NUCLEAR EXPLOSION MONITORING RESEARCH AND DEVELOPMENT ROADMAPS

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Sponsored by the National Nuclear Security Administration

ABSTRACT

In the past ten years, significant progress has been made in nuclear explosion monitoring (NEM) through research and development (R&D) with regard to detection, location and identification, however substantial improvements are yet possible. Today, there is increasing interest in both current and planned NEM R&D technology particularly in light of its relevance to the Comprehensive Nuclear-Test-Ban Treaty (CTBT). At this juncture, the Ground-based Nuclear Explosion Monitoring R&D (GNEM R&D) roadmaps are particularly pertinent because they build upon decades of NEM accomplishments (https://na22.nnsa.doe.gov/mrr) to map future R&D themes. Indeed, the GNEM R&D mission, an essential program within the National Nuclear Security Administration's Office of Nuclear Detonation Detection (NA-222), is, "…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" (Strategic Plan, 2004). Work sponsored by GNEM R&D and collaborators is world-class; conducted by scientists and engineers in national laboratories, universities, and private industry in partnership with international researchers. Waveform and radionuclide technology roadmaps are organized according to four program elements: source physics, signal propagation, sensors, and signal analysis. These elements were chosen to capture the full breadth of the physical representation of signals observed in the environment. Within each element, R&D themes and metrics are presented as illustrative of future directions. The roadmaps show the way forward to attain the goals of the program namely to: perform innovative scientific research, deliver capability-enhancing technologies to monitoring agencies and to motivate and nurture human capital to meet future monitoring challenges.

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14. ABSTRACT

In the past ten years, significant progress has been made in nuclear explosion monitoring (NEM) through research and development (R&D) with regard to detection, location and identification, however substantial improvements are yet possible. Today, there is increasing interest in both current and planned NEM R&D technology particularly in light of its relevance to the Comprehensive Nuclear-Test-Ban Treaty (CTBT). At this juncture, the Ground-based Nuclear Explosion Monitoring R&D (GNEM R&D) roadmaps are particularly pertinent because they build upon decades of NEM accomplishments (https://na22.nnsa.doe.gov/mrr) to map future R&D themes. Indeed, the GNEM R&D mission, an essential program within the National Nuclear Security Administration?s Office of Nuclear Detonation Detection (NA-222), is, ??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? (Strategic Plan, 2004). Work sponsored by GNEM R&D and collaborators is world-classconducted by scientists and engineers in national laboratories, universities, and private industry in partnership with international researchers. Waveform and radionuclide technology roadmaps are organized according to four program elements: source physics, signal propagation, sensors, and signal analysis. These elements were chosen to capture the full breadth of the physical representation of signals observed in the environment. Within each element, R&D themes and metrics are presented as illustrative of future directions. The roadmaps show the way forward to attain the goals of the program namely to: perform innovative scientific research deliver capability-enhancing technologies to monitoring agencies and to motivate and nurture human capital to meet future monitoring challenges.

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OBJECTIVE

The objective of this paper is to convey the central themes in the GNEM R&D technology roadmaps. Two high-level categories of roadmaps capture the signals of interest to the ground-based program: waveform and radionuclide. Utilizing scientific and operational-based program elements and associated technical themes, this roadmapping effort, builds on a continuous succession of past deliberate activities, step-by-step over decades, resulting in scientific and technical achievement, propelling the focus on the future. In the drive to lower detection thresholds, reduce location uncertainty and improve event identification, decades of concerted, peer-reviewed efforts in NEM R&D has paid off attaining a high-level of technical sophistication. In fact, compared to just ten years ago, significant progress has been made in key operational functions (detection, location and identification) and the roadmaps described here are very likely to make similar advancements over the decade to come. These roadmaps outline a way forward to ensure success. In fact, a deciding factor for program element and theme selection was the ability to project forward to credible, mission-inspired, pathways and end-products, thus providing potential topics for future proposal calls, guiding researchers, enabling collaborations with similarly driven agencies, as well as informing treaty policy makers.

RESEARCH ACCOMPLISHED

The progression of NEM R&D themes, starting with simple, empirical approaches to present day almost-real-time, entirely digital methodologies, and finally, projecting to tomorrow's technologies is established in these roadmaps. They intend to build upon the foundation and elaborate important ideas established at the 26th Seismic Research Review, in a paper titled, *Trends in Nuclear Explosion Monitoring* (Andersen et al., 2004) that focused on trends in monitoring agreements, science, technology and instrumentation.

