Ground-based Nuclear Detonation Detection (GNDD) Technology Roadmap

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This Roadmap is intended to provide guidance to potential researchers and help management define research priorities to achieve technology advancements for ground-based nuclear explosion monitoring science being pursued by the Ground-based Nuclear Detonation Detection (GNDD) Team within the Office of Nuclear Detonation Detection in the National Nuclear Security Administration (NNSA) of the U.S. Department of Energy (DOE). Four science-based elements were selected to encompass the entire scope of nuclear monitoring research and development (R&D) necessary to facilitate breakthrough scientific results, as well as deliver impactful products. Promising future R&D is delineated including dual use associated with the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Important research themes as well as associated metrics are identified along with a progression of accomplishments, represented by a selected bibliography, that are precursors to major improvements to nuclear explosion monitoring.

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INTRODUCTION

The GNDD Team conducts research to drive the state-of-the-art in waveform and radionuclide technologies providing science tools and validated geophysics datasets that enable improved analyses of real-world nuclear explosion monitoring.

The goal[1] of the GNDD Team is to:

> ***Advance the U.S. ground-based nuclear explosion monitoring capabilities to detect, locate, identify, and determine yield of events associated with foreign nuclear weapons development.***

GNDD supports the DOE strategic goal[2] to "enhance nuclear security through defense, nonproliferation, and environmental efforts" and the NNSA strategic goal[3] to provide "technical and policy expertise to advise policymakers and to develop technologies to monitor compliance with arms control and nonproliferation commitments." Finally, GNDD supports Defense Nuclear Nonproliferation Research and Development's (DNN R&D) overall strategic direction[4] to develop technologies that support the next generation of emerging arms control and nonproliferation treaties and agreements.

The objectives of the GNDD Team are to:

- Develop advanced methods to detect, locate, determine yield and support identification of foreign nuclear events using waveform technologies (Objective A), and
- Develop advanced methods to detect, identify, and support determination of yield and location of foreign nuclear events using radionuclide technologies (Objective B).

Associated requirements are:

- Waveform source physics (Objective A, Requirement a)
- Waveform signal propagation (Objective A, Requirement b)
- Waveform sensors (Objective A, Requirement c)
- Waveform signal analysis (Objective A, Requirement d)
- Radionuclide source physics (Objective B, Requirement a)
- Radionuclide signal propagation (Objective B, Requirement b)
- Radionuclide sensors (Objective B, Requirement c)
- Radionuclide sensors (Objective B, Requirement d).

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[1] *Ground-based Nuclear Detonation Detection (GNDD) Team – Goals, Objectives, and Requirements,* DOE/NNSA/NA-22/GNDD-GOR-2014, January 2014.

[2] *U.S. Department of Energy Strategic Plan,* DOE/CF-0067, May 2011. Available at http://energy.gov/sites/prod/files/2011_DOE_Strategic_Plan_.pdf.

[3] *The National Nuclear Security Administration Strategic Plan,* U.S. Department of Energy National Nuclear Security Administration May 2011. Available at http://nnsa.energy.gov/sites/default/files/nnsa/inlinefiles/2011_NNSA_Strat_Plan.pdf.

[4] *Office of Nonproliferation and Verification Research and Development Strategic Implementation Plan FY 2013–2017,* U.S. Department of Energy National Nuclear Security Administration, Office of Nonproliferation and Verification Research and Development, April 9, 2012.

The GNDD Team, through the DOE/NNSA Office of Nuclear Detonation Detection is positioning itself with its goal, associated objectives and requirements to address current and evolving nuclear proliferation threats.

In pursuit of the Administration's nonproliferation mission, the GNDD Team supports improvements to the United States (U.S.) Air Force Technical Applications Center (AFTAC) in their mission to monitor nuclear explosions with the U.S. Atomic Energy Detection System (USAEDS) as well as in their role as the U.S. National Data Center (NDC) as an integral part of the verification system of the CTBT. Furthermore, where policy directs, the GNDD Team supports improving international monitoring capabilities.

To fulfill technical monitoring requirements and responsibilities[5], the GNDD Team builds on the broad base of U.S. expertise developed historically through the nuclear weapons program and focuses research and development on detecting, locating, and identifying nuclear explosions in all environments. Program efforts are focused on improving national nuclear explosion monitoring capabilities, such as remotely monitoring tests by proliferators, even in the absence of a treaty.

To share scientific knowledge relevant to nuclear explosion monitoring, the GNDD Team embraces partnering and collaboration as a way to harness relevant creativity irrespective of which organization it resides in.

Historically, the awards funded by any sponsor at any given time that are relevant to GNDD were invited to be included in the publicly available proceedings of the annual Monitoring Research Reviews (MRR). The 1999 to 2012 proceedings are available in PDF at the DOE Office of Scientific and Technical Information (OSTI) SciTech Connect http://www.osti.gov/scitech; (suggested words for the keyword search are, "monitoring research review"). Proceedings from 1985 to 1998 are available at the Defense Technical Information Center http://www.dtic.mil/dtic; (suggested words for the keyword search are "seismic research symposium").

Starting in 2014, the GNDD Team, in concert with other research sponsors, will host a Ground-based Nuclear Explosion Monitoring (GNEM) community research review called the "Program and Technical Review of Monitoring Research" (RMR) in Albuquerque, NM. If this new meeting format is successful, it may be convened on a bi-annual basis in years alternating with the CTBTO Science and Technology meeting in Vienna, Austria.

[5] The DOE/NNSA is responsible for most of the U.S. government's research and development for monitoring nuclear explosions per the 1993 transfer of responsibility from the DoD.

Other research outreach activities include distribution to the GNEM community of GNDD Team software (codes, models, and data) (see Table 1) and the publishing of peer-reviewed GNDD Team articles in the world science literature (see Appendix B – Selected Bibliography).

Table 1. GNDD Team Contributed Software

Software Package Name	URL
BayesLoc	https://missions.llnl.gov/nonproliferation/nuclear-explosion-monitoring/bayesloc
GeoTess	http://www.sandia.gov/geotess
G3D	http://www.iris.edu/dms/products/emc-llnl-g3dv3/
Inframonitor/Bayesian Infrasound Source Location	http://www.lanl.gov/projects/inframonitor/index.html
Regional Seismic Travel Time (RSTT)	http://www.sandia.gov/rstt

Typically, DOE/NNSA funded GNDD R&D is performed by universities, the private sector, other government agencies, and predominantly Federally Funded Research and Development Centers (FFRDC), namely:

- Lawrence Livermore National Laboratory (LLNL)
- Los Alamos National Laboratory (LANL)
- Pacific Northwest National Laboratory (PNNL)
- Sandia National Laboratories (SNL)
- Idaho National Laboratory (INL).

An important function of these FFRDCs is to integrate and reconcile the research products from individual projects as a necessary step in transitioning research products to operations.

Additionally, the DOE/NNSA GNDD Team operates in concert with many other agencies with programs relevant to the CTBT (see Table 2).

Table 2. GNDD Team partners and predominant contributions
(see Appendix A – Acronyms and Abbreviations)

PARTNERS	CONTRIBUTION
CTBTO	International Data Centre, International Monitor System
DoD/AFTAC	U.S. National Data Center, USAEDS
DoD/AFRL	Seismic, Infrasound and Hydroacoustic R&D
DoD/DTRA/OS	On-Site Inspection expertise
DoD/DTRA	Treaty Verification Technologies R&D, U.S. International Monitoring System (IMS) station operations and associated R&D
DoD/OSD	Policy
DOE/NNSA/NA-221	National Center for Nuclear Security at the Nevada National Security Site
DOE/NNSA/NA-222	Full-scope GNDD/CTBT R&D
DOE/NNSA/NA-24	Non-Proliferation Policy
DOS	Policy, Verification and Monitoring Task Force/Backstopping, U.S. Contributions-in-Kind and annual dues to the CTBTO, Nonproliferation Disarmament Fund, V-Fund
NSF/IRIS	Seismic Data Management Center, U.S. Array, EarthScope, Passcal Equipment Center
NSF/IRIS/USGS	Global Seismic Network
NOAA	Atmospheric transport models
NASA	Atmospheric transport models
NRL	Hydroacoustic and infrasound models
USGS	National Earthquake Information Center

MONITORING ENVIRONMENT

Figure 1 shows the physical environment where sources of interest for nuclear explosion monitoring occur, which is predominately near the Earth's surface or slightly into the crust. This environment is rich with confounding natural sources such as earthquakes (1), volcanic activity and the seismic noise caused by the pounding of the surf on shorelines (2), human-engineered events such as mine blasts (3), collapses (4), rock bursts (5), and subsidence (6).

