DOE/NNSA/NA-22-NEMRE-2004

NATIONAL NUCLEAR SECURITY ADMINISTRATION

Nuclear Explosion Monitoring Research and Engineering Program

STRATEGIC PLAN

's Ratio

Ampere's law

$$\oint \vec{\mathbf{B}} \cdot \mathbf{d}\vec{\mathbf{s}} = \grave{\imath}_0 \mathbf{i} + \frac{\mathbf{1}}{\mathbf{c}^2}\frac{\partial}{\partial \mathbf{t}}\int \mathbf{EdA};$$

$$\nabla \times \mathbf{B} = \frac{4\pi k}{\mathbf{c}^2}\mathbf{J} + \frac{\mathbf{1}}{\mathbf{c}^2}\frac{\partial \mathbf{E}}{\partial \mathbf{t}}\mathbf{B}; \qquad k = \frac{1}{4\pi\varepsilon_0}$$

Wave Equation

$$\nabla^2\phi = \frac{1}{\alpha^2}\frac{\partial^2\phi}{\partial t^2}$$

Fermi's Golden Rule

$$\langle \beta | H | \alpha \rangle = -\sum_n \frac{\langle \beta | H | n \rangle \langle n | H | \alpha \rangle}{E_n - E_\alpha}$$

Momentum Equation

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \partial_j \tau_{ij} + f_i$$

Snell's Law

$$u_1 \sin\theta_1(r_1) = u_2 \sin\theta_2(r_2)$$

Klein-Nishina

$$\frac{d\sigma}{d\Omega} = Zr_0^2\left(\frac{1}{1+\alpha(1-\cos\theta)}\right)^2\left(\frac{1+\cos^2\theta}{2}\right)\left(1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)(1+\alpha(1-\cos\theta))}\right)$$

P-wave Velocity

$$\alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

Compton scattering

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2}(1-\cos\theta)}$$

Gauss' law for magnetism

$$\oint \vec{\mathbf{B}} \cdot \mathbf{d}\vec{\mathbf{A}} = \mathbf{0}; \qquad \nabla \cdot \mathbf{B} = \mathbf{0}$$

araday's law of induction

$$\cdot\, \mathbf{ds} = -\frac{\mathbf{d}\Phi_{\mathbf{B}}}{\mathbf{dt}}; \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}}$$

Binomial Distribution

$$p(x) = \frac{n!}{(n-x)!x!}p^x(1-p)^{n-x}$$

Nuclear explosion monitoring and the research and engineering supporting it are, to the surprise of many outside the field, computationally intensive. Equations that form the scientific foundation of our research are displayed on the cover.

NNSA
National Nuclear Security Administration

Los Alamos
NATIONAL LABORATORY
EST. 1943

Sandia National Laboratories

Lawrence Livermore
National Laboratory

Pacific Northwest
National Laboratory
Operated by Battelle for the
U.S. Department of Energy

Comments on this document may be directed to Program Manager: Leslie A. Casey, DOE/NNSA/NA-22, 202-586-2151, or via the feedback feature of the Program web site (see inside back cover for URL).

The research and engineering on this program involve close collaboration among the laboratories whose logos are displayed here -- Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories -- and input from users and other contributors (e.g., universities and private sector researchers). This program is conducted under the guidance of and funded by the Office of Nonproliferation Research and Engineering within the Office of Defense Nuclear Nonproliferation of the National Nuclear Security Administration.

print date: September 2004

NATIONAL NUCLEAR SECURITY ADMINISTRATION

Nuclear Explosion Monitoring Research and Engineering Program Strategic Plan

DOCUMENT ROADMAP

FOREWORD

The threat of a nuclear detonation, whether intentional or accidental, that could kill thousands and inflict widespread catastrophic damage, is still with us, even though the Cold War is over. The persistent and well-documented efforts by other states to develop nuclear weapons, and the potential that sub- or trans-national terrorist groups could obtain nuclear weapons all mean that the United States (US) must remain vigilant to deter and prevent nuclear attacks. Plus, the 1998 nuclear weapons tests in India and Pakistan emphasize that regional tensions persist, and nuclear explosion monitoring capability must be continually improved.

It is far better to identify nuclear weapons development in the testing phase and exert pressure on the proliferator to cease and desist than it is to counter an actual nuclear weapons attack, or, worse yet, deal with its aftermath. The Department of Energy (DOE)/National Nuclear Security Administration (NNSA) Nuclear Explosion Monitoring Research and Engineering (NEM R&E) Program is a unique national asset dedicated to providing knowledge, technical expertise, and products to US agencies responsible for monitoring nuclear explosions in all environments. This program has a long and impressive track record of success in turning scientific breakthroughs into tools for use by operational monitoring agencies in fulfilling validated national requirements. The NNSA NEM R&E program has traditionally supported these requirements with a variety of technologies.

The NNSA, with the national laboratories, is home to the US nuclear stockpile stewardship program, which is a cornerstone of US nuclear deterrence policy. The nuclear weapons design and effects expertise that resides at the National Laboratories and multi-billion-dollar national investment in these facilities, provide a unique, full-scope, and multi-disciplinary scientific capability that supports the US in realizing its nuclear explosion monitoring goals. In addition NNSA, through open competition, provides innovative monitoring solutions using the latest trends in technology drawn in part from extramural research partners at universities and private industry.

We reaffirm our commitment to accomplish our mission, and this strategic plan is our blueprint for success.

tj cerveny

—T. Jan Cerveny, Ph.D.
Assistant Deputy Administrator
for Nonproliferation Research and Engineering
National Nuclear Security Administration

PROGRAM MISSION

To develop, demonstrate, and deliver advanced technologies and systems to operational monitoring agencies to fulfill US monitoring requirements and policies for detecting, locating, and identifying nuclear explosions.

KEY PROGRAM ELEMENTS

Integration of New Monitoring Assets

Advanced Event Characterization

Next-Generation Monitoring Systems

The Problem We Face

Forewarned is Forearmed

At present, the established nuclear weapon states — the United States (US), Russia, the United Kingdom, France, and China — have suspended their nuclear weapons test programs, and we anticipate that they will continue to respect nuclear weapons testing moratoria. India and Pakistan tested in 1998, but each has declared its intention to desist from further testing, if the other does so. Despite strong pressures from the rest of the world, proliferators, from rogue nations to sub- or trans-national terrorist groups, are continuing their quests for nuclear weapons.