NEM R&D waveform and radionuclide technology themes are organized into four program elements: source physics, signal propagation, sensors, and signal analysis. These program elements form the foundation for the roadmaps and, because of major inherent differences between waveform and radionuclide R&D; separate roadmaps were developed for each. Finally, themes and metrics serve as both a guide for researchers and a gauge to assess the merit of new approaches.

GNEM R&D goals are to: perform innovative scientific research, deliver capability-enhancing technologies to monitoring agencies and to motivate and nurture human capital to meet future monitoring challenges. The roadmap is intended to focus and stimulate innovation, enhancing delivery of products and attracting top scientists.

R&D Themes, Goals and Metrics

Delivering state-of-the-art products to operational monitoring systems to improve NEM proficiency is a major goal of the GNEM R&D program. The expectation is that much of this improvement will come from a better understanding of the science behind the generation, propagation, sensing, and interpretation of seismic, infrasound, hydroacoustic and radionuclide signals. To structure, plan and communicate future research advances, a simple four element schema was identified comprised of common elements of both operational and observational considerations. Figure 1 is a diagram of the four program elements displaying both operational and scientific attributes.

The first program element, Source Physics, aims to better understand the underlying principles and mechanisms behind all potential NEM sources with particular attention to complex interactions with the local source-medium (geology, structure, tectonics and emplacement conditions). These interactions can greatly affect the signals before they propagate to the sensors either through the atmosphere or through the Earth. As the signals from that source travel outward, the second program element, Signal Propagation, covers the critical factors that modify, in any way, the signal timing, amplitude and frequency content between the source and the sensor.

Next, these signals are recorded as data at very sensitive instruments carefully installed around the globe. This part of the process is captured in the Sensors program element, where sensors collect the continuous data (signals) that will be processed to detect, locate, and identify events of monitoring interest. The sensors program element addresses continued improvement in sensor size, weight, and lifecycle costs as well as noise reduction, emplacement conditions and system performance optimization. Finally, signals created by sources, propagated through the solid Earth, oceans, or atmosphere, and recorded by sensors must be processed to form hypotheses of possible nuclear events. We refer to this final processing step as the Signal Analysis program element.

These four elements provide a framework capable of capturing the full scope of the GNEM R&D mission, and can be thought of as a high-level amalgamation of nuclear explosion monitoring physical environments with a generalization of the operational systems.

In reality, few projects fit neatly into one program element, nor are the paths from R&D to operational applications simple: most products take several years from development of an idea to operational incorporation. Interactions between the operations leaders and staff and researchers are frequent and significant in order to achieve a successful final product delivery. None the less, the program element framework provides a useful way to view and understand our program. In this way the four program elements of Source Physics, Signal Propagation, Sensors and Signal Analysis bring planning together to improve nuclear monitoring capability. This synthesis is reflected in past and projected future improvements in overall monitoring of event detection, location, and identification as broadly portrayed in Figures 2, 3 and 4.

Each program element is composed of several R&D themes and most themes are related to or dependent on the results from other themes. Themes can span decades, some current themes have been active for more than 12 years while others will start activity in the next few years depending on the results of other themes. Themes are dynamic and can be modified, added and deleted. For each theme we have R&D metrics where appropriate to guide researchers in their work. Themes and R&D directions are reviewed annually in conjunction with the budget process and are the result of a vigorous on-going discussion between program managers, operational leaders and staff, national laboratory researchers, collaborators, and national and international nuclear explosion monitoring experts.

Source Physics R&D Themes and Metrics for Waveform Technologies

Source Physics R&D themes are focused on the ultimate technical goal of providing a physical basis for predicting the seismic 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 S wave generation, drives future R&D in: model synthesis, numerical simulations using realistic material 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 broad areas are monitoring goals of the final synthesis product. An over-arching metric for the synthesis is the ability to predict and match observed seismic signals for all distance ranges and across the entire seismic frequency band.

Numerical simulations and field experimentation test and validate source parameter scaling laws, tie near-source phenomenology to seismic measurements, fill knowledge gaps, and test and validate the overall performance of the models. These efforts and theoretical work provide a foundation for interpreting signals in the context of the source, its emplacement, and the 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 seismic wave generation are important aspects of theoretical work.

R&D themes (and associated metrics) are identified below for various seismic sources and monitoring applications with focus on the underlying principles of Waveform Source Physics described above (WSO).

