LAWRENCE LIVERMORE NATIONAL LABORATORY

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Selected Examples of LDRD Projects Supporting Test Ban Treaty Verification and Nonproliferation

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The Laboratory Directed Research and Development (LDRD) Program at the DOE National Laboratories was established to ensure the scientific and technical vitality of these institutions and to enhance the their ability to respond to evolving missions and anticipate national needs. LDRD allows the Laboratory directors to invest a percentage of their total annual budget in cutting-edge research and development projects within their mission areas.

These laboratories are asked to address difficult and evolving national security challenges that require the best and brightest scientific and technical workforce be engaged in advancing the state-of-the-art with an eye towards applications to national security challenges. LDRD serves a fundamental role in attracting, developing, and retaining a world-class technical workforce by investing in new research projects that attract highly qualified postdocs and early career scientists and engineers to the Laboratory. As a result, it is an essential element of the Laboratory's workforce pipeline strategy. Additionally, LDRD is crucial to the Laboratory's ability to form and sustain collaborations with the broad, external technical community, which means that it is an important tool for assuring that our capabilities are current and at the cutting edge.

Funding of the LDRD program, authorized by Congress in the early 1990's, is assessed on all Laboratory programs and is simply part of the cost of doing business at LLNL. Because of the fundamental nature of LDRD activities, one can easily show that the return on investments to our sponsors far exceeds the contributions from each of our sponsors.

Below we highlight a selected set of LDRD-funded projects, in chronological order, that have helped provide capabilities, people and infrastructure that contributed greatly to our ability to respond to technical challenges in support of test ban treaty verification and nonproliferation.

Colloidal Transport of Actinides in the Vadose Zone; FY00-FY02; $530K
An integrated field, laboratory and modeling approach to investigate the geochemical controls on colloid-facilitated transport of actinides (e.g. Pu, Np). The project investigated mechanisms for Pu sorption on mineral colloids collected at the NTS, but in well-controlled laboratory experiments in which the field chemistry and colloidal content are constrained. The project integrated both field and laboratory studies into a reactive-transport model of subsurface transport with the ultimate objective of developing a framework for predicting when colloid-facilitated transport of actinides may occur in the vadose zone, quantitatively describe these results, and develop a flow and transport model based on our experimental results. How radionuclides from underground nuclear tests are transported through the subsurface is a question of substantial interest for Onsite Inspection (OSI). This project also served as a vehicle for advancing the expertise of Dr. Charles Carrigan (who was a co-investigator) in this programmatic area.

MEDIOS: Modeling Earth Deformation using Interferometric Observations from Space; FY00-FY01; $470K
In this LDRD project, LLNL has acquired the expertise to process and invert InSAR data from a variety of sources and has pioneered the application of InSAR to sources of surface deformation related to national security. These sources include underground nuclear test monitoring and characterization, underground facility detection and characterization, and subtle interferometric-based change detection. The goal of this project has been to build an InSAR data inversion tool that can produce highly accurate models of the subsurface process responsible for the observed surface displacement field. The project focused on three major categories of subsurface processes

that align with LLNL's missions: (1) nonproliferation and defense, (2) energy resource exploitation, and (3) seismic hazard mitigation. The inversion tool was developed using an equivalent elastic half-space forward model rheology for computational efficiency. Establishing a technical basis for discriminating between those observations where deformation is—or is not—consistent with natural causes like earthquakes provides the program with a way to focus its efforts. This has lead to InSAR located earthquakes being used as independent ground-truth for building and validated Earth models used to locate seismic events. This technology also provides a way to assess and monitor the long-lived deformation that persists above underground nuclear tests, with implications for OSI.

Dynamic InSAR: Using InSAR to Image Seismic Waves Remotely from Space; FY01; $206K
The purpose of this project is to determine the feasibility of using InSAR (interferometric synthetic aperture radar) to image seismic waves remotely from space. If shown to be feasible, the long-term goal of this project would be to influence future SAR satellite missions and airborne SAR platforms to include this new capability. The direct imaging of seismic waves via this technology would provide new wavefield data that would improve our understanding of both seismic sources and the Earth structure they propagate through.

