SUPPORT SYSTEM FOR NUCLEAR EXPLOSION MONITORING RESEARCH AND DEVELOPMENT

Robert L. Woodward, Benjamin C. Kohl, and Robert G. North

Center for Monitoring Research
Science Applications International Corporation

Sponsored by Defense Threat Reduction Agency

Contract No. DTRA01-99-C-0025

ABSTRACT

The Research and Development Support System (RDSS) at the Defense Threat Reduction Agency's (DTRA) Center for Monitoring Research (CMR) provides a broad range of support to the nuclear explosion monitoring research and development (R&D) community. This support covers all aspects of R&D, from support for basic research to integration and testing of R&D results.

The RDSS provides researchers with an interface to the wide range of data resources available at CMR, such as: near-real-time waveform data from International Monitoring System (IMS) and other stations; multi-terabyte seismic, hydroacoustic and infrasonic waveform archives; radionuclide databases; and past and present products of both the Prototype International Data Center (PIDC) and the International Data Centre (IDC).

Databases and products available through the RDSS are continually updated and improved. For example, the locations of historical nuclear explosions can, in some cases, be refined to levels suitable for designation as Ground Truth 1 (GT1) or GT2 through the use of high-resolution (1-meter) panchromatic and multi-spectral satellite imagery available from commercial vendors. The process involves the analysis and interpretation of the imagery to identify features that provide constraints on the location. Features are characterized as either providing direct location information (e.g. subsidence craters) or constraining information (e.g. adits, tailings) and are correlated to seismic solutions resulting in the establishment of ground truth locations. One-meter-resolution commercial satellite imagery was also obtained and analyzed for the test sites at Novaya Zemlya, Lop Nor, India, and Pakistan. The ground truth locations obtained for the May 28 and May 30, 1998, underground nuclear tests in Pakistan were used to evaluate the locations produced at CMR using Joint Hypocenter Determination. Imagery data products, including detailed annotated maps derived from the imagery, are being made available through the RDSS web site.

The RDSS receives deliveries from DTRA-sponsored researchers, redistributes these research results, and adds delivered results, when appropriate, to existing databases to create value-added products. Recent deliveries include such items as a unique set of infrasound recordings from atmospheric nuclear explosions in the Former Soviet Union and hydroacoustic recordings of underwater explosions.

The RDSS uses the facilities and capabilities of CMR to evaluate R&D results to assess their potential impact on monitoring system capability. Testing can range from the full data load of the IMS stations and the full processing environment of the IDC, to highly specific tests confined to special data sets. For example, Source Specific Station Corrections (SSSC's) being delivered to the RDSS will be tested under the full IMS data load in both automatic and interactive processing environments.

The RDSS web site (http://www.cmr.gov/rdss) provides a central location for information about the RDSS. The web site provides access to all items delivered to the RDSS, as well as RDSS data and products such as the satellite imagery described above.

KEY WORDS: nuclear explosion monitoring, evaluation, testing, monitoring capability, research and development, satellite imagery, ground truth

OBJECTIVE

The purpose of the Research and Development Support System (RDSS) at the Defense Threat Reduction Agency's (DTRA) Center for Monitoring Research (CMR) is to improve nuclear explosion monitoring capability by supporting the R&D community with a broad range of resources.

The Center for Monitoring Research provides an environment for testing and evaluating promising research results at a wide range of scales. Further, research results delivered to the RDSS are permanently organized and archived in a manner that facilitates their accessibility by the research community. The results of nearly 100 DTRA Program Research and Development Announcement (PRDA) R&D contract projects covering seismic, hydroacoustic, and infrasonic topics are to be archived at CMR over the next three years.

This paper discusses some of the resources available to the R&D research community at CMR and highlights a few recent reports and data sets received from PRDA contractors. We also give a brief description of evaluations of upcoming SSSC's and moment tensor software deliveries. Finally, we conclude with a general overview of resources available for those who will become contributors of products to CMR in the next few years.

RESEARCH ACCOMPLISHED

The Center for Monitoring Research (CMR) houses many unique resources that facilitate research work. Researchers may take advantage of the large volume of seismic, hydroacoustic, infrasound, and radionuclide data, as well as special tools and functionality built to maximize information available for each data technology. In addition, a wide variety of special data products (both databases and data sets) have been assembled to support monitoring research. These data sets are routinely maintained and are augmented with new data as they become available. Commercial satellite imagery is the most recent addition to the suite of special data products maintained at CMR.