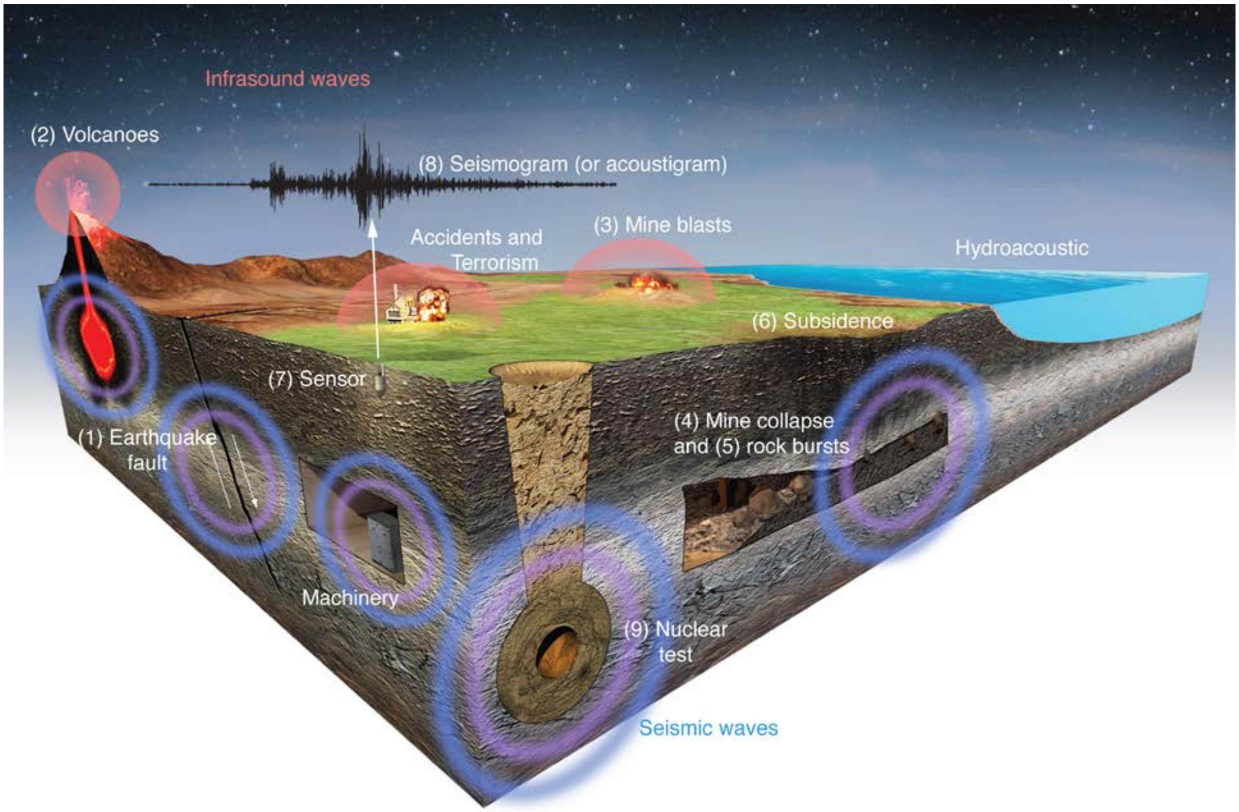

Figure 1. The physical environment near the Earth's surface that nuclear explosion monitoring must operate within is in constant motion at the microscopic scale from a variety of sources.

All these sources generate signals in the form of seismic waves, infrasonic waves (including acoustic waves along the surface of the Earth) and hydroacoustic waves that can be detected at large distances with today's ultra-sensitive sensors (7). Each individual event recorded at a particular station has a unique signature (8). Advanced signal analysis seeks to distinguish the signature of a nuclear test from this background noise and other non-nuclear events.

Since 1980, all declared nuclear tests (9) have been conducted underground, and seismic waves have become the principal means for prompt detection, location, identification of source type (e.g., earthquake, explosion, etc.) and yield estimation. Radionuclide monitoring is predominantly focused on capturing the noble gases that seep or vent from an underground triggering event or the particulates from an atmospheric explosion, and is the principal means in establishing whether or not an explosion is nuclear.

The GNDD Team seeks to deliver products to operational monitoring systems that improve nuclear explosion monitoring proficiency. Much of this improvement is expected to come from better understanding of the science behind the generation, propagation, recording, and interpretation of seismic, infrasound, hydroacoustic and radionuclide signals, while remaining open to "game-changer" R&D results.

A simplified operational monitoring schematic with four elements is illustrated in Figure 2. Starting from the left, an event occurs on or within the Earth (Source Physics), the signals from that source move away from the source (Signal Propagation), these signals are detected, measured and stored as data (Sensors), and those data are processed by the monitoring authority to generate a list of all sources of interest as well as other derived information (Signal Analysis). We have organized the GNDD Team into four corresponding requirements. They provide a framework capable of capturing the full scope of the GNDD processes, and can be thought of as a simplified amalgamation of nuclear explosion monitoring physical environments with a generalization of the operational systems.

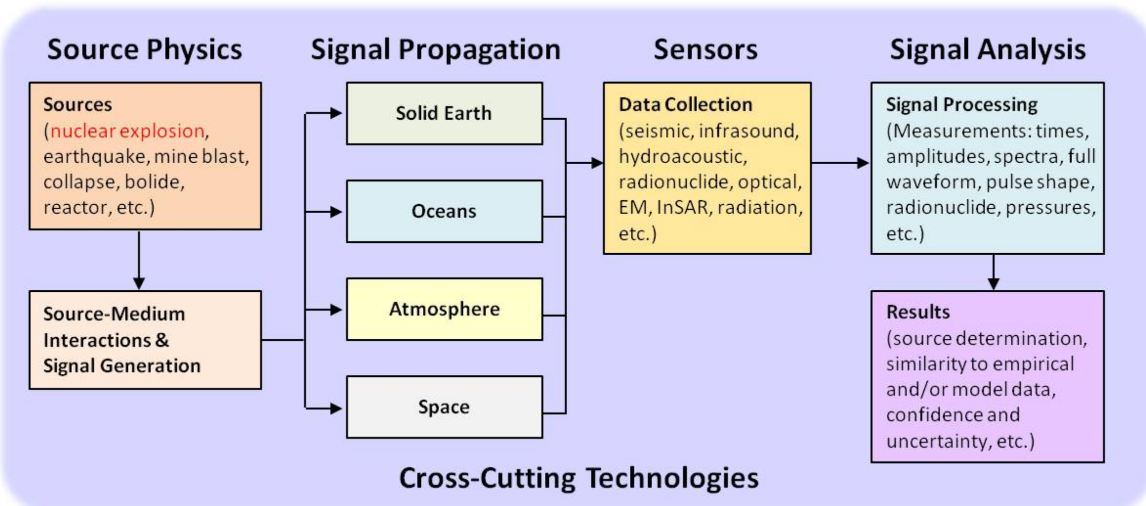

Figure 2. GNDD Team requirements were chosen as a full scope representation of GNDD processes and are shown in a context of operational data and process flow.

While this programmatic framework provides a useful way to view and understand GNDD, the very nature of R&D means that few GNDD Team projects fit neatly into one requirement nor are the paths from R&D to operational use simple. Most products take several years to develop and progress from an idea to operational assimilation. Interactions between the operational leaders and staff and GNDD researchers are frequent and significant in order to achieve a successful final product delivery. In addition to science-based drivers for the GNDD Team, there are overarching drivers than can affect the program and its direction:

1. Cost sharing (e.g., with other countries),
2. Cost savings (e.g., through automation, more efficient next-generation systems),
3. Policy to support monitoring capabilities of the U.S. and international organizations,
4. Policy to engage in international technical discussions/demonstrations,
5. CTBT ratification issues and/or challenges.

R&D THEMES BY OBJECTIVES AND ASSOCIATED REQUIREMENTS

Introduction

Each Requirement is accompanied by text that further describes and highlights R&D themes for each Waveform or Radionuclide objective.

These R&D themes and metrics and are intended to help guide the substance of the GNDD Team calls for proposals to National Laboratory, Small Business Innovation Research (SBIR) program Grants, and Broad Agency Announcements (BAA).

Objective A, Requirement a: Waveform Source Physics

There are many possible sources of seismic, infrasound and hydroacoustic signals, including earthquakes, industrial blasts, volcanoes, bolides and mine collapses. Source Physics seeks to better understand, model and separate these sources. Source Physics also includes the complex source interactions with the local source-medium (geology, structure, and tectonics as well as emplacement conditions), as this can greatly affect the signals before they propagate to the sensors.

The Waveform Source Physics requirement captures R&D activities that advance our understanding of nuclear and conventional explosions, earthquakes, mine collapses and other sources of waveform signals. The emphasis is on developing models that best simulate all of the pertinent physics of a nuclear detonation as it interacts with surrounding local environmental medium. These models need to be developed and validated (typically with field experiments) for new kinds of emplacement conditions that go beyond historic nuclear testing conditions to anticipate future ones. In tectonic regions, earthquakes can be the dominant form of observed seismic signals. In stable regions, mining and industrial explosions can be the dominant signals. Conventional explosions and earthquakes source models are important topics of research both to better identify them as not of monitoring concern and to make use of their signals (after removing the source) to map out propagation effects.

The major R&D themes for Source Physics have evolved as monitoring practices changed from relying primarily on “teleseismic” distances (>2000km) to include “regional” distances (<1500km). Teleseismic monitoring started in the 1960s and focused on narrower band explosion and earthquake signal models seen for larger events (magnitude ~>4) at great distances, such as the Ms-mb method of event identification. Starting in the 1990s, increased access to regional signals greatly increased the available bandwidth and allowed the development of completely new methods of identification that are effective for smaller explosions (magnitude ~< 4). The GNDD Team developed empirical regional discrimination in mid-to-late 1990s and then used a relatively simple earthquake source model to develop the one-dimensional Magnitude and Distance Amplitude Corrections (MDAC) in the early 2000s, extending regional identification methods to new areas without prior nuclear testing. The same simple earthquake source model allowed the development of seismic coda-based magnitudes, which are used to determine the size of earthquakes and the yield of nuclear tests very accurately with small numbers of detecting stations. Source physics research allowed the development of the event categorization matrix (ECM) in the early 2000s. ECM is a statistical method that allows regional and teleseismic identification measurements as well as different waveform types (e.g., seismic and hydroacoustic measurements) to be combined in a robust, rigorous manner.