The Stochastic Engine: Improving Prediction of Behavior in Geologic Environments We Cannot Directly Observe; FY01-FY03; $2,929K
This initiative developed a new solution to the challenge of event-driven simulation. Using modern computational power, the stochastic engine rapidly chooses among a very large number of hypothesized states and selects those that are consistent (within error) with all the information at hand. Predicted measurements from a simulator are used to estimate the likelihood of actual measurements, which in turn reduces the uncertainty in the original sample space via a conditional probability method called Bayesian inferencing. A highly efficient, staged Metropolis-type search algorithm allows us to address extremely complex problems. This combination of probabilistic and deterministic approaches opens the door to solving many data-driven, nonlinear, multidimensional problems. One application of this in earth science is determining the underground connectivity that allows contamination to move through the ground; similar issues arise in imaging rapidly evolving systems, utilizing diverse intelligence data, or rapidly evaluating a large structure's internal flaws. Techniques and technical expertise established by this investment were instrumental in subsequent development (under program sponsorship) of the Bayesian Hierarchical Seismic Event Locator (Bayesloc) code.

Long-Range, Passive Detection of Fissile Material; FY03; $568K
Recent events highlight the increased risk of an attack on the United States with a nuclear or radiological weapon. One of the key needs to counteracting such a threat is the long-range detection of nuclear material. It is theoretically possible to detect gamma-ray emissions from these materials at distances of greater than 100 m. However, detection at 100 m has long been thought to be impractical due to fluctuating levels of natural background radiation. Recent work has shown that this problem can be overcome through the use of imaging gamma-ray detectors. He focus of this project is to completely build a large area gamma ray imager (6400 cm^2) based on individual 10x10x10 cm^3 NaI scintillation detectors. The system will be mounted in a truck to conduct test searches for nuclear materials. Detection of nuclear materials has applications for OSI and other treaty verification work.

Resolving the Earthquake Source Scaling Problem; FY03; $190K
The project focused on addressing questions such as: How does the energy released by earthquakes scale with size? Is a magnitude 8 earthquake just a scaled up magnitude 2, or does

the fault energy density change with earthquake size? by developing developing and implementing the best regional study of earthquake energy estimates. By examining events covering many orders of magnitude in size with consistent techniques, paths and stations we can resolve whether earthquake energy density really is constant or not. The scaling of earthquakes is a key property both for better understanding the physics of the earthquake source, and as a tool to predict ground motion for future large events. Non-constant energy density scaling of earthquakes would lead to significantly larger predicted ground motion for future big earthquakes when such ground motion is estimated by scaling up existing smaller events. This basic R&D effort provided foundational insight on earthquakes that programmatic funding has used to develop the MDAC (Magnitude and Distance Amplitude Correction) technique and other methods for improving the screening of seismic events and identifying outliers such as explosions.

Feasibility of Space-Based Seismometry Utilizing a Satellite-Borne Real Aperture Radar; FY04; $49K
This project explored the feasibility of a real-aperture-radar satellite mission to image propagating seismic waves, which are extremely subtle and may be impossible to detect. The resolution capability of present analyses to characterize and discriminate seismic sources is severely limited by the sparse sampling of two-dimensional (2-D) complex wave fields afforded by regional and global seismograph networks. The project will help define scientific and engineering aspects of a possible mission in collaboration with NASA, including the design of a scaled proof-of-concept mission using current-technology radar flown on a stratospheric balloon and targeted at planned seismic events.

Geophysics Experiments on High-Powered Lasers; FY04-FY05; $51K
Cavity decoupling is one of the research areas that is important for monitoring underground nuclear explosions yet cannot be pursued because of the CTBT. Interest is driven by the desire to know what is possible in decoupling and whether there are signatures that indicate that a seismic event was in a large cavity. This project explored that feasibility of using high power laser driven experiments to create scaled explosion driven systems to study these problems. The project will conduct an experiment at the Z facility at Sandia to provide a demonstration that such experiments can be done on high-powered laser systems. This basic research effort developed methodology and performed scaled experiments on high-powered laser that produced insight into energy coupling and opened the door to a series of follow-on experiments sponsored by the program.