Researchers may also take advantage of the results of the DTRA PRDA research program that are delivered to the RDSS. These results are reviewed, archived and redistributed by the RDSS. The PRDA results are distributed in their raw (as delivered) form, and if appropriate, in value-added form (e.g. added to related data to create a new product).

Finally, researchers may take advantage of the facilities and test capabilities provided by the RDSS. Testing environments can be arranged at any scale, from the full data-load of the IMS network and the full-processing environment of the IDC monitoring system, to highly specific arrangements with historical data sets. Supporting facilities include a large UNIX-based computing environment, databases, data archives, and so forth.

In the remainder of this paper we highlight, and provide some details, on the various data, data products, and capabilities that are available to the R&D community via the RDSS located at CMR.

Data Resources Available

Under the Prototype International Data Center (PIDC) project, the CMR has been continuously acquiring and archiving time-series and radionuclide data since 1992. The IMS network is a global network of sensors and, when completed, will comprise 170 seismic stations, 11 hydroacoustic stations, and 60 infrasonic stations. CMR has been processing and archiving these data on a continual 24/7 basis since 1992 for seismic stations, 1995 for hydroacoustic stations, and 1998 for infrasound stations. The processing performed at CMR utilizes data fusion, allowing signals from all three technologies to contribute to analysis of an event, thereby maximizing event information.

Much interest has been expressed in CMR's hydroacoustic and infrasound data archives, as these technologies are a relatively new and rapidly developing part of the IMS network. The hydroacoustic component of the IMS network comprises six hydrophone stations and five T-phase stations (land-based seismic stations configured to detect hydroacoustic signals), providing global coverage of the world's oceans. The hydrophone stations are actually groups of sensors in close proximity. CMR has developed tools to help analyze the source azimuth of hydroacoustic signals, their spectral characteristics, and the means to extract specific measurements from each signal that is identified by the automatic system. CMR is presently receiving data from the IMS hydrophone station at Diego Garcia, in the Indian Ocean. This station has two triangular groups of sensors, with the sensor groups separated by roughly 200 km.

Infrasound stations of the IMS network are already globally distributed, and include locations in Canada, Hawaii, Antarctica, Germany, Bolivia, and Mongolia. These large baseline stations, with separations of one to three km between sensors, as shown in Figure 1, are designed to detect low-frequency sound waves in the atmosphere, and have been successful at detecting events at long distances.

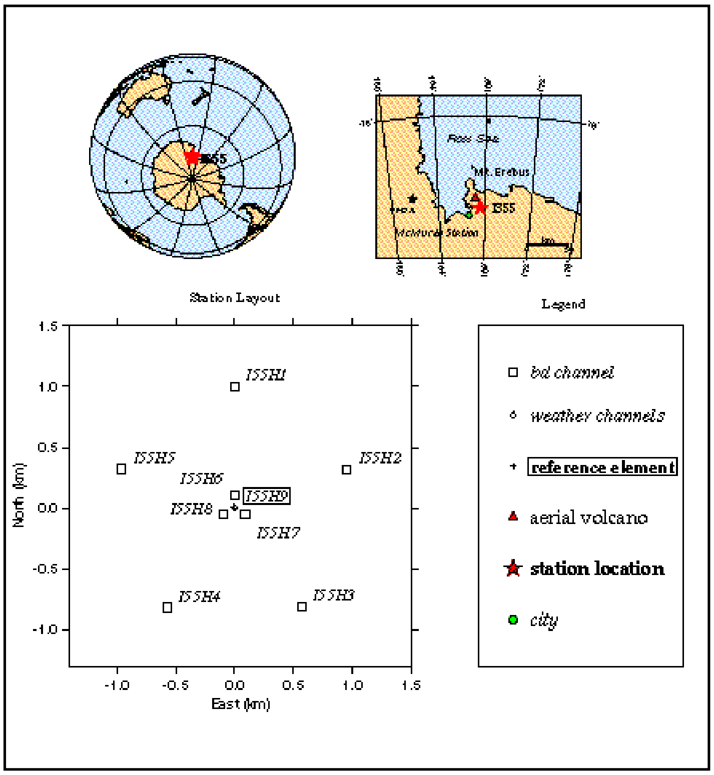

Figure 1. IS55 Infrasonic array, located at Windless Bight, Antarctica, installed on 2001032 (oldest detection date at CMR: 2001149).

