yellow was obtained by using the very consistent arrival picks that were made using the ACD waveform cross-correlation tool (Figure 5). Those picks were used in master event location algorithm and resulted in a mislocation of less than 1 km from ground truth. The panel on the left shows 5-m SPOT imagery as the background, while the zoomed view in the right panel displays 1-m IKONOS multi-spectral imagery. The red hexagons outline the known locations of adits in the northwestern part of the Lop Nor test site.