The metrics for judging progress in Source Physics are directly related to how well GNDD Team can reproduce the observed source signals using models. For explosion, earthquake and collapse models, the predicted waveform signal is compared to observed empirical data and misfit is measured. This is done for multi-phenomenology (i.e., seismic, hydroacoustic and infrasound) spectral amplitudes and for seismic intermediate period full waveforms. Using ECM, a more sophisticated metric has been developed where the misfit is broken into two pieces, one related to errors in the measurement and one related to errors in the model. The second “model inadequacy” error is the part that can be improved through the development of more realistic (i.e., physical) models. Finally, the limitations of the source physics models impact the operational metrics of event identification and yield estimation.

Source Physics R&D themes are focused on the ultimate technical goal of providing a physical basis for predicting the waveform signals emitted by all source types (e.g., earthquakes, explosions, mining blasts, etc.) in a variety of geologic, tectonic and man-made emplacement settings. For explosions, the complexity of the source and the need for far more sophisticated models, especially for shear-wave (S-wave) generation, drives future R&D in: model synthesis, numerical simulations using realistic material- and physics-based models, and field experimentation, with underlying theoretical work supporting the overall development.

Model synthesis emphasizes analytical source models that build on past models and incorporate new information from other R&D. Improved source discrimination, yield estimation, and source-to-receiver waveform modeling capabilities at low yields and for broad areas are monitoring goals of the final synthesis product. An overarching metric for the synthesis is the ability to predict and match observed waveform signals for all distance ranges and across the entire frequency band.

Numerical simulations and field experimentation test and validate source parameter scaling laws, tie near-source phenomenology to waveform measurements, fill knowledge gaps, and test and validate the overall performance of the models. These efforts and related theoretical work provide a foundation for interpreting signals in the context of the source, its emplacement, and the signal generation processes of the surrounding source medium, including material damage, relaxation of pre-stress, material anisotropy, and wave propagation through heterogeneous media with irregular interfaces. Yield scaling and micro-to-macroscopic scaling of material behaviors relevant to wave generation are important aspects of theoretical work. R&D themes (and associated metrics) are selected to focus on the underlying principles of Waveform Source Physics (WSO).

Specific metrics and research questions necessary for improvement of waveform source physics are listed for each R&D theme:

WSO1. Identify new and more effective methods to identify sources of waveform signals (Metric: Improved identification of sources)

- *What are the fundamental physics that govern the generation and propagation of seismic waves from different types of seismic sources?*
    - What are the key elements of an explosion source model necessary to unify diverse seismic measurements such as mb, Ms, and Mw under a physical basis paradigm?
    - Can we resolve differences in the existing explosion predictive models (e.g., Mueller-Murphy, Denny-Johnson, etc.) and build a better representative elastic explosion model of explosion signatures for any realistic emplacement scenario?
- *Can a representative elastic source be used to simulate signals, or must a fully non-linear source be linked to an elastic code to generate the observables? What are the mathematical linkages between an explosion source model and:*
    - The event ID parameters to make event ID operational for new test sites with minimal or no calibration data?
    - The fracture network necessary to model radioactive gas diffusion/migration to surface (including error model)?
- *Can we develop advanced regional discriminants that are indicative of deep earthquakes?*
    - Deep earthquakes present a singular problem for regional discrimination, in that a teleseismic P from a deep earthquake can be confused with a regional P in some situations.
- *Can we improve our nuclear yield determination accuracy and precision for explosions?*
    - Can we improve our ability to determine the needed emplacement parameters from purely surface observables?
    - How do new insights into seismic wave generation by source medium damage aid in developing better magnitude-yield calibration information for new test sites?
- *How can we combine seismic and acoustic waveforms for improved source identification?*
- *Besides near-field ELF (extremely low frequency electromagnetic radiation), and RN (radionuclides), are there other potentially remotely measurable signatures to distinguish nuclear from chemical contained explosions?*

WSO2. Predict nuclear explosion seismic S-wave amplitudes near the source for all emplacements (Metric: Explosion models that better match observables)

- *What are the most important factors that enable explosions to generate shear ground motion? How do explosions generate S-waves as a function of frequency and emplacement?*
- *Why and how do some explosions generate reversed Rayleigh waves?*

WSO3. Tune earthquake waveform amplitude models to their tectonic setting (Metric: Improved earthquake models that better match observables)

- *What are the amplitude modeling consequences of treating all earthquake magnitudes the same?*
- *Are there geographic, depth dependent or other predictive ways to understand the variance of key earthquake parameters such as apparent stress variation?*
- *Can we better take advantage of the expected spatial and temporal distribution of earthquakes to improve monitoring?*

WSO4. Predict industrial explosion local and regional waveform amplitudes (Metric: New mine blast models that better match observables)

- *What are the key parameters that control the ground shaking from industrial explosions? Can we better define and recognize unique signatures (if any) from mine blasting in order to discriminate them from potential nuclear tests?*
- *What is the full range of signatures from mine-blasting globally and how is it evolving in time?*
- *Can we build a physics-based representative elastic predictive model of mine-blast signature for any expected environment?*

WSO5. Predict local and regional waveform signals from the collapse of underground cavities (Metric: New collapse models that better match observables)

- *What are the distinctive signatures of cavity collapses in relation to other seismic sources?*
- *How common are industrial created cavity collapses at smaller magnitudes? How common were cavity collapses at nuclear test sites outside of the NNSS and what are their characteristics?*
- *Can we build a physics-based predictive model of the observable signatures of any realistic mine or post shot cavity collapse?*

WSO6. Calculate energy partitioning for sources near earth-water-air interfaces (Metric: Improved models that better match observables)

- *What are the manifestations of material damage (both prompt and late time) on energy partitioning, wave propagation, and seismic discriminants such as mb-Ms and high frequency P/S ratios?*
  - Source medium damage due to shock waves interactions with the free surface and the effects of stress wave rebound are a source of P- and S-waves from buried explosions. What are the key source medium and emplacement parameters needed for predictions of discrimination performance at targeted sites of proliferation concern?
- *How do we leverage new analytical explosion source models and mature earthquake source models and link them to acoustic source models and the physical theory to model observations?*
  - As a seismic wave moves through the crust it displaces the ground surface, thereby creating a later-arriving acoustic wave through the atmosphere. As an acoustic wave moves across the surface it generates a seismic signal. We need to understand how to exploit the interaction between seismic/acoustic at near-field to regional distances.

A major challenge as work proceeds to develop better models of the nuclear explosion source is the limited historical data to validate them against. The GNDD Team expects to be able to make use of chemical explosion field tests for source model validation. Some dedicated explosion experiments have been conducted in the past, e.g., Nonproliferation Experiment (NPE) and Source Phenomenology Experiments (SPE-A) in Arizona, but field tests are expensive and are rarely funded. The GNDD Team routinely explores joining forces with other sponsors to gain multiple purposes for a single field experiment, e.g., the National Center for Nuclear Security (NCNS) Source Physics Experiment (SPE-N) in Nevada. Field explosions at new scale depths and in new geologies are going to be particularly important, as is tying the results to the computational modeling codes. There are also ongoing mining and industrial chemical explosions that can be sources of opportunity. Coupling non-linear shock codes to elastic codes and running them to frequencies up to 5 Hz or higher is computationally challenging. Continued access to high-performance computing resources is needed. Better ways to integrate and combine disparate measurements such as hydroacoustic, infrasound, and seismic in a well understood statistical framework such as ECM need to be developed.

Current work has focused on improving the nuclear explosion source model. Historical nuclear test data only exists for a limited range of depths, geologies and tectonic settings. To be able to confidently identify and estimate the yield of a new nuclear test in completely new emplacement conditions we must have accurate physics-based models.

Work is proceeding along several fronts: 1) the development of parametric explosion spectral models to incorporate S-waves; 2) the development of moment-based asymmetric explosion models to better understand the interaction of the explosion with the free surface; and

3) coupling non-linear shock physics codes developed at the labs for other purposes (containment, weapons physics) to elastic propagation codes.

In the future these different kinds of explosion source models will need to be combined and validated against new chemical explosions in the lab or field or through sophisticated computational modeling using high-performance computing resources. As the explosion models improve we will also look to improve our earthquake, mine blast and mine collapse models, and extend the results to seismic coda. In the longer term, we expect to be able to use new physics-based models.

Due to funding constraints, infrasound and hydroacoustic studies have had lower levels of effort. Current work has focused on producing a method to use infrasound signals to identify explosions and discriminate them from earthquakes. In addition there has been work on how to best combine seismic and infrasound measurements (seismoacoustic). Infrasound can be particularly helpful with very shallow surface explosions. Hydroacoustic methods of identifying explosions are already quite good. Future work will focus on building more physically-based models of hydroacoustic sources to allow them to be used with existing high-quality models of hydroacoustic signal propagation.