A proliferant nation or group may be able to design a crude, heavy (and consequently difficult to deliver) nuclear weapon. However, in order to either decrease the size and weight of the weapon, so that it could be delivered on a sophisticated platform such as a missile, or increase the yield, a proliferator would likely need to conduct a test. Detecting a first test of a nascent nuclear weapons program or a test to improve capability within an established nuclear weapons program allows the US to be forewarned and to preemptively deal with the testing entity before it can contemplate using its weapons.

No single technology has the capability to monitor nuclear explosions in all of the environments in which they might occur. The Air Force Technical Applications Center (AFTAC), the US agency charged with nuclear treaty monitoring, historically has woven together an integrated system of complementary satellite-mounted optical, radiofrequency, and radiation detection technologies, and ground-based seismic, hydroacoustic, infrasound, and radionuclide technologies to accomplish its mission. Optical, radiofrequency, x-ray, and nuclear radiation sensors mounted on satellite systems detect nuclear explosions in the atmosphere and space. Seismic systems detect subsurface explosions. Hydroacoustic systems detect explosions under and near the surface of the oceans. Infrasound systems detect shallow-buried and atmospheric events. Radionuclide systems detect radioactive gases or particulates that may have resulted from a nuclear explosion. Detections from all these systems are screened by advanced automated data processing technologies, which flag suspect events for further scrutiny by human analysts (Figure 1).

Our delivery of products developed under key program elements (next section) will continue to provide US monitoring agencies with the best tools for carrying out their nuclear explosion monitoring missions. For a description of the previous accomplishments with space-based and ground-based technologies employed in the monitoring systems, see *The Historical NEM R&E Accomplishments of NNSA — The Right Agency for the Job* at the end of this document.

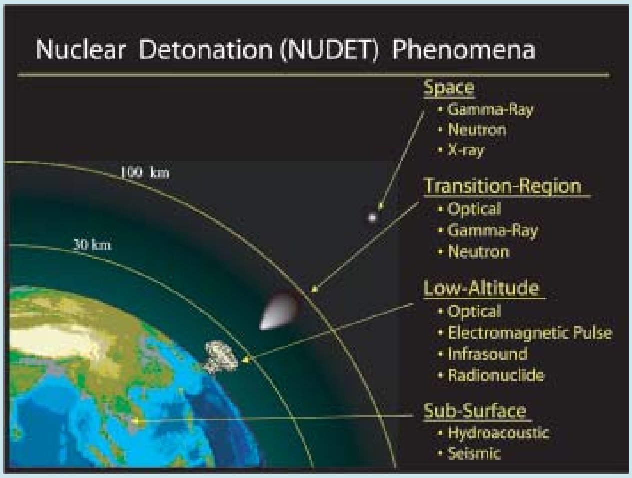

Figure 1. Measurable signals from the physical phenomena of nuclear explosions enable monitoring in all environments.

Program Structure and the Road Ahead

The policy and technology environment in which the NNSA NEM R&E program operates is dynamic. Monitoring requirements change as new threats are identified and old threats are re-evaluated. At present, the US is deploying new assets as part of ongoing efforts to augment national technical means as others are building the international monitoring system. To address this rapidly evolving state of affairs, the NNSA NEM R&E program is structured around three program elements.

Integration of New Monitoring Assets

The purpose of this program element is to provide operationally useful data and software products; for example, through calibration of new monitoring stations and sensors as they are added to existing networks. Calibration in a monitoring context has many meanings. Calibration of the instruments themselves is necessary for quality control and detailed analysis of the data and is well understood and straightforward. Newly launched satellite-borne optical sensors are pulsed with a laser beam to ensure their proper operational capability, and radiofrequency sensors are calibrated with a radiofrequency pulser. For the ground-based seismic waveform technologies, however, calibration also refers to the medium through which the waves pass. The performance of a given station will vary considerably depending on the location where it is deployed, and an extensive, very labor-intensive research effort is required to account for these regional (within 2,000 km of an event) variations. Without such regional corrections, estimates of an event's location can be in error by hundreds of kilometers, and other important signal characteristics may be misinterpreted (Figure 2). A major thrust of our efforts is acquiring the necessary characterization information and supplying it in an operationally useful form to the analyst. To address these objectives, the NNSA NEM R&E program has developed a sophisticated software and database system, known as the NNSA Knowledge Base[1]. Since seismic path calibration requires months to years of data from the station and detailed ground truth,[2] the sooner these calibrations can occur the better prepared the US will be to monitor nuclear explosions.

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[1] To effectively detect small events and distinguish those that are likely to be nuclear from background events such as earthquakes, mining activities, military operations, etc., the US monitoring system must process data from a large network of regional monitoring stations. The system must then sift through this large quantity of detected events and quickly identify those that require further action. Processing these events swiftly and with high confidence requires that detailed knowledge about the earth be available to both automated processing systems and human experts. The NNSA Knowledge Base, which can be likened to a warehouse enclosing a large collection of containers each holding a different type of knowledge, is where this detailed information is stored, maintained, and accessed. Because information in the NNSA Knowledge Base is contributed by a variety of government, university, and private sector researchers, we developed precise guidance for content developers, integrators, and coordination personnel to ensure verification and validation of NNSA Knowledge Base contributions.

[2] Ground truth is the actual *what, where,* and *when* of an event as confirmed by sources, such as instruments owned by mining companies or university research programs, that are independent of the monitoring system.

