A SUPPORT SYSTEM FOR NUCLEAR-EXPLOSION MONITORING RESEARCH AND DEVELOPMENT

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ABSTRACT

A comprehensive support system for Research and Development (R&D) efforts funded by the Defense Threat Reduction Agency that address nuclear-explosion monitoring and verification research and development is provided by the Research and Development Support System (RDSS) at the Center for Monitoring Research (CMR). The RDSS provides resources to support ongoing research and development, most importantly through extensive data sets and testing environments at appropriate scales, and identifies important technical issues for achieving improved nuclear monitoring capability.

The RDSS provides researchers with access to a ten terabyte data archive containing current International Monitoring System (IMS) seismic, hydroacoustic, infrasound, and radionuclide data, as well as data archives spanning several years; past and present products of the International Data Centre (IDC) and Prototype IDC, including Reviewed Event Bulletins and various radionuclide reports; test environments; a variety of special purpose data sets and databases, such as the Nuclear Explosion, Ground Truth, and Infrasound databases; and an on-line technical library.

Defense Threat Reduction Agency (DTRA)-sponsored researchers actively deliver results of their research contracts to the RDSS. These results are archived and are available for download from the RDSS web site (see below) to authorized researchers. Recent deliveries include infrasound recordings of atmospheric nuclear explosions, earthquake bulletins for various parts of the world, Geographic Information System databases, and reports on a wide range of seismic, hydroacoustic, and infrasound research topics.

The RDSS supports and collaborates on integration and testing of R&D results. Recent examples include testing of station-specific source corrections (SSSCs) produced by DTRA-sponsored calibration consortia for IMS stations in Eurasia and North Africa. We also highlight a collaborative effort with researchers at the University of California, Berkeley (UCB) to establish a platform with direct access to near-real-time data for testing and developing Automatic Moment Tensor Analysis software.

The RDSS actively develops tools and products to better serve the nuclear-explosion-monitoring R&D community, as well as to provide a gateway to a wide range of CMR resources. A variety of commercial imagery for nuclear test sites is available on the RDSS web site. We have also recently developed a remote user interface to our EvLoc event location software. Authorized members of the nuclear monitoring R&D community can submit any combination of seismic, hydroacoustic, and infrasound arrival and amplitude information and the EvLoc software running at the CMR (the same software as delivered to the IDC) will compute an event location and magnitude. Comprehensive guides to CMR hydroacoustic and infrasound resources are also available. Further information on RDSS resources and services may be found by researchers on the RDSS web sites (http://www.cmr.gov/rdss).

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 activities and resources.

RDSS activities include providing environments for testing and evaluating promising research results at a range of scales. Such testing provides the US government with quantitative measures of current monitoring capability, identifying obstacles and establishing expectations for achieving improved capability. The RDSS organizes and archives research results produced by the R&D community in a manner that facilitates the access to these results for the entire research community. Finally, a wide range of CMR internal resources is made available to the R&D community via the RDSS.

RESEARCH ACCOMPLISHED

The Center for Monitoring Research (CMR) provides many unique resources to support basic and applied research and development. CMR maintains a large and growing archive 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) has been assembled to support monitoring research. These data sets are routinely augmented with new data as they become available.

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 experimental arrangements with historical data sets. Supporting facilities include a large UNIX-based computing environment, databases, and data archives.

In the remainder of this paper, we describe some of the data, data products, and capabilities that are available to the R&D community via the CMR RDSS.

Data Resources

The CMR has been continuously acquiring and archiving time-series and radionuclide data since 1992. Currently, the CMR receives data from a variety of international stations, including stations of the International Monitoring System (IMS) network. The data archive consists of over 10 terabytes of waveform data from seismic, hydroacoustic, and infrasound stations and is growing at a rate of approximately 1.5 Tb per year. Detailed guides describing the hydroacoustic, infrasound, and radionuclide resources have been prepared and these are available on-line at the RDSS web site. These guides provide detailed descriptions of the stations, instructions on accessing data, and detailed information on data availability. A guide to CMR seismic resources will be prepared in the future, though usage patterns for the data archive indicate that the R&D community is generally more familiar with the existing CMR seismic resources than either the hydroacoustic or infrasound data resources.

CMR 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 other data products obtained from the International Data Centre (IDC) in Vienna, Austria. The RDSS is presently developing a streamlined, web-based graphical user interface to the data archive. We expect this new interface to be online in the fourth quarter of 2002.

Special Databases

The RDSS produces a variety of special databases and data products that are useful to nuclear explosion 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 DTRA-sponsored contractors are added to these databases, such that the value of both the delivered data, and the database, are increased.