Objective A, Requirement b: Waveform Signal Propagation

Signal Propagation covers the critical factors that modify, in any way, the waveform signal timing, amplitude and frequency content between the source region and the sensor. Signals travel like sound waves through the solid earth, oceans, and the atmosphere. Waveform Signal Propagation R&D must deal with issues related to: (1) the solid earth, such as seismic waves traveling through material of different velocity, density and attenuation; (2) the atmosphere, such as infrasound waves traveling through air with highly-variable densities and wind speeds; and (3) ocean transport, such as hydroacoustic waves traveling through water of different temperatures and depths.

Many factors control the timing, amplitude and frequency content of propagating waveform signals. The dominant factor is the heterogeneity of the Earth’s crustal velocity and attenuation. In real application, other factors arise and must be considered, such as, processor and algorithm optimization. For seismic waveforms, specific factors include improved understanding of the subsurface density, wave velocities and associated attenuation. For infrasound, specific factors include understanding the velocity profile and dynamics of the atmosphere, which is in constant motion and has daily and seasonal variations. For hydroacoustic, specific factors include improved understanding of the velocity profile of the oceans, which undergoes seasonal variations, as well as the bathymetry. The major goal of Waveform Signal Propagation is improved waveform signal prediction, which impacts event detection, location, identification and magnitude/yield estimation.

The metrics for judging progress in Waveform Signal Propagation are directly related to how well the GNDD Team can use the models to predict the key signal attributes, such as travel time and amplitude. For full waveform techniques the predicted waveform signal is compared to observed empirical datasets and misfit is measured. This is done for seismic, hydroacoustic and infrasound spectral amplitudes and for seismic intermediate-period full waveforms. Using statistics, a more sophisticated metric is to break the misfit into two pieces, one related to errors in the measurement and one related to errors in the model. The second "model inadequacy" error is the part that can be improved through the development of more realistic models (geophysically-based). Finally, the limitations of the earth models do impact the operational metrics of event location.

The purpose of Waveform Signal Propagation (WSP) R&D is to improve waveform signal prediction and thereby impact event detection, location, and identification as well as magnitude/yield estimation.

Specific metrics and research questions necessary for improvement of waveform signal propagation are listed for each R&D theme:

WSP1. Improve travel time predictions (Metric: Improved travel time and dispersion predictions that better match observables)

- *Can we develop reliable methods to automatically and reliably assess quality for individual data within catalogs?*
    - Developing broad regional or global models implies the use of very large data sets, hence utilizing catalog information. Catalog quality is uneven and individual data often lack quality assessment.
- *Can multi-parameter tomography address crustal heterogeneities and areas of limited data coverage, and improve travel time and short-period dispersion predictions?*
    - Even the most complete data sets lack adequate coverage for some areas of interest: will joint inversion with other data sets provide high-quality travel time and dispersion predictions for those areas? We know joint inversion produces intriguing images of the Earth's interior, but does it help improve predictions and hence event locations?
- *Can we develop appropriate path-specific uncertainty estimates for travel times calculated through 3D earth models?*
    - 3D tomographic models have tremendous geographic variation in both variance and covariance reflecting data resolution and data coverage.
- *How can we develop combined probability models for infrasonic phase identification as a function of distance, azimuth, and time?*
    - Infrasonic wave paths are a stochastic process that is indexed by time (e.g., season, month, diurnal) and meteorological parameters.

WSP2. Improve amplitude modeling (Metric: Improved amplitude predictions that better match observables)

- *How can we develop advanced, region-specific, near-field to regional spreading and attenuation models and their associated calibration strategies and error models?*
- *How can we develop advanced surface-wave attenuation models accounting for elastic effects, and using cutting-edge technologies and multiple datasets including ambient noise?*
- *How can we properly account for topography, turbulence, and gravity waves in the prediction of infrasound amplitudes?*

WSP3. Predict travel-time, amplitude and full waveform signals from these models (Metric: Improved synthetic waveforms that better match observables)

- *What are the most accurate and efficient methods of waveform simulation? What are the best methods of waveform simulation for different distance ranges?*

- For example, finite difference may be best for distances out to 100-200 km, but spectral element methods may be best for global computations.

- *What computational resources are required to simulate signals at various distance ranges and frequencies?*
  - How do we take advantage of high performance computing information technology initiatives for earth, atmosphere and ocean model development?
- *To what high-frequency limit can synthetic waveforms ultimately match the data?*
  - What are the limitations? Is it computational capability or earth structure information or both?
- *How can we properly account for topography, turbulence, and gravity waves in the prediction of infrasound waveforms?*
- *Does synthetic waveform modeling have a role in pipeline processing and routine analyst review, or will it be limited to detailed analysis of a few selected events?*

Three-dimensional (3D) seismic velocity and attenuation earth models and associated algorithms for location and identification are active program research areas and the research prize is a set of research products that have been designed for operational usefulness. Demonstrating 3D operational improvement over existing operational models will be an R&D challenge.

As with Source Physics, the focus of Signal Propagation R&D has evolved as monitoring moved from stations primarily at large distances ("teleseismic" or >2000km) to include regional distances (<1500km). At short distances the signals travel through the most complex and heterogeneous part of the Earth – the crust and uppermost mantle. For travel time predictions, signals traveling through heterogeneous paths can lead to larger errors for shorter distances providing the counter-intuitive result that adding a few close distance stations can actually make the seismic location accuracy worse. In the late 1990s to the early 2000s this problem was addressed through the development of criteria to determine the event location accuracy ("ground truth" criteria) and the development of geo-statistical techniques ("Bayesian Kriging') to allow the well located events to be used to make corrections surfaces for the current models. A shortcoming of this technique is that good ground truth events are not available for all areas. In the mid 2000s focus turned toward the development of good 2.5D earth models (Regional Seismic Travel Time [RSTT]) using the regional seismic signals, allowing better location anywhere in the model. Current research on travel time prediction is now focused on developing 3D earth models that would allow seamless mixing of regional and teleseismic distance measurements. This work includes travel time prediction and tomography, as well as, azimuth and slowness amplitude R&D.

As with travel time, regional amplitude predictions from models are also highly variable due to the heterogeneity of the shallow part of the Earth. In the most extreme cases, attenuation can eliminate the ability to see a particular seismic signal. The relative lack of S-wave signal can be used as a means of identifying an explosion if that lack is a source effect. However, if the path removes the S-waves and one does not realize this, it could lead to mis-categorizing an earthquake as explosion-like. In the mid 1990s to the mid 2000s the emphasis for event identification was on small regions where 1D or low-resolution 2D models were adequate using the MDAC methodology. Current research includes development of better resolution regional 2D Q (inverse of attenuation) models that incorporate all the regional phases in areas of interest. Future work may extend the 2D models to 2.5D. Attenuation models are also very critical for yield estimation. It is essential that any attenuation models developed include uncertainty information, because errors in the models map directly into errors of magnitude and yield.

Finally, the ultimate goal of Signal Propagation R&D would be to combine travel time and attenuation information to predict full waveforms from models. Currently about 15s period [and longer] full waveforms for regional scale models are the state of the art for waveform simulation. The goal is to reduce the 15 seconds to 10 in the near future and eventually to 5 seconds. For small local regions it is possible to calculate full waveforms up to 8 Hz, and this is being done for studies looking at effects such as topographic scattering. An important caveat to full waveform calculation is that the predicted signals are only as good as the model from which they are determined.

Research is needed for model validation – how good is a 3D model at representing the true physics of the Earth? What are some of the limiting factors to producing this model and how many data are needed for a model to be considered "good enough"? Significant work is needed to develop global 3D models that accurately predict waveforms. Typically such work requires collecting millions of measurements, culling the data and combining multiple types of measures together (i.e., multi-parameter) in ways that make statistical sense. Such work usually requires large databases, some high performance computing, and a reasonable amount of time.

Lastly, ground-truth data collection, validation, error analysis and model calibration will continue to evolve and change, reflecting new method development and model fine-tuning. Can we uniquely identify and quantify sources of error for large-scale 3D models? Will we be able to make 3D earth models accurate enough that the use of empirical correction surfaces is unnecessary? By developing a single model for the Earth, can information on all scales (local, regional, teleseismic) be captured?

Objective A, Requirement c: Waveform Sensors

Sensors come into play at the operational stage after signal propagation. Sensors collect the continuous data (waveforms) that will be processed to detect, locate, and identify events of monitoring interest. Sensor systems take into account seismic, hydroacoustic and infrasonic signals and vary based on deployment strategies, the sensors themselves, data acquisition equipment (often including high-resolution digitizers), and the processes to archive those data acquired along with their metadata (i.e., database activities).

Though developing more sensitive instruments is generally desirable, it is not always the highest priority. For example, explosion monitoring seismic sensors that go below the standard physical noise level (background vibrations) in the Earth have been widely available since the 1970s. However, these instruments are large, fragile, and expensive. Thus for seismometers, developing smaller, cheaper, lower power and more robust instruments are relevant goals. New types of sensors (e.g., rotational gradiometers) may also be of use to the program.

Some opportunities for improvement may come from leveraging other work: there is a rapidly growing number of sensors in the world deployed for purposes other than nuclear explosion monitoring. How do we best take advantage of these alternative sensors? Should we?

As outlined above, the Sensors program element encompasses all aspects (hardware and software) associated with recording waveform data, including testing, evaluation, and building metadata. For waveform technologies, seismometers, hydroacoustic, and infrasound instruments are in the Sensors requirement arena.