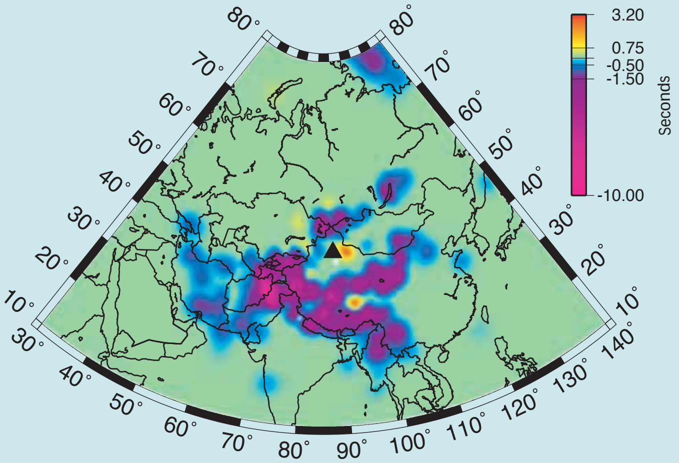
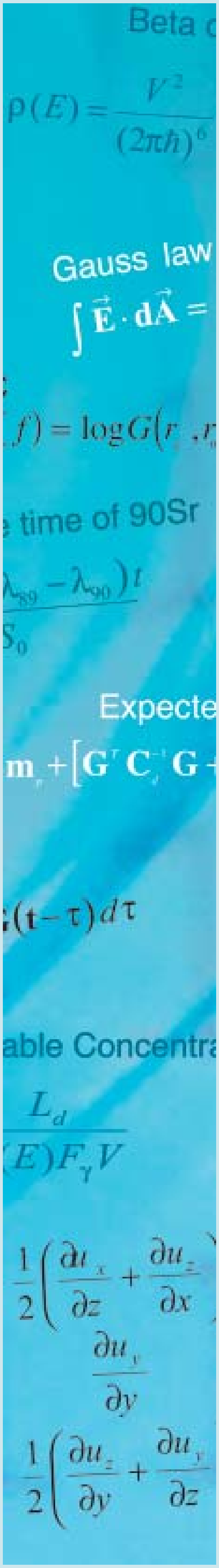
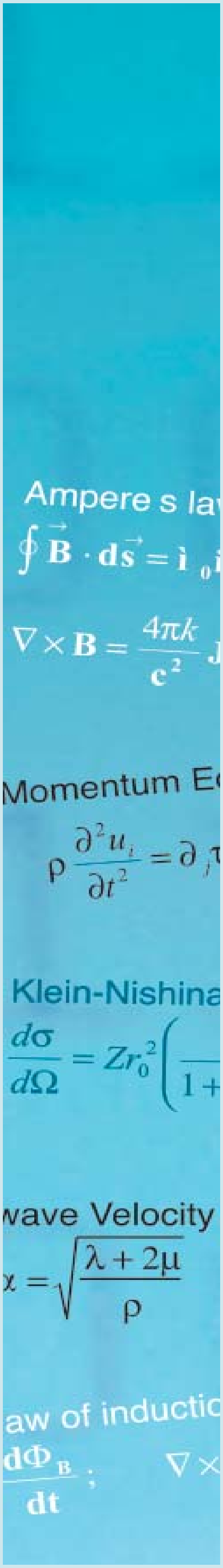


Figure 2. This is a station-specific travel-time correction surface used to account for changes in seismic-wave velocity that results from paths through inhomogeneous geology. This surface was generated by comparing the travel time (in seconds) from well-located events to those calculated by the 1-dimensional IASPEI91 model. The corrections are used iteratively to converge on a refined location for the event.





Advanced Event Characterization

Research and engineering to produce technologies for advanced event characterization are crucial for refining detection, location, and identification for nuclear explosions of very low magnitude anywhere they might occur. There are several signature observables from tests in each environment; the information they contain is complementary and a monitoring system that incorporates sensors for observing each of these phenomena is needed.

The monitoring environments addressed by satellite sensor systems, which are designed for both nuclear test monitoring and support of war fighting, include the earth's atmosphere (0- to 30-km altitude), the transition region (30- to 100- km altitude), and near-space (100- to 100,000-km altitude). Any major change in national requirements, as occurred when attention shifted from cold-war concerns to proliferation concerns, usually calls for substantial changes in the technical approaches used by the satellite sensors. In such cases the research and engineering start with laboratory proofs-of-principle and culminate, whenever possible, with on-orbit demonstration/ validation experiments. These proven technologies are then designed into operational systems that are delivered to users.

Satellite systems are capable of providing an exact locations and identification of an atmospheric, transition region, or near-space event, if all available techniques are utilized (Figure 3).

Infrasound detection complements our satellite capability in the atmosphere, and this technology is particularly well suited for use in cooperative programs with other nations. Radionuclide monitoring is critical in establishing unequivocal identification of nuclear events.

Seismic and hydroacoustic detection systems provide the primary means to effectively monitor subsurface nuclear explosions. Our experience with nuclear tests at the Nevada Test Site has shown that without some prior knowledge of the propagation medium, the uncertainty in a yield estimate using these methods can be as high as a factor of ten. However, with some knowledge, the uncertainty can be cut to a factor of two, and with very detailed knowledge, it can be cut even further. We are currently engaged in an effort to characterize regional seismic properties. This effort will enable regional seismic monitoring to work along with classical teleseismic monitoring to improve our understanding of the regional wave propagation of

Figure 3. Nuclear Detonation Detection payloads are provided on both the global positioning system navigational satellites (left) and the digital signal processing early launch detection satellites (right) .

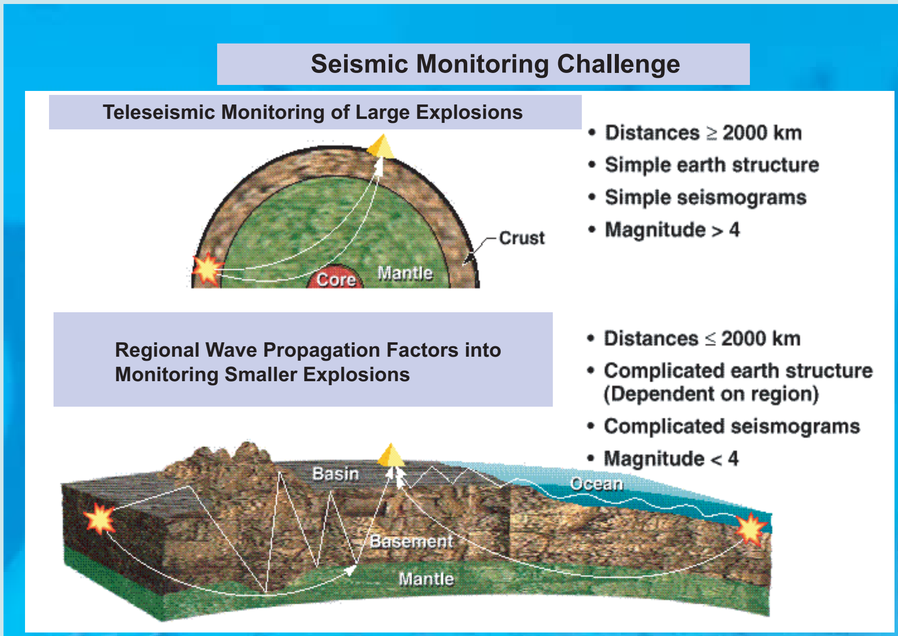
smaller explosions (Figure 4). Once these studies are complete, we will turn our attention to ways of improving the overall data processing performance of monitoring networks.