Table 1. Research databases 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)
Lop Nor	• An extensive compilation of seismic data for events in and around the Lop Nor nuclear test site region, China

Recently, an Advanced Concept Demonstration (ACD) was performed at CMR (Kohl *et al*, 2002). This ACD focused on improving the capability for monitoring the Chinese nuclear test site at Lop Nor. As part of this ACD, an extensive data set was assembled. The RDSS has now integrated the Lop Nor ACD data set into a data product for public distribution, referred to as the Lop Nor Database (LNDB). The LNDB includes nuclear explosions and earthquakes, as well as various synthetic events. All relevant information, including parameters, waveforms, and extensive metadata, are collected together in this product. As for the other RDSS research databases, all information is loaded into a centralized relational database, with waveforms and metadata stored on local disks. Database tables have been created to store metadata that do not fit within the standard IDC database schema.

The Lop Nor Database consists of 421 events (Figure 1) in the Lop Nor ACD "box" (defined as 39°--44° N and 86°--92° E), with approximately 43,000 arrivals. For each event there are multiple data sources, and a preferred origin is chosen based on the location accuracy. Data sources for events and arrivals include:

- ACD analysis results
- PIDC Reviewed Event Bulletins (REBs)
- IDC REBs
- CMR Nuclear Explosion Database
- CMR Ground Truth Database
- International Seismological Centre
- Annual Bulletin of Chinese Earthquakes (ABCE)
- PIDC GAMMA bulletin

A total of 205 events were thoroughly analyzed during the ACD work, including 25 out of all 45 nuclear explosions. Waveform data were obtained from the CMR archive system, CMR Nuclear Explosion Database, Incorporated Research Institutions for Seismology (IRIS) Data Management Center, and Blacknest UK data archives. Synthetic seismograms for small nuclear tests were obtained by applying frequency dependent scaling relations to actual recordings of large nuclear tests and embedding the result in noise recordings. Ground truth information is available for most of the nuclear explosions and for the scaled/embedded events. There are approximately 100 Gb of waveform data in total.

There are 37 tables in the LNDB providing detailed metadata for waveforms and events. Metadata tables are developed to document data sources, references to data sources, and various computational results. This database uses unique event identifiers (evid) to identify all related solutions for an event and the associated waveforms. Metadata are also associated with each event through the metadata tables. Arrivals from the ACD analysis and from bulletin collections are associated with their corresponding origins. Additional details about the Lop Nor database, including a complete description of the schema, will be published as a CMR Technical Report (to be completed in fourth quarter, 2002).

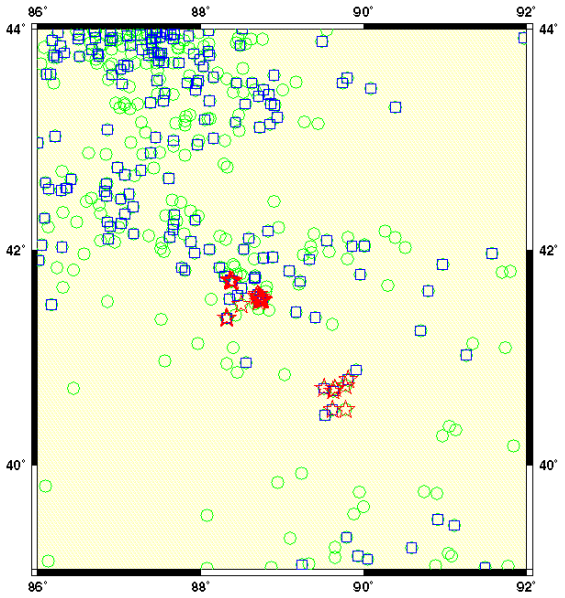

Figure 1. Preferred origin of 421 events (green circles) in the Lop Nor Database, including nuclear explosions (red stars) and events for which waveform data were analyzed (blue squares).

Commercial Satellite Imagery

A variety of high-resolution commercial satellite images are available through the RDSS (Skov *et al*, 2002). Images include 1-m panchromatic and 4-m multi-spectral satellite imagery obtained from commercial vendors. At CMR these images have been used in conjunction with re-analysis of seismic data to obtain definitive locations of historical nuclear explosions with accuracy suitable for designations as Ground Truth 1 (GT1) or GT2 events. Images have been obtained for the test sites at Novaya Zemlya, Lop Nor, India, and Pakistan.