Current waveform sensor R&D is focused on regional and local environments, the areas where data collection must occur to record the small events that have increasingly become the focus of explosion monitoring. The existing installed regional sensor systems, especially seismometers, have outstanding response characteristics and consequently are not the focus of this program element. Local seismic monitoring will require a new breed of small sensors able to operate in the short period (SP) regime.

For local monitoring, in-situ signal processing is of interest because the data acquisition systems will not necessarily be able to transmit continuously and might have very constrained power supplies. Robust sensor packaging is also an important consideration, especially if the devices need to persist in challenging deployment conditions/environments. Sensitive instrumentation is needed to detect extremely small (< nanometer displacements) signals and the Sensors program element is focused on improving sensitivity, signal-to-noise ratio, frequency bandwidth and operational and implementation issues of new sensors. R&D subthemes include micro-seismometers, micro-acoustic sensors and seismo-acoustic integration. Sensor emplacement planning tools are necessary for doing feasibility analyses as well as optimal sensor placement studies. If the systems will communicate with each other, as is proposed by some researchers, then planning tools are an important consideration. Finally, whatever the scale of monitoring (global, regional or local), sensor testing and evaluation will continue to be necessary to maintain consistency and quality control, especially for aging sensor systems.

There is a well-established suite of metrics used to measure progress in sensor technology: sensor noise, sensor dynamic range, etc. (see Figure 3). In addition, cost of production as well as of deployment and expected maintenance costs are assessed. Table 3 lists the weak motion accelerometer requirements for micro-electro-mechanical systems (MEMS). Currently, no suitably small devices meet these requirements.

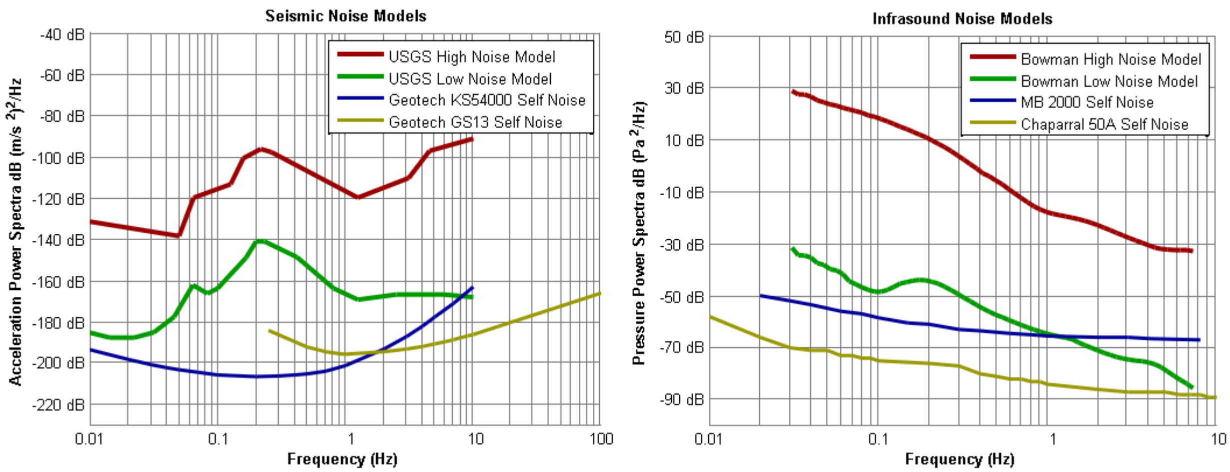

Figure 3. Seismic (left) and infrasound (right) noise models. Research and development directions are bounded by sensor noise constraints. High Noise (red) and Low Noise (green) models are shown along with noise models for some well-known seismic and infrasound instruments (blue and gold).

Table 3. MEMS weak motion accelerometers requirements

Parameter	Requirement
Noise	< 1 ng/√Hz
Bandwidth	SP: 0.1 Hz to 10's Hz LP: < 0.01 Hz to 1's Hz BB: 0.01 Hz to 10's Hz
Peak Acceleration	< 0.25 g
Dynamic Range	>120 dB

A particularly vexing challenge is overcoming the long-period noise (known commonly as "1/f noise") restriction for any small reference mass. Deploying local networks has several troublesome issues: optimal spatial distribution, inter-sensor and station communications, on-board processing, and, of course, long-term power, and weight and size constraints. Therefore, Waveform Sensor (WSE) R&D themes (and associated metrics) include development, network configuration analyses, and testing facility support.

Improved performance, reduced power consumption, size, and costs have shaped the Sensors R&D program for several years. Regional sensor applications have not provided as much of a challenge to existing capabilities as local applications. Local applications have strained the materials, signal to noise ratio and power consumption requirements to the point where the constraints of physics have come in to play. Thus, fundamentally different approaches to sensor technologies are well-justified.

Specific metrics and research questions necessary for improvement of sensors are listed for each R&D theme:

WSE1. Build new short-period (SP) micro seismometers and micro acoustic sensors (Metric: Design and build low power (<100 mW) micro-seismometers with internal noise levels below the reference low noise models (USGS model for seismic, Bowman model for infrasound) in the frequency range of approximately 0.2 to 40 Hz and high dynamic range (> 110 dB))

- *How do we lower cost, reduce size and decrease power requirements while maintaining the ability to see the broadband signals of interest?*
  - How do we best take advantage of emerging commercial technology?
  - What are the fundamental physical limitations that constrain performance of a micro sensor?
- *Are the low noise models the best standard/guide for development, i.e., are sensors still useful even if they don't have sensitivity below the low noise models?*

WSE2. Prototype local monitoring sensor system (Metric: Demonstrate local monitoring system performance)

- *What are the detection, location, and discrimination capability metrics for a prototype monitoring sensor system?*

WSE3. Develop sensor network deployment software (Metric: Demonstrate capability to accurately model local network performance prior to deployment)

- *Can we develop local-scale models with sufficient accuracy to predict observables used for monitoring (travel time, azimuth, slowness, amplitude)?*

WSE4. Maintain a sensor testing and evaluation facility (Metric: Provide testing and evaluation for data acquisition systems for waveform technologies)

- *What are the effects of aging on monitoring hardware components and sensors? Does this have an impact on station calibration?*
- *What, if any, role do digital sensors have for future monitoring system upgrades?*
  - What methodologies do we use to test digital sensors? (currently used methods were developed for analog sensors)
- *Is there a better design for infrasound wind noise cancellation? Of particular concern is cancelling noise without significantly attenuating signal.*

Objective A, Requirement d: Waveform Signal Analysis

Signals created by sources, propagated through the solid earth, oceans, or atmosphere, and recorded by the sensors must be processed to form hypotheses of possible nuclear events. We refer to this final processing step as Signal Analysis. First, data from each sensor are processed separately to find signals of interest, then the set of signals from the full network are associated to generate hypothetical events (times and locations) that can account for the signals. Next, magnitudes (sizes or yields) of the events are estimated, along with likely source type (e.g., earthquake or explosion). All of this is done automatically, but due to the complexity of the problem and the relative scarcity of data, particularly for smaller events, the automatic results must be carefully reviewed by an analyst and any errors/omissions must be corrected before further action will be taken on any events of interest for nuclear explosion monitoring.

As more continuously-recorded waveform data become accessible, we must rely more heavily on automated processing. To do this effectively, we must address several key questions. How do we make fuller use of the entire signal from an event of concern (e.g., How do we take advantage of the parts of the signal we are not currently using)? With the increased data availability, can we take advantage of advancing information technology resources (e.g., high-performance computing), including investigating techniques employed by oil exploration and other industries? Are there better ways to process multiple events and/or sensors (e.g., arrays and networks) simultaneously to improve monitoring?

Because Signal Analysis covers such a broad range of topics, we choose to divide R&D into two categories: Signal Processing and Results. Signal Processing is concerned with manipulating the data to enhance and find signals of interest, while the Results portion covers the higher-level processes used to generate source hypotheses (location, size, event type). For these types of processes, the refined measurements are compared to values from synthetic signals calculated using a model of the Earth, and uncertainties of source parameters are estimated.

The Signal Analysis program requirement is meant to include all signal processing techniques that are applied to data to detect and categorize events of interest for nuclear explosion monitoring. This is a very rich set of techniques spanning signal enhancement (filtering, beaming, rotation, principal component analysis, waveform correlation, etc.), signal detection, parameter measurement, signal association, event location, magnitude/yield determination, and event identification. The desired product is a high-quality, comprehensive list of well-described possible nuclear events. Because direct evidence is seldom available, a further challenge is to provide rigorous uncertainty estimates for each event parameter. Also, because earthquakes are so much more common than explosions and thus dominate the typical set of signals on any given day, a large proportion of signal analysis work focuses on identifying and screening the signals from earthquakes.

The metrics for judging progress in Signal Analysis are directly related to how well the GNDD Team can detect and describe events based on the recorded signals. What is the detection threshold (magnitude/yield units)? How accurately can we locate events (km)? What is the probability of identifying the type of a source correctly (percentage)? How accurately can we determine the size of an event (magnitude/yield units)? Typically these capabilities are estimated by processing data from well-described events where the true quantities are known independently. As exact determination of the event parameters is not possible, proper understanding of their uncertainties is essential: how likely is it that an event occurred? How precise are our estimates of the location, type, and size? Further, as with Source Physics and Signal Propagation, this uncertainty can be broken into two components: one related to errors in the measurement and one related to errors in the model. The first type of error can be directly improved by better parameter estimation methodologies. The second “model inadequacy” error is the part that can be improved through the development of more realistic Source Physics and Signal Propagation models.