Next-Generation Monitoring Systems

The operational US monitoring system (the US Atomic Energy Detection System[3] or USAEDS) will evolve as monitoring networks continue to expand, software and hardware technologies advance, signal processing improves, and the monitoring system requirements become more demanding. We must ensure that next-generation monitoring systems are robust, automated, and user-friendly, and have backward compatibility with the existing system. We know, based on the constant advancement of science, that our current tools will need to be replaced by revolutionary new technologies emerging from universities, the private sector, and government agencies, particularly DOE/NNSA, which are focused on this arena.

Experience with USAEDS has shown that system configuration changes are very expensive and take many years to fully implement, requiring intervention by knowledgeable experts and considerable investment of time and money. The future monitoring environment will require much more flexible processing that will allow the users themselves to quickly focus on different areas of the world at different levels of detail without time-consuming redesign of the system. The next-generation systems must effectively integrate data from various monitoring technologies, while responding quickly to changes.

Our scientists and engineers are always watching for technologies relevant to the monitoring task and will engineer ways to integrate them into our users' systems. We are leading in the development of concepts for monitoring systems including data processing technologies, as well as in breakthroughs in monitoring technologies.



Seismic Monitoring Challenge

Teleseismic Monitoring of Large Explosions

- Distances ≥ 2000 km
- Simple earth structure
- Simple seismograms
- Magnitude > 4

Regional Wave Propagation Factors into Monitoring Smaller Explosions

- Distances ≤ 2000 km
- Complicated earth structure (Dependent on region)
- Complicated seismograms
- Magnitude < 4

Figure 4. The challenge of monitoring explosions through teleseismic and regional wave propagation.

KEY MEMORANDA OF UNDERSTANDING BETWEEN NNSA AND OTHER AGENCIES

Tri-party MOU amongst Air Force Technical Applications Center (AFTAC) and United States Geological Survey (USGS) and National Nuclear Security Administration (NNSA), dated May 9, 2001.

Integration, Launch, and Spaceflight of the Space and Atmospheric Burst Reporting System Validation Experiment — tri-party Memorandum of Agreement amongst DoD Space Test Program (STP) and US Air Force (USAF) Defense Support Program (DSP) and Department of Energy (DOE), dated September 22, 1999.

US Nuclear Detonation Detection System (USNDS) – four-party MOU amongst USAF Space Command, USAF Space and Missile Systems Center (SMC), AFTAC, and DOE, dated January 8, 1997 covering all aspects of providing the USNDS.

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[3] USAEDS is operated by the Air Force Technical Applications Center (AFTAC), which is the sole Department of Defense agency operating and maintaining a global network of nuclear event detection sensors. When USAEDS senses an event underground, underwater, in space, or in the atmosphere, AFTAC's experts analyze the event and report findings to the national command authorities.

Challenges and Technology Solutions

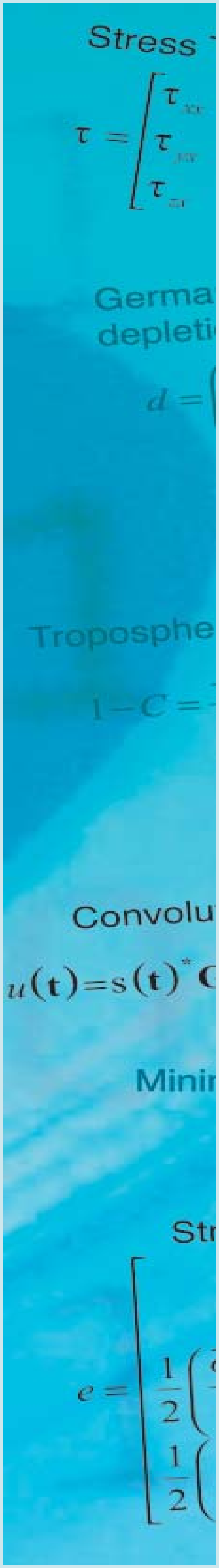
Tables 1 and 2 summarize the challenges for the satellite-based and ground-based nuclear explosion monitoring research and engineering programs, and the technology solutions we plan to develop to answer those challenges.

Table 1. Satellite-Based Challenges and Solutions by Program Element

Challenges	Technology Solutions
Program Element: Integration of New Assets	
Incorporate vastly increased data flows from new optical and electromagnetic pulse sensors into existing system architecture	Additional downlink capacity through either more ground sites or more storage and bandwidth Sophisticated on-board triggering algorithms Algorithms for ground processing Improved methods of processing/identifying nonnuclear events
Program Element: Advanced Event Characterization	
Increase the absolute sensitivity of sensors for detecting and locating atmospheric nuclear detonations	Focal plane array active pixel technology (thousands of individual optical sensors implemented in a space not appreciably larger than that required for today's single optical sensor) New sensor technologies as integrated circuit technology improves
Provide multi-phenomenology sensing capabilities to increase confidence in identification of nuclear detonations from space	Autonomous electromagnetic pulse sensors and associated techniques to distinguish radiofrequency generated by nuclear explosions from natural phenomena Neutron and gamma-ray sensors on new satellite platforms
Program Element: Next-Generation Monitoring Systems	
Reduce detection thresholds for satellite systems while maintaining low false-event rates	Array-based optical sensors Wide-band radiofrequency systems Sophisticated real-time triggering algorithms
Reduce size, weight, and power required for monitoring systems	Advanced electronics, including Z-plane technology and field-programmable gate arrays Multi-function sensors Advanced packaging technologies to allow more electronics integration