A New Capability for Regional High-Frequency Seismic Wave Simulation in Realistic Three-Dimensional Earth Models to Improve Nuclear Explosion Monitoring; FY05-FY06; $483K
The goal of this project is to lower nuclear explosion detection thresholds by representing observed seismic signals in terms of an optimal combination of model-based signals. Model-based signals were calculated using an accurate parallel method for seismic wave propagation in 3D earth models. The earth models were taken from application of the Markov-Chain Monte Carlo method (Stochastic Engine—see above) for seismic velocities and densities in the Korean Peninsula region. The model-based signals were decomposed and combined to form an optimal linear representation of the observed signals for a moderate (M~5.0) earthquake recorded at four seismic stations in the region. The research addresses several challenges to current nuclear explosion monitoring technologies. Making it possible to generate Earth models for areas with few or no earthquakes or explosions will allow for monitoring in broad, uncalibrated areas. This R&D project advanced capabilities in the development of Earth models and synthetic signal generation from those modes for seismic monitoring purposes that programmatic funding has leveraged in subsequent years.

A New Method for Wave Propagation in Elastic Media; FY05-FY08; $1,560K
Simulation of elastic-wave-propagation phenomena is essential for many LLNL applications, including monitoring possible underground nuclear explosions or other seismic events and nondestructive evaluation of complex parts. The project aims to develop significant improvements of the traditional finite difference technique that (1) allow a fully second-order accurate treatment of boundary conditions in complex domains to handle topography and internal layers and (2) use local mesh refinement to avoid partial oversampling of the solution due to varying wave speeds. This project focused on developing a verified, accurate, and efficient elastic-wave-propagation code for numerical simulation in complex 2-D and 3-D media. The WPP code produced by this LDRD project and its successor code, SW4, are widely used today in research efforts that support the CTBT Program. Among other benefits, these efforts are enabling development of improved Earth models that are necessary for CTBT work.

Broad-Area Search for Proliferant Infrastructure; FY07-FY08; $335K
This project focused on determining the feasibility of using long-term observations of ambient noise to detect, locate, and characterize industrial infrastructure. The project utilized very long-term (1- to 100-day) estimates of coherent noise structures across networks of sensors to detect and locate infrastructure and vehicular and rail traffic that radiate continuous noise-like signals. The ultimate application of this technology is to detect and locate proliferant infrastructure and traffic supporting possible sites of weapons of mass destruction (WMD) development. Capabilities and expertise developed during this LDRD project helped lead to the later data correlation infrastructure techniques developed under programmatic funding for the nuclear test monitoring by Drs. Dave Harris and Doug Dodge.

Broadband Heterodyne Infrared Spectrometer: A Path to Quantum Noise-Limited Performance; FY09-FY10; $812K
The objective of this project is to demonstrate a new form of infrared spectrometry for chemical detection based on the heterodyne principle of generating new frequencies by mixing signals. The project utilized a unique approach in that a broadband source was used to enable hundreds of individual spectral channels to simultaneously record a high-resolution infrared spectrum. This approach can potentially achieve quantum noise-limited performance with a room-temperature infrared spectrometer. Previously, the requirement for cooling the spectrometer and detector limited the size, weight, and power, creating a significant impediment to implementation for a number of applications. Room-temperature operation has been a long-sought goal to minimize size, weight, and power and is the only approach capable of achieving that goal. This project also served to advance the expertise of Dr. John Henderson (who was a co-investigator) on multispectral and infrared (MSIR) imaging systems. Dr. Henderson is one of the main U.S. experts providing advice to the U.S. and the CTBTO on MSIR as a CTBT OSI technology.