Specific research questions necessary for improvement of signal analysis are listed for each R&D theme:

WSA1. Improve the robustness and accuracy of parameter estimation
(Metric: Demonstrate improved parameter and uncertainty estimates)

- *Can we better analyze and thus remove background noise (e.g., seismic, acoustic, hydro) to improve processing?*

- *Can we develop significantly improved signal detection algorithms?*
- *How can we optimally design infrasound arrays to enhance direction of arrival and detection performance?*

WSA2. Develop new waveform parameters (Metric: Demonstrate improved monitoring capability due to new waveform parameters)

- *Can we create better templates to more fully utilize the full time-bandwidth nature of event signatures to improve analysis and processing of event signatures?*
    - For example, what is optimal in the range of possibilities between matching full ground motion seismograms versus the broader applicability of simplified (derived) motion (e.g., spectrograms)?

WSA3. Improve parameter-based methods for monitoring (Metric: Improved detection, location, and/or identification)

- *Can we improve our methods to quantify how well parameter-based monitoring methods work?*
    - Implies developing metrics and tools to calculate those metrics.
- *Can new approaches be developed for event detection that lower detection thresholds and lower false alarm rates?*
- *Can we improve location estimation by combining seismic and infrasound at local, regional, and global distances?*

WSA4. Improve waveform-based methods for monitoring (Metric: Improved detection, location, and/or identification)

- *What are the optimal parameters for empirical waveform correlation (e.g., distance to event, time window, frequency bandwidth)?*
- *Can empirical waveform correlation be modified to be more tolerant to changes in source parameters (e.g., separation in epicenter, depth difference, mechanism difference, size difference, etc.)*
- *Can empirical waveform correlation be applied on a broad regional or even global scale?*
    - What fraction of events can we expect to correlate?
    - What are the computational challenges and can they be met with available resources?
- *How fully can we realize the potential of waveform correlation using physics-based synthetically generated signals as templates?*
    - What are the highest frequencies we can expect to match in observations?
    - Can we develop realistic enough Earth models to generate waveforms with sufficient fidelity?
    - Can computational demands be met?

A general challenge for all Signal Analysis methodologies is robust estimation of uncertainties associated with signal or source parameter estimation. Because Signal Analysis is accomplished with mathematical algorithms that produce discrete numbers (e.g., event locations and sizes), there is a tendency to assume that these numbers are perfectly determined. In fact, they are only estimates and should not be interpreted without a robust estimate of their uncertainties.

The primary focus of Waveform Signal Analysis has traditionally been on the extraction of a small set of parameters from the waveform data, and the use of these parameters to locate and describe events of interest. Typical parameters of interest include arrival time, amplitude, azimuth, slowness (equivalent to angle of incidence), and dominant frequency. Once these parameters have been measured, all subsequent analysis is then done using the parameters, not the original waveforms. Thus, it is the availability and accuracy of these measurements that determines the completeness and quality of the resulting list of events. Because monitoring pipelines are still primarily parameter-based, much R&D, both within the GNDD Team and external, continues to focus on improving parameter extraction and exploitation. This includes better methods to measure established parameters, identification of new parameters, and improved algorithms to use parameters to detect, locate, and describe events. For all of these, robust estimation of uncertainty is extremely important.

Ultimately, the parameter-based approach to Waveform Signal Analysis is limited because it reduces the richness of the overall waveform into a relatively small set of quantities. In reality, the waveform from a nuclear event encompasses a continuum of frequencies with different amplitudes and phases, and the more of this information that can be used, the more accurate the derived event hypothesis. The obvious way to enhance the existing approach is to expand the set of parameters used to capture more of the overall information, and much R&D has been and will continue to be focused on this. However, it is recognized that at some point this approach becomes cumbersome and overly complex. A more straightforward approach is to use the entire waveform (or large portions of it) to *directly* to constrain the hypothesized event. This approach is known as waveform-based analysis, and is the focus of a growing body of research. Because so much more information is used, waveform-based techniques have the potential to dramatically improve detection, location, and event identification, often achieving results using one or two stations that are comparable to processing data from a large network of stations. Waveform-based analysis is particularly attractive for smaller events for which very few recordings may be available.

Waveform-based analysis can be sub-divided into empirical approaches and synthetic approaches. Empirical approaches compare incoming waveforms to waveforms previously recorded for well-described events. This is an incredibly effective technique because the waveform from a known previous event recorded at the same station correctly encompasses all of the factors affecting how the signal looks at that station: Source Physics, Source Propagation, and Sensors. These factors are all correctly accounted for, without necessarily understanding in detail exactly how to model them. In fact, no modeling is needed: if nothing has changed since the previous recording all that is needed is to compare the incoming data against the previous signal.

For empirical waveform-based analysis, the primary challenge is the collection of comprehensive sets of waveforms spanning as many source locations, source types, and receiver locations as possible. If empirical waveform-based analysis is to be used for the data from a given station, one must somehow acquire waveforms for that station that span all the event scenarios of interest. Thus, empirical waveform-based analysis works best for stations with a fairly long history of recording and for monitoring areas that routinely have events that are recorded at those stations. Research focuses on how to extrapolate/interpolate existing waveforms to fill in gaps in source location, source type, or recording station locations. Also, empirical waveform correlation analysis is computationally expensive, so applying the technique routinely on a broad scale presents significant computational challenges, hence this is another area of active research.

The shortcoming of the empirical approach, and the reason that something more is needed, is that this approach can *only* be used when a previous, similar event has been recorded. This means we must have for comparison waveforms recorded from the same type of event occurring in the same area and recorded by the same station. Any violation of those assumptions will be problematic, often to the point where waveform-based techniques will perform poorly or even fail entirely. (By comparison, parameter-based approaches are much less sensitive to differences in these factors…. a key reason why they remain so popular.) Thus, for a new type of test and/or a new testing site and/or a new recording station, the empirical waveform analysis technique will not work. This motivates the much more challenging R&D of synthetic waveform matching.

Synthetic waveform modeling requires the mathematical calculation of the expected ground displacement at a given remotely sited sensor from a hypothetical source. In addition to the computational requirements of the calculation itself, which can be very costly for signal frequencies and durations of interest, this requires very good knowledge of all of the key factors that determine what a recorded waveform will look like: Source Physics, Signal Propagation, and Sensors. This is a formidable challenge, but the potential benefit is tremendous. In theory, at least, synthetic waveform-based signal analysis can be used for any type of event anywhere, which is exactly what is needed for monitoring new testers, new types of tests, and/or new test sites. The success of synthetic waveform modeling is directly dependent on progress in Source Physics and on Signal Propagation. Our current understanding of these areas is sufficient to use synthetic waveform modeling to answer general questions about an event (e.g., how deep might it have been? Could observed waveform complexity be related to local topography?), but more specific questions will require better understanding of how the signals are generated and propagated.

Very impressive synthetic waveform-based analysis techniques are being used in some areas of the world where there is excellent information available about these factors (e.g., for predicting ground motion for earthquakes in the San Francisco Bay area), but whether similar results can be realized for areas of monitoring interest is not yet clear. Matching “wiggle for wiggle” the observed waveforms at frequencies high enough to usefully constrain source parameters (location including depth, type) is currently a challenge even at the most well-described areas. Achieving this at areas where our information about signal generation and propagation is limited will be a tremendous challenge.

Multidisciplinary Questions

The GNDD Team plays a central role in developing and incorporating regional methods of detection, location and identification that have resulted in significant monitoring improvements. Functional operational monitoring metrics draw on advances from all four waveform requirements. Although this four-stage framework provides a very useful way to categorize projects within the GNDD Team, many multidisciplinary science questions remain to be addressed.

Specific multidisciplinary research questions include:

- *How do we shift from a purely empirical understanding of monitoring phenomenology to a physics-based one in order to confidently monitor regions without previous signatures of the kind we are looking for?*
- *How do we best combine multiple phenomenologies (e.g., seismic, hydroacoustic, acoustic, electromagnetic, radionuclide, remote sensing, etc.) when available, to improve monitoring?*

- *What key experiments (physical and/or numerical) are needed to generate data to build, test, and validate the physics-based monitoring models or to test empirical models for scenarios of concern?*
- *Do regional distance seismic monitoring algorithms (e.g., P/S discrimination, coda yield estimation, 3D velocity models) work as well at local distances, allowing thresholds to be lowered? If not, why not? Can we discover new local and near-regional distance algorithms using the broader bandwidths potentially available at closer distances?*
- *How do we best take advantage of the rapidly evolving information technology advances, both the R&D and in the NDC and IDC redesigns? (e.g., high performance computing, data mining, data intensive computing, and modular design).*

Objective B, Requirement a: Radionuclide Source Physics

While a seismic signal begins as a release of energy within the environment, a radionuclide event is the release of radioactive atoms. Radionuclide sources include nuclear explosions, normal or anomalous reactor operations, and releases from other nuclear industry, particularly medical isotope production. These overlay on natural radioactivity such as primordial isotopes (e.g., potassium, uranium, and thorium and their decay products) and isotopes produced from the interactions of cosmic rays with the atmosphere (e.g., ^{7}Be and ^{24}Na).