Table 2. Ground-Based Challenges and Solutions by Program Element

Challenges	Technology Solutions
Program Element: Integration of New Assets	
Reduce time and resources required to calibrate new stations	Automated data processing of labor-intensive calibration steps Refined calibration techniques Universal validation techniques
Develop new/improved ground-truth collection techniques	Multi-path calibration by reciprocal calibration explosions Overhead imagery as ground truth for reference event locations Partnerships with local scientists
Optimize the NNSA Knowledge Base to meet operational requirements	Data acquisition and integration of research products translated into operational form A framework for quantifying and reducing uncertainties and errors in signal and data-processing technologies Exploitation of multi-technology information for event characterizations
Program Element: Advanced Event Characterization	
Data Centers Enhance data acquisition, communication, and interpretation capabilities	Advanced data processing tools to extract events from the monitoring station data streams and facilitate evaluation by human analysts Extensive NNSA Knowledge Base framework Data surety
Seismic Develop a remote characterization capability for regions of interest	Transportable magnitude measurements and procedures Overhead imagery to aid characterization of the geologic environment High-frequency array signal processing
Hydroacoustic Operationalize accurate event location and identification methods	Experimentally validated long-range propagation predictions Empirically validated theory for amplitudes of underwater and low-atmospheric nuclear explosions NNSA Knowledge Base location grids of bathymetry incorporating signal reflection and blockages
Infrasound Establish accurate event location and identification analysis tools	Efficient automated signal- and event-processing drawing upon a reference event library Advanced analysis and location tools incorporating signal reflection and blockages Source characterization for discriminant development to reduce false alarms, particularly from mining events and bolides
Radionuclide Tailor sensitivity and discrimination methods while reducing maintenance and analysis costs	Analyses that identify new signatures for small nuclear detonations New radiation detection technologies such as pulse shape analysis New materials for more selective, rapid sample preparation and higher resolution detection of characteristic radioactive emissions Station-centric analysis tools to establish the monitoring background levels and to facilitate operations, including state of health
Program Element: Next-Generation Monitoring Systems	
Lead in the development of concepts for monitoring systems including data processing technologies, as well as in breakthroughs in monitoring technologies including backward compatibility of systems	Tools and techniques to automatically acquire, store, analyze, display, and disseminate/report data and information from a variety of sources and systems using cognitive task analysis and decision-centric design approaches and the latest in distributed, object-oriented design methodologies Guarantee data surety, including techniques for system security, reliability, and data integrity



Program Management and Coordination

How the DOE/NNSA NEM R&E Program Fits into the National Effort

Figure 5 illustrates the role played by NNSA in the national nuclear explosion-monitoring arena. NNSA enables the realization of US goals and requirements by providing technologies to operational agencies. Data from the events are analyzed in near real time, primarily at AFTAC, and then results are provided to policy makers.

Through the technology development expertise at its national laboratories, NNSA is the enabler. Because the NNSA national laboratories are the only US entities that have hands-on experience in designing and testing nuclear weapons, they have a unique perspective on technologies required for detecting nuclear explosions, dating back to the beginning of the nuclear age. The NNSA understands both the constraints and the goals of the policy community and the resource needs of the technical community in support of national nuclear explosion monitoring goals. The DOE/NNSA laboratories draw on a broad-scope, multi-disciplinary cadre of some of the world's foremost technical experts. Over the years, these experts have demonstrated their ability to combine results from their own activities, basic research (by universities and the private sector at home and abroad), and applied research, and integrate the technological advances into monitoring systems.

We Are Structured For Management Success

In carrying out our research and engineering program, our management philosophy is to be ever mindful of the needs of our various stakeholders, from the US private sector to the international community to government users and ultimately to US taxpayers.

Partnering

We partner with our users to leverage assets, including the budget and technology assets, of several agencies working together on nuclear explosion monitoring issues. We use Memoranda of Understanding as formal and informal management partnering tools for coordination with the users. Memoranda of Understanding are critical for delineating roles, responsibilities, and areas of cooperation.

As we approach the hand-over point, where our technologies become operational systems serving our country, the users themselves help fund that final step to ensure the success of the transfer process. In several cases, multimillion dollar Department of Defense (DoD) acquisitions have followed this process, with full NNSA consultation and support.

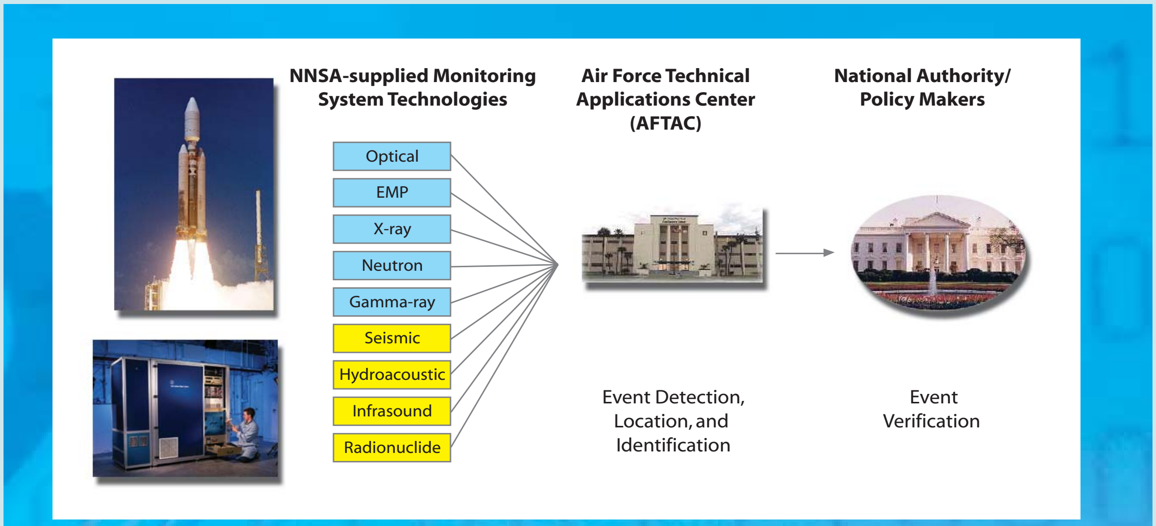
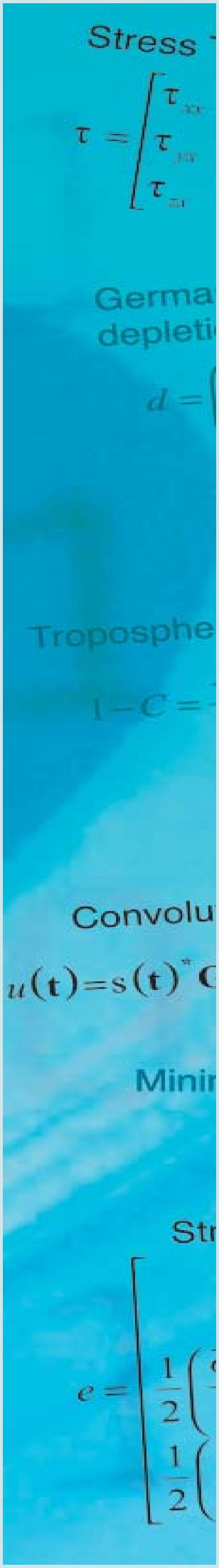


Figure 5. The role of the NNSA-supplied monitoring system technologies.