Researchers can request and take advantage of all CMR data, from raw waveforms, to individual signal characteristics, to whole event characterization. The data are easily accessed from remote sites by using the AutoDRM (Automatic Data Request Manager) interface, an e-mail-based request mechanism. RDSS users are also provided access to bulletins and data obtained from the IDC in Vienna, Austria.

Special Databases Available

The RDSS produces a variety of special databases and data products that are useful to monitoring research and development, and these are summarized in Table 1. These data products provide data and metadata assembled in a manner to maximize their utility for research purposes. Where appropriate, data being delivered to the RDSS by PRDA contractors are added to these databases, such that the value of both the delivered data, and the database, are increased.

Table 1. Special data sets available to R&D community via the RDSS.

Radionuclide	• High-resolution gamma-ray spectroscopy • Beta-gamma coincidence spectroscopy
Ground Truth	• Nuclear and chemical explosions, industrial events, earthquakes, mixed data sets
Reference Event	• Small- to medium-sized, well located, uniformly globally distributed events
Nuclear Explosion	• Nuclear explosions (1945 – 1993), announced nuclear explosions since 1984, and Australian Geological Survey Organization database (1945 – 1996)

Commercial Satellite Imagery Available

As part of an ongoing effort to update and improve the data sets available through the RDSS, high resolution, 1-meter panchromatic and 4-meter multi-spectral satellite images were obtained from commercial vendors. The objective of the effort was to utilize imagery in conjunction with re-analysis of seismic data to obtain definitive locations of historical nuclear explosions with an accuracy suitable for designations as Ground Truth 1 (GT1) or GT2 events. To achieve this objective, the following approach was used:

1. Acquire and process high-resolution commercial satellite imagery for each of the test sites at Novaya Zemlya, Lop Nor, India, and Pakistan.

2. Analyze the imagery to identify features in one of three categories:

   A. direct evidence of disturbances resulting from nuclear detonations, typically collapse features. These provide an unambiguous constraint on the location. The accuracy of the location depends solely on the accuracy of the registration of the imagery with respect to established location benchmarks. In principle, direct evidence of the disturbance would allow an interpretation resulting in a GT0 location; however, limitations in the accuracy of the imagery's registration result in designations as GT1.

   B. direct evidence of test site artifacts highly correlated with locations of nuclear tests. Typically, these are the surface manifestations of shaft emplacements. The features include roads, buildings, fences and organized patterns of all of these. The features allow for interpretations resulting in GT1 designations.

   C. direct evidence of test site artifacts constrained to the vicinity of nuclear detonations. These are typically features associated with the tunnel emplacements of nuclear tests. The features include roads, adits and tailing piles, all adjacent to mountainous terrain suitable for providing the necessary overburden to contain the event. An analysis of the features evidenced in the imagery, in conjunction with analysis of the terrain data in the vicinity, result in GT1 or GT2 designations.

3. Estimate the uncertainties of the locations of the features. To determine uncertainties, highly visible and distinct but spatially constrained features, such as the intersections of major roadways, are identified on a number of different sources. Older imagery from lower resolution sensors (SPOT, LANDSAT, KVR), digital terrain elevation data, and high-resolution maps available through the National Imagery and Mapping Agency were registered with respect to one another, demonstrating variations of no more than several hundred meters.

The results of the imagery analysis are assembled in a series of imagery products that are available through the RDSS web site. The imagery products are provided in Portable Document Format (PDF) to insure maximum portability and all include progressive levels of zoom so that researchers can make independent assessments as to the nature of the features annotated in the imagery products (Figure 2).

As review of the imagery by CMR analysts progresses, the imagery products will be updated with the latest interpretations and periodically uploaded to the RDSS web site. Table 2 presents a list of the imagery products available through the RDSS web site as of August, 2001.

Table 2. List of imagery products available through the RDSS web site.