These sources interact, sometimes heavily, with the medium in which they are created or released, analogous to seismic energy. Most of these sources produce extremely hot atoms that are chemically reactive with rock, soil and atmospheric dust, which governs their release from underground or underwater, and also determines how far downwind they can travel before they fall out of the atmosphere. Noble gases, of course, do not react, which makes them and their isotopic ratios useful as tell-tale indicators of underground tests. Nuclear properties like half life are important, too, and interplay with chemistry to determine, in each particular underground case, the time of the separation of parent and daughter nuclides, like iodine and xenon, whether from an underground test or in a medical isotope facility hot cell. Local barometric pressure variation may pump radioactive gases from the source location for months after the pressure of the explosion has subsided.

The Radionuclide Source Physics requirement must capture the evolution of radionuclide signatures from production through release into the sampled media (atmosphere, ocean, soil gas, ground water, etc.). Even in the "simple" case of a nuclear detonation in the atmosphere, the evolution of the radionuclide source is not expected to be a uniform process; geometric fractionation effects are likely to occur during the detonation itself. Effects that impact the downwind distribution of radionuclides become more severe for surface or low altitude bursts due to interaction of the fireball with the surface of the Earth. Sub-surface explosions represent the most challenging case for interpreting radionuclide data from samples collected remotely. In this case, release mechanisms involve escape from the blast cavity and transport through micro-fissures, fissures, and fault lines to the Earth's surface. This process entails chemistries that depend on both the element being transported and the subsurface geochemistry. Understanding the release is complicated by radioactive decay processes, which allow signatures of interest to transition from very reactive species to very non-reactive species during the subsurface transport process (e.g., iodine → xenon). To further complicate matters, atmospheric properties also affect the release of subsurface radionuclides into the atmosphere through mechanisms like barometric pumping.

Starting in the mid-1990s, real environmental observation of xenon (Xe) in the atmosphere began, and transient sources were readily observed in the Northern Hemisphere, taken to be reactor emissions. The first publication of ^{135}Xe in the atmosphere was done by the GNDD Team: low-level reactor emissions in the vicinity of Manhattan. Ratios of the isotopes observed in Manhattan, and later as part of the International Noble Gas Experiment (INGE), pointed to a useful ratio scheme to differentiate reactor operations from explosion signatures. INGE was intended to speed development and acceptability of noble gas sensor science, but has also come to be a catalyst in seeking scientific understanding of noble gas radioisotopic backgrounds. Atmospheric backtracking of INGE signals led to the understanding of the magnitude of medical isotope releases: one such facility in Canada emits more radioxenon than all the reactors in the world combined, by a factor of ten. The emergence of medical isotope backgrounds has been the second major scientific revolution in xenon observation science.

The production of radionuclides during a nuclear detonation is well understood, however significant research opportunities exist to improve our understanding of the modifications that occur shortly after the event, or prior to material release into a long range transport medium. These opportunities include sub-surface tracer studies, background studies, and background mitigation efforts (e.g., efforts to reduce emissions from medical radioisotope studies have a direct beneficial impact on nuclear explosion monitoring sensitivities).

Over and above natural radioactivity, radionuclide sources include nuclear explosions, normal or anomalous reactor operations, and releases from other nuclear industry, particularly medical isotope production.

Radionuclide Source Physics (RSO) R&D themes (and associated metrics and science questions) include:

RSO1. Determine the risk of innocuous background false alarms (Metric: Calculate risk)

- *What is the isotopic makeup, amounts, and environmental fate and transport of manmade radionuclides in the environment and how do these isotopes interfere with measurements of radionuclides of interest for nuclear explosion detection?*

RSO2. Improve knowledge of subsurface gas transport (Metric: Reduce the number of samples by an order of magnitude)

- *What is the time, concentration and isotopic dependence of fission and activation product gases reaching the surface and subsurface following a nuclear detonation under various geologic emplacement and atmospheric conditions?*

RSO3. Determine the amount of radionuclides produced in various nuclear testing conditions (Metric: Improve input to geologic and atmospheric transport models)

- *What are the abundances of activation (i.e.,* ^{37}Ar*) and fission product gases that are produced in various testing scenarios, what is the behavior of these gases in the subsurface, and what mechanisms can be used to collect and measure these isotopes?*

To better understand worldwide radioxenon backgrounds, both atmospheric and subsurface, and how they can interfere with the current set of International Monitoring System (IMS) sensors, significant scientific improvements of the radioxenon sensor hardware is needed. These improvements are driven be the lessons learned from INGE and related measurements of worldwide radioxenon backgrounds. The INGE lessons learned have unveiled radioxenon background sources that were not anticipated when the systems were initially designed. Research to develop improved sensors that will deliver more Xe for less energy will push the cutting edge in chemical separation science. Also, advances in the precision of physical measurements like pressure and gas composition are needed, far below the standard of today's IMS capability. A robust quality assurance (QA) method (traceable calibration) is also needed to get matching gains in accuracy.

Objective B, Requirement b: Radionuclide Signal Propagation

While radionuclides can move in subterranean water, the dominant source propagation for radioactive atoms in the treaty monitoring context is atmospheric transport. Atmospheric Transport Modeling (ATM) is central to weather prediction and therefore has large national and international academic research support. The excellent state of ATM, the existing R&D support by other agencies like NOAA and NASA and the highly capable operational CTBT ATM capability are reasons that the GNDD Team is a user of ATM rather than a supplier. Understanding signal propagation is a necessary input to signal analysis.

Signal Propagation R&D for radionuclides is not part of the GNDD Team, but advances at the CTBTO and elsewhere are still part of the drivers for GNDD research and require thoughtful coordination. The earliest concepts of radionuclide signal propagation included calculating a Field of Regard (FOR) for each station for each day. In addition, rather than a yes/no decision for each pixel in a world map, the recent successor of the FOR is the Source-Receptor Strength field (SRS) which shows the absolute strength of connection of any point on the map with the sensor point. This allows two or more SRS fields to be compared or merged, and enables advanced network calculations and multiple-technology fusion.

The input data, worldwide meteorological measurements of wind speed and direction at a variety of altitudes, is obtained from the World Meteorological Organization (WMO), and WMO centers have an agreement to provide support services to the CTBTO for inter-comparison and improved science. Worldwide models have undergone improvement due to these CTBTO-organized tests.

Driven by background source knowledge from INGE and the upcoming local scale predictions needed for On-Site Inspection (OSI), finer mesh calculations are being introduced. The WMO input data can be obtained in successively finer interpolations of actual measurement data.

The maximum useful WMO resolution is 3 hours in frequency and 0.25 degrees in spatial separation. It is anticipated that the CTBTO calculation output will be refined in a stepwise way, always increasing the calculation and storage requirements. These refinements help to shrink the SRS for any given station (precision) and make it more accurate. In light of the current situation described above, only one overall theme (and associated metric and science questions) for Radionuclide Signal Propagation was proper:

RSP1. Fine tune atmospheric modeling by bettering local sources (Metric: Reduce uncertainty in the deduced release point for radionuclides)

- *What are the expected atmospheric concentrations of isotopes emitted from nuclear explosions as a function of collection method, collection height, atmospheric stability, and transport to the surface?*

If a station integrates the radioxenon sample over 24 hours of air, finer resolutions models are useless. It will be impossible to tell when the sample hit the station with longer sample integration. The potential ability to discriminate close vs. far sources (plume duration) and improved precision and accuracy of a backtrack calculation are drivers for the Sensor program element where sampling frequency can be addressed and could affect particulate as well as noble gas sensors. Even if the GNDD Team does not directly fund improvements to meteorological models, researchers must remain cognizant of how operational agencies use them and be alert to necessary changes to sensors and signal analysis to better interface with plume tracking.

Objective B, Requirement c: Radionuclide Sensors

Similar to the waveform sensors requirement, radionuclide sensors are complete sampler/analyzers rather than simply transducers. The systems definitions encompass automatic collection of particulate material or gases, chemical processing if required, then measurements of temperatures, pressures and radioactive decay. Research funded by this program has broken scientific barriers in field and laboratory sensitivity, created whole new areas of scientific measurements of the environment, and then driven accuracy and precision to finer and finer levels.

Sensors, defined broadly here to include a sampler/analyzer system complete with radiometric measurement, are an important focus of the radionuclide part of GNDD. Science breakthroughs in Sensors have enabled science breakthroughs in Signal Processing, and Source Physics as well. In a sense, these advances (and Signal Propagation advances at the CTBTO and elsewhere) are now driving the next generation of science in sensors.

Key metrics in the past have been the existence of automated capabilities, sensitivity, accuracy and precision. These will continue to be important metrics, but ruggedness/uptime, power and complexity per cubic centimeter of Xe separations, processing speed and sample throughput will grow in importance as the OSI challenge and INGE results mount.