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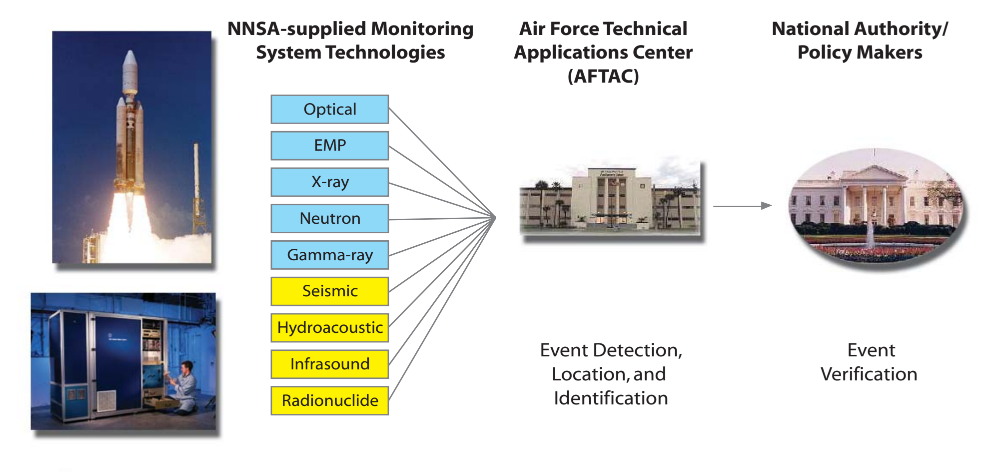


Figure 5. The role of the NNSA-supplied monitoring system technologies.

We work closely with the Air Force to coordinate specifications and delivery schedules for satellite instruments, so they can be integrated smoothly onto their host satellites. We also provide expert assistance for pre-launch and on-orbit testing. The NNSA Knowledge Base is an essential component of the operational AFTAC data processing pipeline and must integrate seamlessly into it, a systems design challenge that is no trivial task. We have worked with national and international partners who have funded the laboratories to conduct site surveys for new infrasound stations. We have also worked with private companies to transition our prototype radionuclide sampler-analyzers to commercially produced versions.

Collaboration with Other Organizations in the US

A key to optimal external collaboration is enabling each entity to do what it does best. The NNSA NEM R&E program and other government agencies sponsor universities and private sector researchers who excel at specific research projects that do not require the multi-billion dollar infrastructure and broad multi-disciplinary staff of a national laboratory. The national laboratories then fill in the gaps between these targeted research endeavors, optimize their results, and provide overall integration. To this end, we are publishing and maintaining contributor guides that define the process of "vetting" and integrating new data sets into information products for the NNSA Knowledge Base.[4] A key objective of the NNSA program is the integration of research products into a form that is useful in operations (Figure 6). Many of our partnering activities do not involve transfer of funds. For example, we coordinate each year with the DoD to produce a joint research solicitation, so there is mutual cooperation and no duplication of effort between the two agencies. DoD and DOE/NNSA also cooperate in peer reviews and program reviews of ongoing research in both agencies. We participate in mutual data sharing with the United States Geological Survey,[5] and we assist in product integration to fold the contributions of private sector researchers into the overall monitoring system. To foster and strengthen the vital links between NNSA laboratory scientists and the wider community, NNSA partners with DoD in support of an annual research review on monitoring topics, attended by university, private sector, and NNSA laboratory scientists. The result is a very positive and broad contact and collaboration between scientists and engineers in support of our combined objective. This forum has produced numerous examples of cooperation, sharing of assets, and coordination of results.

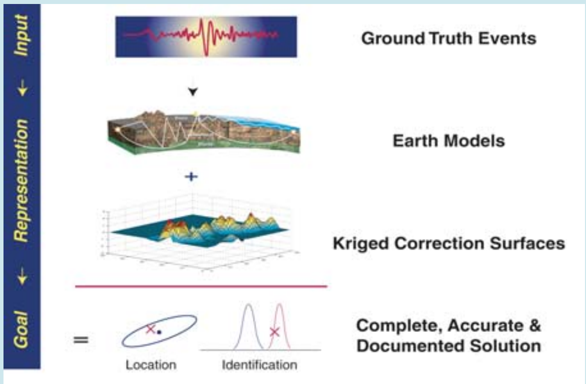
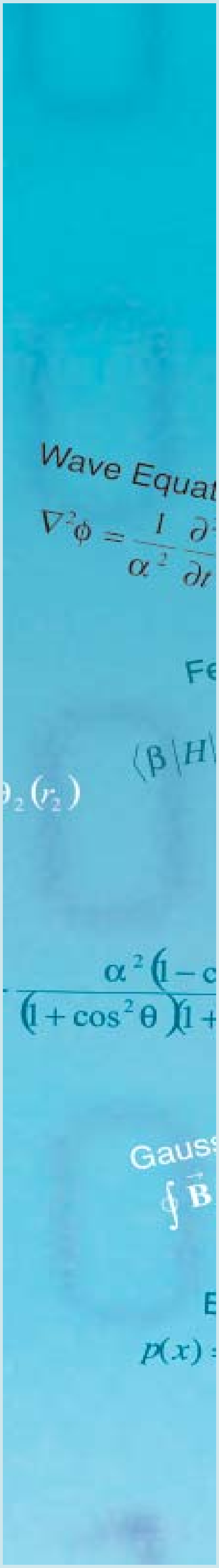

Integrated Research Products

Figure 6. Accurate location and identification of seismic events depend on appropriate integration of the ground-truth data with research products like earth models and correction surfaces.



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[4] D. Carr, (8/03), National Nuclear Security Knowledge Base Contributor's Guide, Sandia National Laboratories Report SAND2002-2771 (Revised), and David P. Gallegos, Dorthe B. Carr, Christopher J. Young, Preston B. Herrington, J. Mark Harris, C.L. Edwards, Steven R. Taylor, Julio C. Aguilar-Chang, John J. Zucca, David B. Harris, Dale N. Anderson, and Leslie A. Casey, (11/03), The Integration Process Design for Incorporating Information Products into the National Nuclear Security Administration Knowledge Base, Sandia National Laboratories Report SAND2002-2772. These documents can be found at https://www.nemre.nnsa.doe.gov under Knowledge Base.