The imagery has been analyzed to identify features in one of three categories: 1) direct evidence of disturbances resulting from nuclear detonations, typically collapse features; 2) direct evidence of test site artifacts highly correlated with locations of nuclear tests; 3) direct evidence of test site artifacts constrained to the vicinity of nuclear detonations. To estimate 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 ensure maximum portability. Table 2 presents a list of the imagery products presently available through the RDSS web site. This collection will continue to grow as new images are acquired as part of CMR's imagery acquisition program. A comprehensive discussion of the use and analysis of satellite imagery at CMR can be found in Skov *et al*. (2002).

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

Site	Acquisition Dates	Imagery Type	# of Nuclear Tests Within Area of Imagery
Novaya Zemlya	June 26, 2000 July 20, 2000 August 3, 2000	1-m panchromatic, mosaic of 3 images	31
Lop Nor	February 26, 2000	1-m pan + 4-meter multi-spectral	6
	July 1, 2000	1-m pan + 4-meter multi-spectral	13
India	August 10, 2000	1-m pan + 4-meter multi-spectral	2
Pakistan	July 9, 2000	1-m pan + 4-meter multi-spectral	1
	July 9, 2000	1-m panchromatic	1

Hypocenter Location Server

The RDSS has recently developed the Hypocenter Location Server (HLS) to provide a remotely accessible interface to the powerful hypocenter location program *EvLoc*. The *EvLoc* software is a core element of the CMR processing system and is part of the complete system provided to the IDC. *EvLoc* is capable of using any combination of seismic, hydroacoustic, and infrasound arrivals to determine hypocenters and to compute magnitudes (seismic only). The HLS is accessed by sending formatted e-mail messages to the server (in this sense it looks much like an AutoDRM server), as illustrated in Figure 2. The user provides data files, configuration files, and custom parameter files via FTP (using a flat-file structure or using XML). The HLS processes requests, with their associated input files, and then e-mails the results to the user.

EvLoc is a complex software component that relies heavily on a carefully configured database environment (e.g. Oracle) to function properly. As such, *EvLoc* is not readily portable. By providing access to *EvLoc* functionality through the Application Service Provider model as described here, researchers can readily use *EvLoc* in their analysis without worrying about software portability or configurability. Further, the capability provided by the HLS completely supercedes that provided by CMR's stand-alone hypocenter determination program *LocSAT*. Note that the HLS is fully backward compatible with *LocSAT* input files.

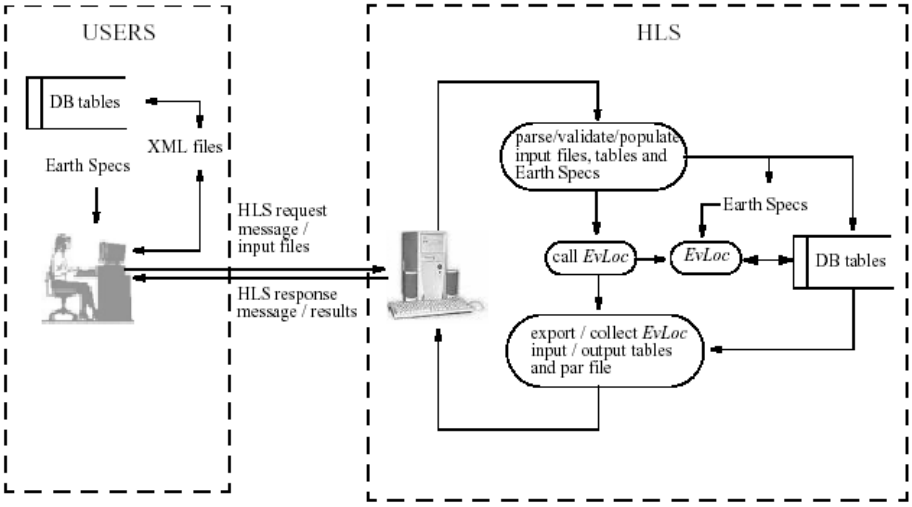

Figure 2. Data flow for the Hypocenter Location Server, showing the relationship between the user and the server.

DTRA Contract Results

A key activity of the RDSS is receiving, accepting, and testing results from the R&D community. In general, the RDSS receives 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. All of the R&D products received by

the RDSS are archived and are made available for redistribution to the entire R&D community via the RDSS web site. Table 3 summarizes the deliveries from DTRA-sponsored researchers that have been received to date. To learn more about any of the products listed in Table 3, please consult the RDSS web site.