Radionuclide Sensors (RSE) R&D themes (and associated metrics and science questions) include:

RSE1. More sensitivity (Metric: Increase sensitivity to aerosols and short-lived xenons by an order of magnitude)

- *Taking into consideration basic physics and chemistry, background sources, and expected stability of measurements performed in a field setting, what is the highest sensitivity detection that is possible and is useful for detection nuclear of explosions using radionuclides?*

RSE2. More xenon for less energy, less liquid nitrogen, in less size, or with less adsorbent material (Metric: Increase xenon yield while reducing complexity)

- *What are the theoretical and logistical limitations to the maximum efficiency collection of xenon gases and other radionuclides, and how could one implement a reliable system capable of operating in a field environment?*

RSE3. Improve transfer of collected radionuclides into the radiation detector (Metric: Improve radionuclide detection sensitivity by a factor of 2X)

- *What are physical and chemistry mechanisms (and limitations – such as cryogenic gaseous vapor pressures, absorption coefficients, gas purity and molecular flow region constraints) affecting the efficient transfer of small amounts of fission and activation products into 4π detection systems using ordinary engineering means?*

RSE4. Higher uptime and less maintenance (Metric: Meet or exceed an operation uptime of 95%)

- *What are statistical and preventative techniques to either provide early detection of, or prevent the failure of automatic radionuclide detection systems for short-lived radionuclide detection systems?*

RSE5. Solving near-field radionuclide measurement and operations problems, including on-site inspection (Metric: Demonstrate technologies)

- *What are the sensitivity limits to the near-field, on-site detection of radionuclides following a nuclear explosion and can these techniques be made reliable under extreme conditions?*

Improved sensor processing, measurement and precision technology is necessary to achieve measurement capabilities below the ambient radioxenon concentrations in the atmosphere. Research designed to improve sensor accuracy and precision can result in, for example, making more xenon with less power per cc while also finding ways to measure the quantity of stable xenon in a mixed and variable gas sample.

Objective B, Requirement d: Radionuclide Signal Analysis

Radionuclide Signal Analysis is also divided into two categories: signal processing and results. The primary radionuclide analysis is of the decay information for atoms in a sample, a so-called nuclear spectrum. Gamma-rays from particulates are recorded in a histogram, and this is a mature scientific technique, in the science community at large including CTBTO. Noble gas collection and analysis is a new field, and the GNDD Team continues to contribute greatly to establishing a regular analysis algorithm for the coincidence spectrum created by the emission of beta particles and gamma rays in Xe decay, known as beta-gamma spectrum.

To turn these measurements into useful information ('screening' in the CTBT context) it is necessary to compare the measurement to previous measurements at this or other locations to determine if it is anomalous (in size and in frequency of detection – has this isotope been detected often at this size before?). It is also critical for noble gas isotopes to compare the ratio of isotopes, if more than one is detected, with that expected from medical isotope and reactor emissions. For example, the IMS detected a pair of xenon isotopes at a Japanese station shortly after the 2009 DPRK event. The ratio of isotopes indicated decayed reactor emissions however, and the signal was confidently rejected as not being nuclear explosion related.

The users cannot make use of the Sensor program requirement without signal processing. The GNDD Team began by simply using the gamma-ray spectroscopy capabilities available commercially and within the National labs; entirely adequate to perform basic signal processing for particulates. As noble gas systems became useful, signal processing was done by hand, as particulate signal processing was in the 1950's. A rapid evolution of signal processing for beta-gamma spectra, using modern tools and techniques of nuclear and particle physics brought about a basic xenon analysis scheme that is being actively refined today.

Future research will be toward refined screening for both radionuclide and xenon data, as well as the new area described as 'network analysis' in which many stations' results on many days are combined with the source-receptor strength fields to create a wholly new product, the maximum release possible from a suspected site as a function of time. This was a key result of 2009 DPRK analysis.

Radionuclide Signal Analysis (RSA) R&D themes (and associated metrics and science questions) include:

RSA1. Develop methods and techniques to increase the sensitivity and selectivity of radionuclide detection (Metric: Improve radionuclide detection sensitivity and selectivity by an order of magnitude or more)

- *What are order-of-magnitude options exist for the more sensitive/selective measurement of radionuclides following a nuclear explosion and are these techniques viable and competitive with existing ones?*

RSA2. Improve discrimination of detected signals from background with algorithms (Metric: Demonstrate refined algorithms)

- *Can a complex multi-dimensional radionuclide analysis algorithm be implemented that improves the current state-of-the-art for radionuclide detection?*

RSA3. Evaluation of intra-station dependencies to maximum network capabilities (Metric: Improved understanding of global coverage)

- *When data is combined/fused from different monitoring technologies or within technologies (such as fission product gases and particulates), can additional information gained allow for significantly lower or more selective measurements be made and an this allow for better discrimination or event location?*

The aim of the GNDD R&D themes is to improve overall monitoring going beyond over five decades of progress. By and large, Source Physics will provide a deeper understanding of the processes inherent in the explosion mechanisms that will enable lower detection thresholds, improved location accuracy and yield estimates. Success with Signal Propagation themes will reduce location error; improve attenuation models and thus improve discrimination, detection and yield estimation. Better, in-close Sensors will lower detection thresholds, and improve signal-to-noise ratios allowing for better timing and thus locations. Finally, progress in Signal Analysis themes will allow full signal processing furthering operations while opening new opportunities for extracting even more information from these complex data.

Similar to waveform signal analysis challenges, exploratory research is needed to try new ideas. This will involve statistics, ATM expertise, and earth science knowledge in addition to the scientific heritage of observation of the environment and development of sensors. It will be a challenge to reach out within the labs and the US/International academic community to find multi-disciplinary expertise of this nature.

The ultimate challenge for any signal processing science endeavor is signal-to-noise ratios. Finding new ways to tag and eliminate noise increases the sensitivity of the measurement, even with the same components. This is true for a single sampler/analyzer and true for a network. The coincidence method for a sensor uses a second (or third, and so on) signal to make the measurement much more selective, based on our expectations of the differences between the signal and the noise.

Successful research in this area will deliver new monitoring capability, within the existing network and systems, but may also, in the long view, affect the community view regarding expansion of the IMS and cooperating national facilities.

SUMMARY

This document describes the path forward for the GNDD Team to address current and evolving nuclear proliferation threats. The Roadmap is based upon and organized around goals, objectives and requirements and measured by operational metrics.

This roadmap delineates the science questions that must be pursued to ensure success.
The central scientific and technical themes of the Ground-based Nuclear Detonation Detection R&D requirements and the R&D metrics are formulated to help guide research. The associated R&D themes and science questions for the four scientific and operational-based elements (Source Physics, Signal Propagation, Sensors, and Signal Analysis), build on a continuous series of scientific and technical achievements to further lower detection thresholds, reduce location uncertainty and improve event identification. The program is poised to deliver additional increases in operational effectiveness similar to the one in the 1990s related to improvements in event location.

Work sponsored by GNDD and collaborators is conducted by world-class scientists and engineers in national laboratories, universities, and private industry. In the past ten years, significant progress has been made in nuclear explosion detection, location and identification with substantial improvements yet possible.

Though support for national monitoring is the primary goal of the GNDD Team, GNDD R&D technology is relevant to the Comprehensive Nuclear-Test-Ban Treaty as well. The GNDD Team roadmaps are designed to improve both national and international monitoring for nuclear explosion by focusing primarily on monitoring methodologies that are used by both communities: waveform technologies, (including seismic, hydroacoustic, and infrasound) and radionuclide monitoring.

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APPENDICES

Appendix A – Acronyms and Abbreviations

Acronym	Definition
AFRL	Air Force Research Laboratory
AFTAC	Air Force Technical Applications Center
ARSA	Automated Radioxenon Sampler/Analyzer
ATM	Atmospheric Transport Modeling
BAA	Broad Agency Announcement
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
DAS	Deployable Analysis System
DoD	Department of Defense
DOE	Department of Energy
DOS	Department of State
DPRK	Democratic People's Republic of Korea
ECM	event categorization matrix
FFRDC	Federally Funded Research and Development Centers
GNDD	Ground-Based Nuclear Detonation Detection
GNEM	Ground-Based Nuclear Explosion Monitoring
GT	Ground truth
GTx	Ground truth information of accuracy x km
HPGe	High Purity Germanium
JVE	Joint Verification Experiment
IDC	International Data Centre
IMS	International Monitoring System
INL	Idaho National Laboratory
INGE	International Noble Gas Experiment
KB	Knowledge Base
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
mb	Body wave magnitude
MDAC	Magnitude and distance amplitude corrections
MEMS	Micro-electro-mechanical systems
Ms	surface wave magnitude
NA-22	NNSA Office of Defense Nuclear Nonproliferation Research & Development
NA-222	NNSA Office of Nuclear Detonation Detection
NASA	National Aeronautics and Space Administration
NCNS	National Center for Nuclear Security at the NNSS
NDC	National Data Center
NDD	Nuclear Detonation Detection
NEIC	National Earthquake Information Center (USGS)
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site (formerly known as the Nevada Test Site)
NPE	Nonproliferation Experiment
NOAA	National Oceanic and Atmospheric Administration

NTS	Nevada Test Site (now called NNSS)
OSI	on-site inspections
PNE	peaceful nuclear explosions
PNNL	Pacific Northwest National Laboratory
PTS	Provisional Technical Secretariat for the CTBTO
RASA	Radionuclide Aerosol Sampler Analyzer
R&D	research and development
RSTT	Regional Seismic Travel-Time model
SBIR	Small Business Innovation Research
SNL	Sandia National Laboratories
SPE-A	Source Phenomenology Experiments in Arizona
SPE-N	Source Physics Experiments in Nevada at the NNSS
TVT	Treaty Verification Technologies
USAEDS	United States Atomic Energy Detection System
USGS	United States Geological Survey
USNDC	United States National Data Center

Appendix B – Selected Bibliography

Entries in this selected bibliography were chosen due to their technical relevance to the GNDD goal and consist of predominantly peer-reviewed articles, books with a verification technology focus, and top-level GNDD documents. This GNDD bibliography guards against research duplication, provides a starting point and education for new researchers, and delineates the state-of-the-art.

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