- WSO1. New and more effective methods to identify sources of waveform signals (Metric: Improved identification of sources),
- WSO2. Predict nuclear explosion seismic S-wave amplitudes near the source for all emplacements (Metric: Explosion models that better match observables),
- WSO3. Tune earthquake seismic amplitude models to their tectonic setting (Metric: Improved earthquake models that better match observables),
- WSO4. Predict industrial explosion local and regional seismic amplitudes (Metric: New mine blast models that better match observables),
- WSO5. Predict local and regional seismic signals from the collapse of underground cavities (Metric: New collapse models that better match observables), and

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

Signal Propagation R&D Themes and Metrics for Waveform Technologies

Many factors control the timing, amplitude and frequency content of propagating waveform signals. Foremost among these 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 this includes improved understanding of the subsurface density, wave velocities and associated attenuation. For infrasound this includes understanding the velocity profile and dynamics of the atmosphere, which is in constant motion and has daily and seasonal variations. For hydroacoustic this includes improved understanding of the velocity profile of the oceans which undergoes seasonal variations as well as the bathymetry. The major goal of Signal Propagation is improved waveform signal prediction which impacts event detection, location identification and magnitude/yield estimation. R&D themes (and associated metrics) for Waveform Signal Propagation (WSP) are:

WSP1. Improve travel time predictions (Metric: Improved travel time and dispersion predictions),
WSP2. Improve amplitude modeling (Metric: Improved amplitude predictions), and
WSP3. Predict travel-time, amplitude and full waveform signals from these models (Metric: Improved synthetic waveforms that better match observables).

Sensors R&D Themes and Metrics for Waveform Technologies

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 these sensors. The existing installed sensor systems, especially seismometers, have outstanding response characteristics and consequently are not the focus of this program element (see Figures 2 and 5). Sensor R&D is currently developing Micro-Electro-Mechanical Systems (MEMS) technology for local monitoring situations. MEMS requirements have been developed by working expert groups and continue to drive the innovation (see Table 1). MEMS as well as other types of miniature seismometers are predominantly funded by Small Business Innovation Grants (SBIR) with some GNEM R&D support. A particularly vexing challenge is overcoming the 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, weight and size constraints. Therefore, Waveform Sensor (WSE) R&D themes (and associated metrics) include development, network configuration analyses, and testing facility support, namely:

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 for seismic, Bowman for infrasound) in the frequency range of approximately 0.2 to 40 Hz and high dynamic range (> 110 dB)),
WSE2. Prototype local monitoring sensor system (Metric: Demonstrate local monitoring system performance),
WSE3. Develop sensor network deployment software (Metric: Demonstrate capability to accurately model local network performance prior to deployment), and
WSE4. Maintain a sensor testing and evaluation facility (Metric: Provide testing and evaluation for data acquisition systems for waveform technologies).

Signal Analysis R&D Themes and Metrics for Waveform Technologies

The Signal Analysis program element is meant to include all signal processing techniques that are applied to data to detect and characterize events of interest for nuclear explosion monitoring. In an operational network, each and every sensor is interrogated, separately, to discern signals of interest, then these are associated into hypothetical events, and finally, magnitudes of the events are estimated, along with an estimate of the likely source type (e.g., earthquake or explosion). This is all done in as close to real-time as possible. So, in some ways, Signal Analysis covers a broad range which we choose to divide 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.

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. Waveform Signal Analysis (WSA) R&D themes (and associated metrics) include:

- WSA1. Improve the robustness and accuracy of parameter estimation (Metric: Demonstrate improved parameter and uncertainty estimates),
- WSA2. Develop new waveform parameters (Metric: Demonstrate improved monitoring capability due to new waveform parameters),
- WSA3. Improve parameter-based methods for monitoring (Metric: Improved detection, location, and/or identification), and
- WSA4. Improve waveform-based methods for monitoring (Metric: Improved detection, location, and/or identification).

Source Physics R&D Themes and Metrics for Radionuclide Technologies

Quite different from seismic signals, which begin 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). The R&D themes (and associated metrics) for Radionuclide Source Physics (RSO) are:

- RSO1. Determine the risk of innocuous background false alarms (Metric: Calculate risk),
- RSO2. Improve knowledge of subsurface gas transport (Metric: Reduce the number of samples by an order of magnitude), and
- RSO3. Determine the amount of radionuclides produced in various nuclear testing conditions (Metric: Improve input to geologic and atmospheric transport models).