Site	Acquisition Dates	Imagery Type	Summary of Features	# of Nuclear Tests Within Area of Imagery
Novaya Zemlya	June 26, 2000 July 20, 2000 August 3, 2000	1-meter panchromatic, mosaic of 3 images	Roads, adits, tailings, collapse features	31 events
Lop Nor	February 26, 2000	1-meter pan + 4-meter multi-spectral	Roads, adits	6 events
	July 1, 2000	1-meter pan + 4-meter multi-spectral	surface features related to shaft emplacements	13 events
India	August 10, 2000	1-meter pan + 4-meter multi-spectral	surface features related to shaft emplacements	2 events
Pakistan	July 9, 2000	1-meter pan + 4-meter multi-spectral	Roads, adit	1 event
	July 9, 2000	1-meter panchromatic	surface features related to shaft emplacements	1 event

The imagery products for Novaya Zemlya and Lop Nor include within their bounds the locations of numerous historical nuclear explosions. Currently there remain ambiguities as to which particular features correlate with specific nuclear explosions recorded seismically. At the Indian and Pakistani sites this is not the case and an unambiguous identification of the ground truth locations is possible.

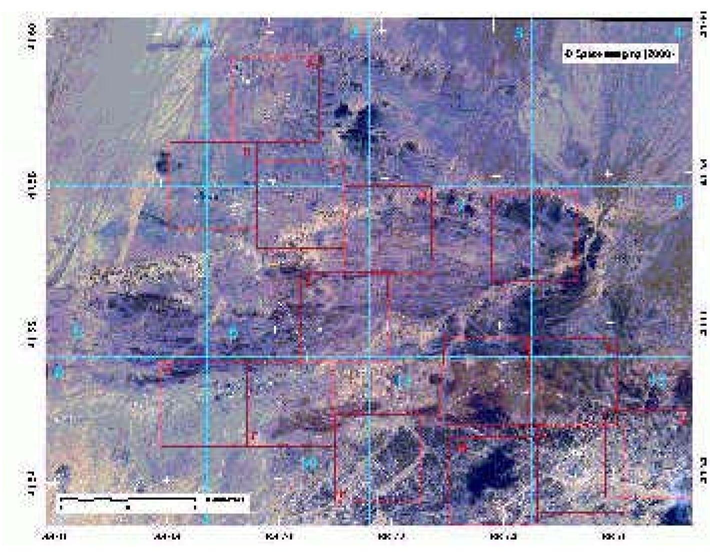

Figure 2. Overview image (July 1, 2000) of the eastern portion Lop Nor test site. The area depicted in this image covers the part of the test site where more than a dozen nuclear tests were conducted, all with shaft emplacements. The imagery product available via the RDSS includes two levels of zoom, the first at a scale of 1:15000 and the second at a scale of 1:7500 and containing areas with features possibly correlating to test artifacts.

The GT locations for the May 28 and May 30, 1998, Pakistani nuclear tests are listed in Table 3, along with the locations obtained by CMR's nuclear monitoring detection system in 1998, based on the IMS stations operating at the time and without the benefit of ground truth information. The absolute locations for the two events, obtained utilizing the IMS data, were systematically biased to the northwest. Table 3 also lists a JHD solution obtained for the May 30, 1998, test based on holding the May 28, 1998, test fixed at the ground truth location.

Table 3. Location estimates for the 1998 Pakistan nuclear tests. The ground truth estimates presented below are direct interpretations from 1-meter resolution commercial satellite imagery.

Date	Solution	Latitude	Longitude	Uncertainty	Distance from Ground Truth
May 28, 1998	GT estimate from imagery	28.7924 N	64.9456 E	500 meters	-
	REB	28.90	64.90	Semi-major = 10.4 km Semi-minor = 8.4 km Strike = 178	13 km
	JHD	28.7924 N	64.9456 E	-	fixed
May 30, 1998	GT estimate from imagery	28.3589	63.8584	500 meters	-
	REB	28.49	63.78	Semi-major = 11.4 km Semi-minor = 9.4 km Strike = 4	17 km
	JHD	28.411	63.864	Semi-major = 6.6 km Semi-major = 5.2 km Strike = 8	6 km

<u>PRDA Contract Results Available</u>

A key component for success of the RDSS is the receipt, test, and acceptance of results from the R&D community. In general, the RDSS expects three types of deliveries: technical reports, data to receive and store, and software components or parametric results to evaluate and possibly integrate into a monitoring system. A number of deliveries from PRDA contractors has already been received and these are summarized in Table 4.