Creating Optimal Fracture Networks for Energy Extraction; FY11-FY14; $5,228K
The key to developing unconventional subsurface energy resources is the creation of fracture permeability, which provides access for extracting hydrocarbons from tight formations and enhances circulation of water for more effective use of hydrothermal energy resources. Our inability to predict the development of fracture networks and their performance limits our ability, for example, to develop resources such as geothermal resources at depths greater than 3 km. The amount of clean, carbon-free energy in such enhanced geothermal systems is virtually unlimited. This project focused on developing the computational and observational capabilities needed to unlock these resources. Among several technical advances that are related to modeling the development of subsurface fractures for energy applications, this recently completed LDRD project yielded new modeling and seismic capabilities to understand the generation and growth of

fracture networks. Such networks are key pathways for the potential seepage of noble gases that could occur after an underground nuclear test. The project also generated new understandings of how to use micro-seismic signals to locate and characterize subsurface features. Simulation tools produced by this project may turn out to be an effective way to engage the international community in a broad range of follow-on research activities, some of which are likely to be related to the development of improved location and monitoring techniques with clear programmatic applications.

A Coupled Seismic and Acoustic Simulation Capability; FY14-FY15; $866K

Many events of interest occur near or above the interface between the air, water, and solid earth. Currently, we cannot jointly model acoustic and seismic signatures from these events with existing tools. This project is focused on developing a coupled seismic and acoustic simulation capability. The project is extending the current capability of the openly available WPP (Wave Propagation Program) and SW4 (Seismic Waves, 4th order) codes for seismic motions in solid earth to model energetic sources and motions in fluid regions of the Earth (air and water) and properly account for the flow of energy between the solid and fluid regions. Energetic events such as explosions and earthquakes near the Earth's surface generate motions in the atmosphere and water as well as seismic motions in the solid earth. Simulation of these waves, including propagation biases from the intervening material, enables more accurate inference of source properties. This will be accomplished by extending recent work on elastic waves to acoustics. Developing a capability to simulate coupling between infrasound, acoustic, and seismic signals has clear programmatic applications for CTBT monitoring and builds on expertise and capabilities developed by previous LDRD investments. These openly available codes are available to members of the international community of monitoring experts and can serve as technically sophisticated ways for experts to interact and collaborate.

Summary Table of LLNL LDRD Investments related to CTBT Program technologies.

Project Number	Years Funded	Project Title	Total Funding ($K)	PI
00-ERD-011	FY00-FY02	Colloidal Transport of Actinides in the Vadose Zone	529.64	Kersting
00-ERD-056	FY00-FY01	MEDIOS: Modeling Earth Deformation using Interferometric Observations from Space	470.27	Zucca/Vincent
01- ERD-051	FY01	Dynamic InSAR: Using InSAR to Image Seismic Waves Remotely from Space	206.36	Vincent
01-SI-003	FY01-FY03	The Stochastic Engine: Improving Prediction of Behavior in Geologic Environments We Cannot Directly Observe	2929.21	Aines
03-ERD-048	FY03	Long-Range, Passive Detection of Fissile Material	567.51	Fabris
03-LW-004	FY03	Resolving the Earthquake Source Scaling Problem	190.46	Walter
04-FS-023	FY04	Feasibility of Space-Based Seismometry Utilizing a Satellite-Borne Real Aperture Radar	49.04	Foxall
04-FS-031	FY04	Geophysics Experiments on High-Powered Lasers	50.65	Zucca
05-ERD-019	FY05-FY06	A New Capability for Regional High-Frequency Seismic Wave Simulation in Realistic Three-Dimensional Earth Models to Improve Nuclear Explosion Monitoring	483.44	Rodgers
05-ERD-079	FY05-FY08	A New Method for Wave Propagation in Elastic Media	1559.57	Petersson
07-ERD-011	FY07-FY08	Broad-Area Search for Proliferant Infrastructure	335.35	Harris
08-ERD-016	FY09-FY10	Broadband Heterodyne Infrared Spectrometer: A Path to Quantum Noise-Limited Performance	811.95	Tringe
11-SI-006	FY11-FY14	Creating Optimal Fracture Networks for Energy Extraction	5227.86	Ryerson
14-ERD-001	FY14-FY15	A Coupled Seismic and Acoustic Simulation Capability	865.90	Rodgers
		Total Funding ($K)	**$14277.21**	