Table 3. Summary of research 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	Report ; Software for cepstral F-stat analysis
3	Characterization of Reflected Arrivals for Hydroacoustic Test Ban Monitoring	BBN Tech.	Gibson	Final Report; 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; database of KNET and CAB bulletins
5	Long-Period Surface Wave Dispersion and NDC Global Association Database	Boston College	Harkrider	Final Report; FORTRAN versions of travel time codes
6	Infrasound Excitation and Propagation Research	Maxwell Tech.	Stevens	Final Report; database of infrasound recordings; IDG Final Report
7	Statistical Calibration & Regionalization of China & Surrounding Region	New Mexico State Univ.	Hearn, Ni	Annual Bulletin of Chinese Earthquakes 1985, 1986, and 1991-1995
8	Collection and Analysis of Regional Seismic Data for Underground Explosions	Mission Research Corp.	Fisk	Final Report; waveform database
9	Reconnaissance of Backgound Infrasound at Selected Future IMS Locations, Atlantic Ocean	UC San Diego	Hedlin	Final Report
10	Development of Ultrahigh Sensitivity Xenon Detectors for Enhancement of Ability to Monitor Nuclear Testing	Univ. of Cincinnati	Valentine	Final Report
11	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
12	Advanced Regional Array Studies	NORSAR	Kvaerna	Final Report
13	Source Char. and Reg. Discr. of N. Idaho Rockbursts and Earthquakes	Univ. of Idaho	Sprenke	Final Report
14	Signal Det. and Estimation Directional Parameters for Multiple Arrays	UC Davis	Shumway	Final Report
15	CTBT Seismic Monitor Issues at Local Distance Ranges	Univ. Bergen	Husebye	Technical Report
16	Regionalized Velocity Models and Improved Locations for Pakistan and the Surrounding Area	Weston Geophysical	Reiter	Technical Report
17	Joint Inversion of Receiver Function and Surface Wave Dispersion for Local Crustal Structure in the Mideast	St. Louis Univ.	Herrmann, Ammon	Final Report
18	Various contracts	Columbia Univ., LDEO	Kim, Richards	Report; Borovoye digital seismogram archive
19	Development of Event Screening Procedures	Australian Geol. Survey Org.	Jepsen	Summary report; database of nuclear and chemical events, CSS3.0 format
20	Path Corrections for Regional Phase Discriminants	UC Santa Cruz	Lay	Final Report
21	Improve Monitoring of the CTBT in Middle East by Israel SeisNet	Geophysical Institute Israel	Gitterman	Final Report; data, video, etc.
22	A Ground Truth Database for Regional Seismic Research	Multimax	Henson	313 CEB events China, FSU, and N. Am
23	A Damage Mechanics Model for Underground Nuclear Explosions	Univ. Southern CA	Sammis	Final Report
24	Basic Research on Seismic Monitoring Problems	UC Berkeley	Johnson	Final Report
25	Auto Interpretation of Seismic Signals Using CUSUM-SA Algorithm	ENSCO	Der	Final Report; software – Matlab M-scripts
26	Global & Regional GIS Database Development in Support of CTBT	Cornell	Barazangi	Final Report
27	Probabilistic Integration of Seis, Hydro & Infra Data in Disc Sch	ENSCO	Der	Final Report

	Contract/Task Title	Performing Org.	P.I.	Products Received
28	Seismic Calibration for IMS Stations in North Africa and Western Asia (Group 2)	SAIC	McLaughlin	Reports; SSSCs and numerous data products
29	Integration of Enhanced Propagation, Environmental Variability, and Network Performance Models into the InfraMAP Software Toolkit	BBN Tech.	Norris	InfraMAP Users Guide, V2.1; InfraMAP V2.1 (available from BBN)
30	Constraining Depth and Source Mechanisms of Small Events at Far-regional to Teleseismic Distances	ANU	Kennett	Final Report
31	Regional GIS Databases in Support of CTBT Monitoring	Cornell	Barazangi	Final Report; GIS digital data sets
32	Physical Basis and Improved Criteria for Phase Spectral Ratio Discrimination	Columbia Univ., LDEO	Xie	Final Report
33	Integrated Study of Seismic and Infrasonic Signals from Sources in Southern Siberia, Eastern Kazakhstan, and Western China	Columbia Univ., LDEO	Kim	Final Report
34	Seismic Calibration for IMS Stations in Eastern Asia (Group 1)	Columbia Univ., LDEO	Richards	Pn SSSCs for subset of group 1 IMS stations
35	Application of Joint Inversion of Receiver Functions and Surface-Wave Dispersion for Local Crustal Structure	St. Louis University	Herrmann	Seismological software
36	Development of Improved Capabilities for Depth Determination and Research on the Frequency Dependence of Regional Seismic Phases	MRC	Fisk	Final Report; software
37	Statistical Calibration & Regionalization of China & Surrounding Region	New Mexico State Univ.	Hearn, Ni	Final Report; velocity models,; Annual Bulletin of Chinese Earthquakes, 1984-1999
38	Seismic Calibration for IMS Stations in Eastern Asia (Group 1)	SAIC	Murphy	SSSCs for group 1 IMS stations
39	Enhanced Depth Determination Using Cepstral Techniques	Weston Geophysical	Reiter	Final Report; software