Table 4. Summary of products received by the RDSS.

	Contract/Task Title	Performing Org.	P.I.	Products Received
1	Development of a Dynamic Infrasound Knowledge Database	BBN Tech.	Farrell	Software and User's Guide
2	Enhanced Depth Determination Using Cepstral Techniques	Weston Geophysical	Reiter	Software for cepstral F-stat analysis; Scientific Rpt. "Application of a Cepstral F-Statistic for Improved Depth Estimation"
3	Characterization of Reflected Arrivals for Hydroacoustic Test Ban Monitoring	BBN Tech.	Gibson	Final Report (Draft); database 15 events between 1965 and 1970
4	Feasibility of the Use of 3D Models to Improve Regional Locations in W. China, Central Asia, and Parts of the Middle East	Univ. of Colorado at Boulder	Ritzwoller	Final Report, "Use of the Kyrgyz Seismic Network to Assess the Performance of the Int'l. Monitoring System in and Around Kyrgyzia"; database KNET and CAB
5	Long-Period Surface Wave Dispersion and NDC Global Association Database	Boston College	Harkrider	Final Technical Report; FORTRAN versions travel time codes

	Contract/Task Title	Performing Org.	P.I.	Products Received
6	Infrasound Excitation and Propagation Research	Maxwell Tech.	Stevens	Technical Report (Draft); database SAC format files; IDG, Final Report
7	Statistical Calibration & Regionalization of China & Surrounding Region	New Mexico State Univ.	Hearn, Ni	bulletins of Chinese earthquakes 1985, 1986, and 1991-1995
8	Collection and Analysis of Regional Seismic Data for Underground Explosions	Mission Research Corp.	Fisk	Final Technical Report (Draft), "Regional Seismic Event Characterization Using Bayesian Calibration"; waveform database
9	Development of Ultrahigh Sensitivity Xenon Detectors for Enhancement of Ability to Monitor Nuclear Testing	Univ. of Cincinnati	Valentine	Final Report
10	Discr., Det., Dep., Loc., and Wave Propagation Studies Using Intermed. Period Surface Waves in the Mid-East, C. Asia, and the Far East	Univ. of Colorado at Boulder	Levshin	Final Report (Draft)
11	Advanced Regional Array Studies	NORSAR	Kvaerna	Final Report (Draft)
12	Source Char. and Reg. Discr. of N. Idaho Rockbursts and Earthquakes	Univ. of Idaho	Sprenke	Final Scientific/Technical Report (Draft), "Rockburst Model Validation"
13	Signal Det. and Estimation Directional Parameters for Multiple Arrays	Univ. of CA, Davis	Shumway	Final Scientific Report (Draft)
14	Joint Inversion of Receiver Function and Surface Wave Dispersion for Local Crustal Structure in the Mideast	St. Louis Univ.	Herrmann, Ammon	Final Report , "Lithospheric structure of the Arabian shield from the joint inversion of receiver function and surface-wave dispersion observations"
15	Various contracts	Columbia Univ., LDEO	Kim, Richards	Report "Borovoye Digital Seismogram Archive for Underground Nuclear Tests during 1966-1996"; waveform data files
16	Development of Event Screening Procedures	Australian Geol. Survey Org.	Jepsen	Summary; database nuclear and chemical events, CSS3.0 format
17	A Ground Truth Database for Regional Seismic Research	Multimax	Henson	313 CEB events China, FSU, and N. Am
18	A Damage Mechanics Model for Underground Nuclear Explosions	Univ. Southern CA	Sammis	Final Technical Report
19	Basic Research on Seismic Monitoring Problems	Univ. of CA, Berkeley	Johnson	Final Report

In the following discussion we highlight two examples of recent deliveries that are likely to prove very useful to the nuclear explosion monitoring R&D community.

PRDA Results -- Example 1

CMR received a preliminary report from Maxwell Technologies, associated with research conducted under the DTRA contract titled "Infrasound Excitation and Propagation Research" (Stevens, 2000; Stevens et al, 2000). The report covers topics in the areas of modeling of infrasound signals from atmospheric explosions, evaluation of IMS network performance for infrasound signals, and analysis of infrasound instrumentation. The delivery consisted of a draft final report, provided primarily to describe the accompanying data set. The report contains tables describing event locations, time, and yield, station locations, calculated infrasound magnitudes, and two appendices describing how instrument responses are defined and which instruments were used at which stations.