[5] In addition to AFTAC and others, we partner with the United States Geological Survey (USGS), which is responsible for monitoring national and worldwide seismicity and reporting to national and international emergency response agencies, and to other interests including the media and the general public. USGS contributes geological expertise to the national effort and appropriate products to the NNSA Knowledge Base.

International Cooperation

National and international organizations are in the middle of an ongoing process to increase coverage of the globe by installing or upgrading networks of ground-based monitoring stations for a variety of reasons (e.g., earthquake monitoring, monitoring by the Provisional Technical Secretariat for the Comprehensive Nuclear-Test-Ban Treaty, Global Seismic Network operation, hazard mitigation, regional stability). The more stations around the globe producing and sharing high-quality data, the better the identification and location capability; the more international cooperation, the more data for the US to utilize and the less cost to US taxpayers. Like the US, other countries are in the process of installing and upgrading monitoring stations, and we are cooperating with and assisting them, when it complements or supports US interests.

Scheduling Considerations

Our programmatic schedules are closely coordinated with our customers. The following planning assumptions come into play in our scheduling.

Satellite–Based Systems

Approximately three operational payloads per year are delivered to Air Force hardware integrating contractors.

Launch schedules and satellite technology changes are driven by Air Force requirements.

Demonstration/validation experiments are developed for future generation technologies.

Ground–Based Systems

Joint (NNSA and DoD) annual solicitation of research proposals featuring electronic transactions, including peer reviews in support of the E-Government Initiative within the President's Management Agenda.

Core integration function transitioning research to AFTAC, including regular delivery of NNSA Knowledge Base releases to improve the capability of operational systems.

New seismic station installation, roughly 3-4 per year for the next ten years, guiding reprioritization of calibration resources with the user.

Budget

The NNSA NEM R&E target budget, which is approximately $100M per year, is designed to provide valuable products to the user community and to be a natural progression from our previous successful activities. This budget is designed to deliver integrated systems that dovetail into user satellite- and ground-based systems deployment schedules.

Actual appropriations are made annually and vary in complex ways. A variety of factors impacts the budget, such as administration budget guidance, actual Congressional appropriations, user modifications to deployment schedules, research results that complete some tasks and begin new areas of promising research, and interagency programmatic transfers.

The Historical NEM R&E Accomplishments of NNSA — The Right Agency for the Job

Expertise plus Experience

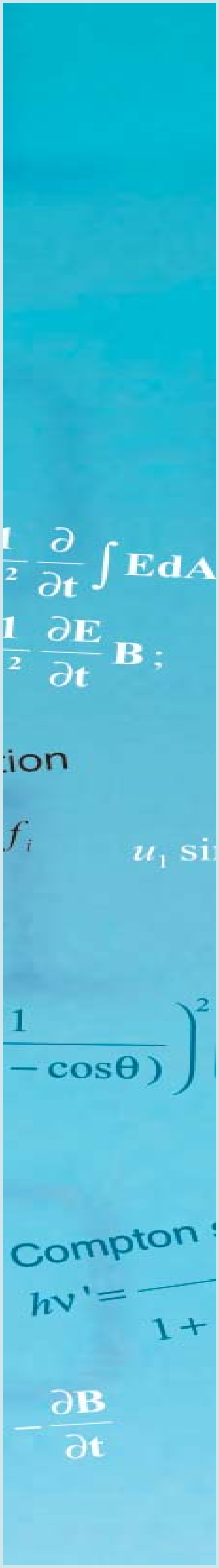
A truly impressive array of technologies has been developed and transferred to monitoring agencies by DOE/NNSA (and its predecessors) over the last 55 years to enable monitoring of nuclear explosions and verification of the many treaties that have played a role in preventing nuclear war. We have contributed substantially to the monitoring technologies used by the USAEDS. Today our technologies are monitoring the earth from below the oceans, under and on the continents, high in the atmosphere, and far overhead in space. Over many years, we have provided expert support for policy formulations and creative solutions for technological requirements related to nuclear explosion monitoring.

Since the initial nuclear-weapon test at Trinity Site near Alamogordo, New Mexico, in 1945, US policy has sought to limit the spread (proliferation) of this awesome destructive power, but at the same time to monitor worldwide events in order to detect the activities of other nations and proliferators. Over time, the US has employed various strategies to prevent the proliferation of nuclear weapons, including becoming party to several treaties such as the Limited Test Ban Treaty (LTBT), the Nuclear Non-Proliferation Treaty (NPT), and the Threshold Test-Ban Treaty (TTBT).[6]

Over the years, NNSA NEM R&E staff have been instrumental in developing the actual sensors and, equally important to the capability, developing methods for interpreting the data they produce. Incorporating these diverse technologies into an integrated system takes advantage of the synergy provided by complementary measurement techniques, and often provides the important advantage of multi-phenomenology detection. Furthermore, it allows us to capitalize on similarities in the research, development, and engineering tasks associated with the different technologies. The reward for success is a cost-effective, extremely powerful monitoring system capable of global, full-time detection of nuclear explosions to support national decision-making processes.

An important characteristic of our applied research program is our emphasis on developing products that can be transitioned directly into operational monitoring systems. This emphasis on real-world applications is facilitated by close coordination of product deliveries with key operational schedules (e.g., schedules for satellite launches, data processing upgrades, equipment deployment).

Table 3 gives specific examples of science-based methods and technologies for enhanced detection, location, and identification of low-yield nuclear explosions under development or already developed by the NNSA NEM R&E program.



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[6] For more information about the LTBT, the NPT, the TTBT, and other treaties relevant to nuclear explosion monitoring, go to http://dosfan.lib.uic.edu/acda/treaties.htm

Table 3. NNSA-Developed Nuclear Explosion Monitoring Satellite-Based and Ground-Based Technology Highlights

(2004) NNSA Knowledge Base incorporating tri-annual releases of event location and magnitude estimation in sparse networks for monitoring test sites in the European arctic and in Asia, and containing a new interface, a Geographic Information System, new storage formats, and a suite of analytical tools for automating signal characterization and maximizing the skills of analysts

(2003) Array-based optical detectors for improved capability to detect, locate, and identify low-yield atmospheric nuclear explosions from global positioning system satellites

(2003) Electromagnetic pulse sensors for autonomous (not requiring optical sensor corroboration), all-weather atmospheric nuclear-explosion monitoring from global positioning system satellites

(2003) Safe deep-water implosion sources for hydroacoutic systems and ocean-basin calibration