Integration and Testing

Many of the deliveries to the CMR R&D Support System comprise software components, parametric results, or other components that are to be tested to determine their potential for use in large-scale monitoring systems. To perform such tests, a test plan, with evaluation criteria, is generated by the researcher in collaboration with RDSS staff.

Deliveries that require full-scale testing require special planning. For example, the DTRA IMS Location Calibration Program is funding three consortia to provide SSSCs 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 CMR nuclear-explosion-monitoring system software. To date, the RDSS has performed testing for two of the consortia (Yang *et al*, 2001; Richards *et al*, 2002).

Part of the DTRA tasking to the location consortia has been to develop depth-dependent SSSCs. In the past, SSSCs have only been specified for a single source depth, typically either 0 km or 10 km. To support the consortia activities, the RDSS has now developed a new version of *EvLoc* that can utilize SSSCs that are specified for multiple source depths (Figure 3). Additionally, the new *EvLoc* will be available to the R&D community via the Hypocenter Location Server discussed earlier.

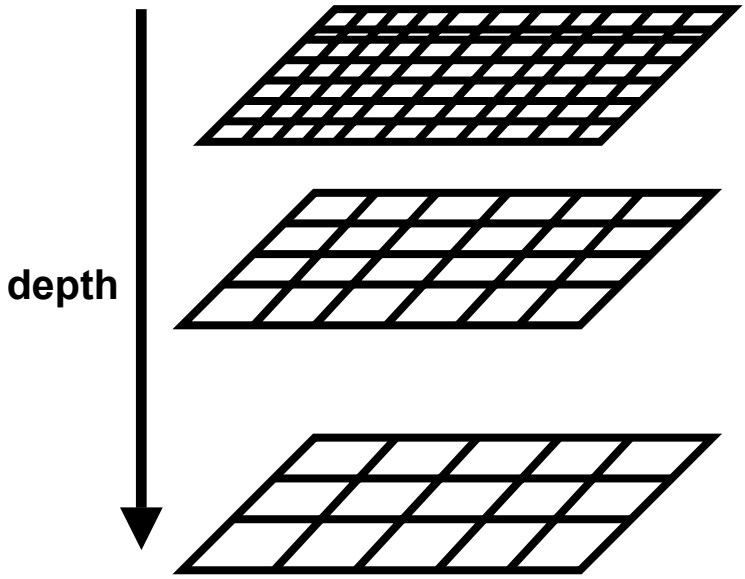

Figure 3. Depth-dependent SSSCs are parameterized as a sequence of horizontal 2-D grids at various depths. The software supports arbitrary depth sampling and variable horizontal gridding. The software is backward compatible with non-depth-dependent SSSC files.

In another testing effort at the RDSS, investigators at the University of California, Berkeley, and RDSS staff are working on a plan for integrating UCB's automated moment tensor software (Dreger *et al*, 2001) into the nuclear monitoring system developed at CMR. 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 support UCB, the RDSS staff have configured a dedicated test platform, with direct access to the near-real time disk loops at CMR (kept online for 20 days) and to the database containing the Reviewed Event Bulletins produced by the IDC. In this way the UCB software can access the bulletins to cue their processing and can take advantage of the high-speed access to full waveform data that is provided by the online diskloops. This dedicated test platform will allow UCB researchers to refine and tune their software by experimenting with large numbers of events in different parts of the world. Ultimately, the software will be integrated into the CMR processing pipeline architecture and will provide improved source characterization capabilities for the nuclear-explosion monitoring system.

CONCLUSIONS AND RECOMMENDATIONS

The RDSS supports R&D aimed at improving nuclear-explosion monitoring and treaty verification capabilities by drawing on the facilities, resources, and expertise of the CMR.

In summary, basic RDSS activities include:

- Supporting the R&D community, from the inception of research through to testing and archiving of results.
- Archiving research results to ensure important work is not lost and results can be shared readily amongst the R&D community.
- Providing a mechanism for the test, evaluation, and integration of R&D results.

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 available RDSS resources.

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