The Maxwell infrasound data set is comprised of a total of 220 data files in SAC format and consists of signals recorded at 17 locations in the former Soviet Union (e.g. Figure 3), from 22 atmospheric nuclear explosions

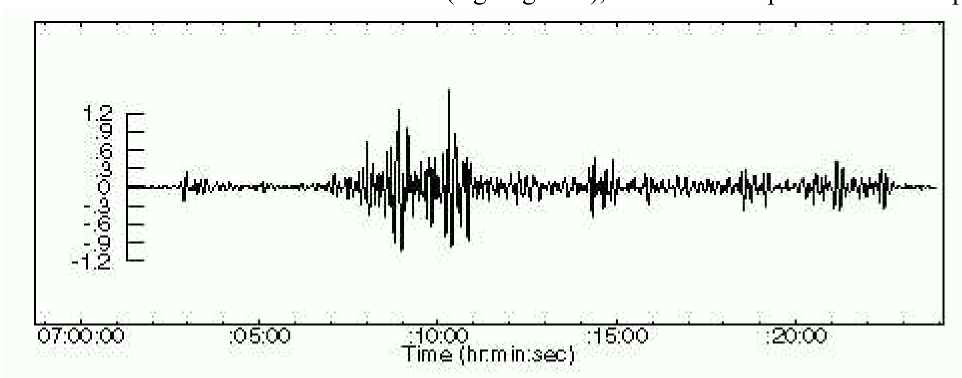

Figure 3. A 13-kT shot at Semipalatinsk recorded at Yeniseysk on 1961/10/04.

ranging in size from 0.8 kT to 58 MT. A total of 138 of the waveforms have measurable, unclipped signals, known instrument responses, yields and calibrations. This is a unique data set that will be useful for source scaling studies, testing signal detection and characterization, and other aspects of infrasonic modeling and processing.

PRDA Results -- Example 2

BBN Technologies recently submitted the report "Characterization of Reflected Arrivals and Implications for Hydroacoustic Test-Ban-Treaty Monitoring" (Pulli, et al, 2000a, 2000b). The study included a review of historical and contemporary data sets and a CD-ROM of these edited data sets along with source and receiver information.

The BBN contract assessed the potential use of long-range hydroacoustic reflections for the location of hydroacoustic events. A data set of source information and hydroacoustic waveform data for 15 events - 12 "Chase" and one other underwater explosion, and two Aleutian underground nuclear explosions (Longshot and Milrow) - was assembled in CSS3.0 format with source information provided in tabular form for each event. In most cases, the absolute location of the source is known, but some event locations had to be inferred from the recorded signals. The waveform data are from the Wake and Ascension MILS arrays and from single hydrophones at three other Pacific locations.

The waveforms collected in the BBN study are valuable for a number of research purposes, such as validating travel times and algorithms for estimating arrival azimuth, and testing source characterization of underwater explosions. The BBN analysis of these data for reflections demonstrated that these were usually easy to identify, and included a recommendation that location algorithms should use the reflected as well as the direct arrival.

The deliverable items submitted by both Maxwell Technologies and BBN Technologies are examples of research reports with accompanying data sets that are extremely valuable to the R&D community. All deliveries received by the RDSS (Table 4) are being made available to the R&D community in the form in which they were delivered (see URL below). In addition, the data sets submitted by Maxwell will be added to the CMR Nuclear Explosion and Infrasound databases. The data sets contributed by BBN Technologies will be added to both the CMR Nuclear Explosion (Longshot and Milrow recordings) and Hydroacoustic databases.

Evaluation and Testing Capabilities Available

Many of the deliveries to the CMR R&D Support System comprise software components, parametric results, or other components that are to be evaluated. To perform such evaluations, a test plan, with evaluation criteria, is generated by the researcher in collaboration with RDSS staff.

Deliveries that require testing at the full scale of the NTDS require special planning. For example, the DTRA IMS Location Calibration Program is funding three consortia to provide SSSC's for stations of the IMS. In this endeavor, integration, testing, and evaluation are required at CMR to ensure that the results produced by the three consortia are compatible with the nuclear explosion monitoring system software. Demonstration of location improvements will require extended full-scale operational test and evaluation and this will be crucial to producing a consistent and tested product.