(2003) Neutron/gamma-ray sensors, combining multiple detectors into a single box and using on-board processing to reduce telemetry requirements, for defense support program satellite follow-ons

(2003) Enhanced models of nuclear weapon electromagnetic pulse outputs for assessing our capability to monitor potential proliferant weapons

(2002) Failure detection/prediction tools developed for aerosol and xenon systems using State-of-Health data

(2001) Combined particle dosimeters/x-ray detectors in a single package, with the x-ray detectors having extended ranges in both the high and low energies, for enhanced ability to detect unsophisticated weapons

(2000) Data authentication technology securely integrated with seismic, hydroacoustic, infrasound, and radionuclide sensor equipment

(1999) Innovative discriminants, which proved the viability of regional seismic event discrimination using the Regional Seismic Test Network and the Livermore and Sandia regional seismic networks surrounding the Nevada Test Site

(1999) Automated radioxenon sampler analyzer for real-time detection of short-lived radioactive noble gases released during nuclear explosions

(1998) Radionuclide aerosol sampler analyzer for detecting short-lived particulates

(1997) Autonomous electromagnetic pulse sensor flight validation on the NNSA FORTÉ small satellite

(1997) Prototype low-frequency sound (infrasound) detection system ready for transfer to users

(1993) Imaging x-ray detector flight validation on the NNSA ALEXIS small satellite

(1991) Radio-frequency zapping for quarterly calibration of electromagenetic pulse on-orbit sensors

(1987) Regional Seismic Test Network demonstrating the feasibility of National Seismic Station stand-alone, autonomous, regional seismic monitoring sites transmitting to satellites for verification of the proposed, but not completed, comprehensive test ban between the US, UK, and Soviet Union

(1985) Hydrodynamic yield estimation technology (CORRTEX), which was subsequently adopted for verification of the Threshold Test-Ban Treaty

(1985) Innovative small-aperature, regional seismic-array design developed in collaboration with DoD-funded NORSAR

(1971) Laser zapping for quarterly calibration of optical on-orbit sensors

(1965) Optical and electromagnetic pulse sensors for Vela satellites

(1963) X-ray, neutron, gamma-ray, and charged particle sensors for Vela satellites

For more information:

The NNSA NEM R&E Program web site facilitates coordination among fellow researchers and users on the best use of research products, data, and results. Please visit us at

https://www.nemre.nnsa.doe.gov
and
https://www.nemre.nnsa.doe.gov/coordination

Stress Tensor

$$\tau = \begin{bmatrix} \tau_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \tau_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \tau_{zz} \end{bmatrix}$$

Marginal posterior probability density

$$P_L(\mathbf{m}) = \int_D P_L(\mathbf{d},\mathbf{m})d\mathbf{d} = P_p(\mathbf{m})\int_D P_p(\mathbf{d})P_G(\mathbf{d} \mid \mathbf{m})d\mathbf{d}$$

Photoelectric effect

$$E_{e-} = h\nu - E_b$$

Beta decay density of states

$$\rho(E) = \frac{V^2}{(2\pi h)^6}\frac{d}{dE_{\max}}\int p_e^2 dp_e d\Omega_e p_\nu^2 dp_\nu d\Omega_\nu$$

Young’s Modulus

$$E = \frac{(3\lambda + 2\mu)}{(\lambda + \mu)}$$

Germanium depletion voltage

$$d = \left(\frac{2\varepsilon V}{eN}\right)^{1/2}$$

Gauss’ law for electricity

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{\mathbf{q}}{\mathring{a}_0}; \qquad \nabla \cdot \mathbf{E} = \frac{\tilde{n}}{\mathring{a}_0}$$

Aerosol deposition in tubes

$$\frac{c_{out}}{c_{in}} = 1 - \frac{4}{\sqrt{\pi}}\sqrt{\frac{DL}{uR^2}}$$

MDAC

$$\log A_{ij}(f) = \log G(r_{ij}, r_0) + \log S_i(f) - \frac{\pi f \log e}{Q(f)v}r_{ij} + \log P_j(f)$$

Poisson’

$$\sigma = \frac{\lambda}{2(\lambda +}$$

Troposphere residence time of 90Sr

$$1 - C = \frac{-S_0 + T\exp(\lambda_{89} - \lambda_{90})t}{T_0 - S_0}$$

Gamma Peak Shape

$$F(e) = \frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(e-e')^2}{2\sigma^2}}$$

Expected values

$$\langle \mathbf{m} \rangle = \mathbf{m}_p + \left[\mathbf{G}^T \mathbf{C}_d^{-1} \mathbf{G} + \mathbf{C}_m^{-1}\right]^{-1} \mathbf{G}^T \mathbf{C}_d^{-1}(\mathbf{d} - \mathbf{G}\mathbf{m}_p)$$

Coaxial electric field

$$-E(r) = -\frac{\rho}{2\varepsilon}r + \frac{V + (\rho/4\varepsilon)(r_2^2}{r\ln(r_2/r_1)}$$

Convolution

$$u(\mathbf{t}) = \mathrm{s}(\mathbf{t})^* \mathbf{G}(\mathbf{t}) \equiv \int_0^{\mathbf{t}} \mathrm{s}(\tau)\mathbf{G}(\mathbf{t} - \tau)d\tau$$

S-wave Velocity

$$\beta = \sqrt{\frac{\mu}{\rho}}$$

Minimum Detectable Concentration

$$MDC = \frac{L_d}{\varepsilon(E)F_\gamma V}$$

Charge collection

$$Q(t) = \frac{q_0}{\ln(r_2/r_1)}\left[\ln\left(1 + \frac{v_e t}{r_0}\right) - \ln\left(1 - \frac{v_h t}{r_0}\right)\right]$$

Strain Tensor

$$e = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial u_y}{\partial x} + \frac{\partial u_x}{\partial y}\right) & \frac{\partial u_y}{\partial y} & \frac{1}{2}\left(\frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y}\right) \\ \frac{1}{2}\left(\frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z}\right) & \frac{1}{2}\left(\frac{\partial u_z}{\partial y} + \frac{\partial u_y}{\partial z}\right) & \frac{\partial u_z}{\partial z} \end{bmatrix}$$

Bulk Modulus

$$\kappa = \lambda + \frac{2}{3}\mu$$

Currie’s Detection Level

$$L_d = 2.33 + 4.65\sqrt{BKG}$$

Fa

$$\oint \mathbf{E}$$