In another testing effort at the RDSS, investigators at the University of California, Berkeley (UCB), and RDSS staff are working on a plan for integrating UCB's automated moment tensor software (Dreger, et al, 2000) into the explosion monitoring system. One component of enhanced monitoring involves augmented source characterization capabilities, some examples of which may include robust depth estimation or consistency with tectonic release. The purpose of the UCB effort is to develop software to automatically determine moment tensors for seismic events recorded at the IMS network stations. To achieve this goal, the software must be capable of functioning automatically, and must be tightly integrated into the monitoring system environment.

Computing Facilities Available

A comprehensive infrastructure environment exists at CMR to support the RDSS user community and the R&D Support System itself. A substantial Commercial Off the Shelf (COTS) software and hardware environment is maintained and documented on the RDSS web site, and includes over 60 servers, over 90 work stations, mass storage systems, multiple Oracle instances, multiple web sites (open and secure) multiple networks, and firewall security. A number of these resources can be utilized directly by the R&D community (e.g. accounts are available for direct use of the Oracle database), while others are used to provide community support (e.g. the mass storage system is used to archive and serve data).

CONCLUSIONS AND RECOMMENDATIONS

The RDSS makes use of all the facilities, resources, and expertise of CMR for the purpose of improving nuclear monitoring and verification capabilities. This role can be summarized in terms of the following broadly stated goals:

- • The RDSS supports the R&D community, from the inception of research through to testing and archiving of results. Such support can take the form of providing access to current IMS data, production results, IDC results, data archives, and more.

- • The RDSS archives research results to ensure important work is not lost and results can be shared readily amongst the R&D community.

- • The RDSS provides a mechanism for the test, evaluation, and integration of R&D results. Testing can be conducted at various scales, ensuring proper test environments. Such test and evaluation provides the US government with quantitative measures of current monitoring capability, identifying obstacles and establishing expectations for achieving improved capability.

Most importantly, we note that the RDSS is a collaboration between DTRA, the R&D community, and CMR. A wide range of CMR staff, including scientific, software development, testing, and infrastructure support teams are available to support all phases of R&D activity. Please watch for news and developments (or contact us) at:

http://www.cmr.gov/rdss . The web site contains a wide range of information, such as listings of current DTRA contracts, contract deliverables received, documents describing the access and use of the RDSS, and information on RDSS resources available.

REFERENCES

Dreger, D., B. Romanowicz, and J. Stevens, (2000), Development of Automated Moment Tensor Software at the Prototype International Data Center, Proceedings of the 22nd Annual Seismic Research Symposium, Vol. 3, 365-373.

Pulli, J., Z. Upton, R. Gibson, J. Angell, T. Farrell, and R. Nadel, (2000a), Characterization of Reflected Arrivals and implications for Hydroacoustic Test-Ban-Treaty Monitoring, BBN Technical Memorandum W1380, contract DSWA01-97-C-0164.

Pulli, J., Z. Upton, R. Gibson, and T. Farrell, (2000b), Modeling Long-Range Hydroacoustic Reflections in the Atlantic and Pacific Oceans, Proceedings of the 22nd Annual Seismic Research Symposium, Vol. 3, 75-84.

Salzberg, D., R. Woodward, and R. North, (2000), Delivering Research Results to the DTRA CMR R&D Testbed, Proceedings of the 22nd Annual Seismic Research Symposium, Vol. 3, 419-427.

Stevens, J., (2000), Infrasound Excitation and Propagation Research, Maxwell Technologies, draft final report, contract DSWA01-97-C-0129.

Stevens, J., D. Adams, G. Baker, H. Xu, J. Murphy, I. Divinov, and V. Bourchik, (2000), Infrasound Modeling Using Soviet Explosion Data and Instrument Design Criteria from Experiments and Simulations, Proceedings of the 22nd Annual Seismic Research Symposium, Vol. 3, 259-269.

Woodward, R., D. Salzberg, and R. North, (2000), A Testbed for Nuclear Explosion Monitoring Research and Development, Proceedings of the 22nd Annual Seismic Research Symposium, Vol. 3, 441-445.