Signal Propagation R&D Themes and Metrics for Radionuclide Technologies

While radionuclides can move in subterranean water, the dominant source propagation for radioactive atoms in the context of NEM is atmospheric transport. Atmospheric transport modeling (ATM) is central to weather prediction and therefore has large national and international academic research and operations 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 GNEM R&D is a user of ATM rather than a supplier. Signal Propagation R&D for radionuclides is not part of the GNEM R&D program, but advances at the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) in conjunction with their partnership with the World Meteorological Organization, are still part of the drivers for research and require thoughtful coordination. In light of this, there is an overall theme (and associated metric) for Radionuclide Signal Propagation:

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

Sensors R&D Themes and Metrics for Radionuclide Technologies

Sensors are the cornerstone of the Radionuclide part of the GNEM R&D Program. Sensors for radionuclide are complete sampler/analyzers rather than simply a transducer. 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 the main focus of the radionuclide part of the GNEM R&D program. 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.

Radionuclide Sensor (RSE) R&D themes (and associated metrics) include:

- RSE1. More sensitivity, (Metric: Increase sensitivity to aerosols and short-lived xenons by an order of magnitude),
- RSE2. More xenon for less energy, less liquid nitrogen, in less size, or with less adsorbent material, (Metric: Increase xenon yield while reducing complexity)
- RSE3. Improve transfer of collected radionuclides into the radiation detector, (Metric: Improve radionuclide detection sensitivity by a factor of 2X)
- RSE4. Higher uptime and less maintenance, (Metric: Meet or exceed an operation uptime of 95%), and
- RSE5. Solving near-field radionuclide measurement and operations problems, including On-Site Inspection (Metric: Demonstrate technologies)

Signal Analysis R&D Themes and Metrics for Radionuclide Technologies

Radionuclide signal analysis is also divided into two topics: 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 this program 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 element without signal processing. The GNEM R&D program 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 which is being actively refined today. Coincidence signal processing for particulates is now in development to support the multi-crystal germanium detector CASCADES for laboratory use.

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 DPRK 2009 analysis. Radionuclide Signal Analysis (RSA) R&D themes (and associated metrics) 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),
- RSA2. Improve discrimination of detected signals from background with algorithms (Metric: Demonstrate refined algorithms), and
- RSA3. Evaluation of intra-station dependencies to maximum network capabilities (Metric: Improved understanding of global coverage).

The aim of the GNEM R&D themes is to improve monitoring overall and Figures 2, 3 and 4 illustrate progress over five decades. By and large, Source Physics will provide a deeper understanding of the processes inherent in the explosion mechanisms which 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 improving 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.

CONCLUSIONS AND RECOMMENDATIONS

The central scientific and technical themes of the Ground-based Nuclear Explosion Monitoring R&D roadmaps were portrayed and R&D metrics stated to help guide research progress. Four scientific and operational-based program elements (Source Physics, Signal Propagation, Sensors and Signal Analysis) with associated technical themes, build on a continuous series of scientific and technical achievements that lowered detection thresholds, reduced location uncertainty and improved event identification. The program is poised to deliver another giant step in operational effectiveness similar to the one in the 1990's related to improvements in event location and this roadmap delineates a way to get there and provides the scientific foundation and wherewithal to ensure success. These roadmaps are reviewed annually in conjunction with the budget process. We invite comments on the GNEM R&D roadmaps and your comments may be sent at any time to Leslie.Casey@nnsa.doe.gov.

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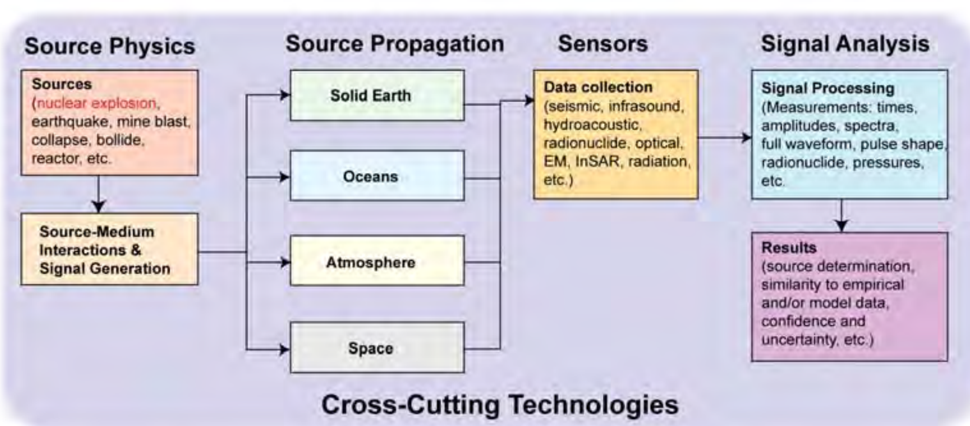

Figure 1. GNEM R&D program elements were chosen as a full scope representation of GNEM processes and are shown in a context of operational data and process flow.

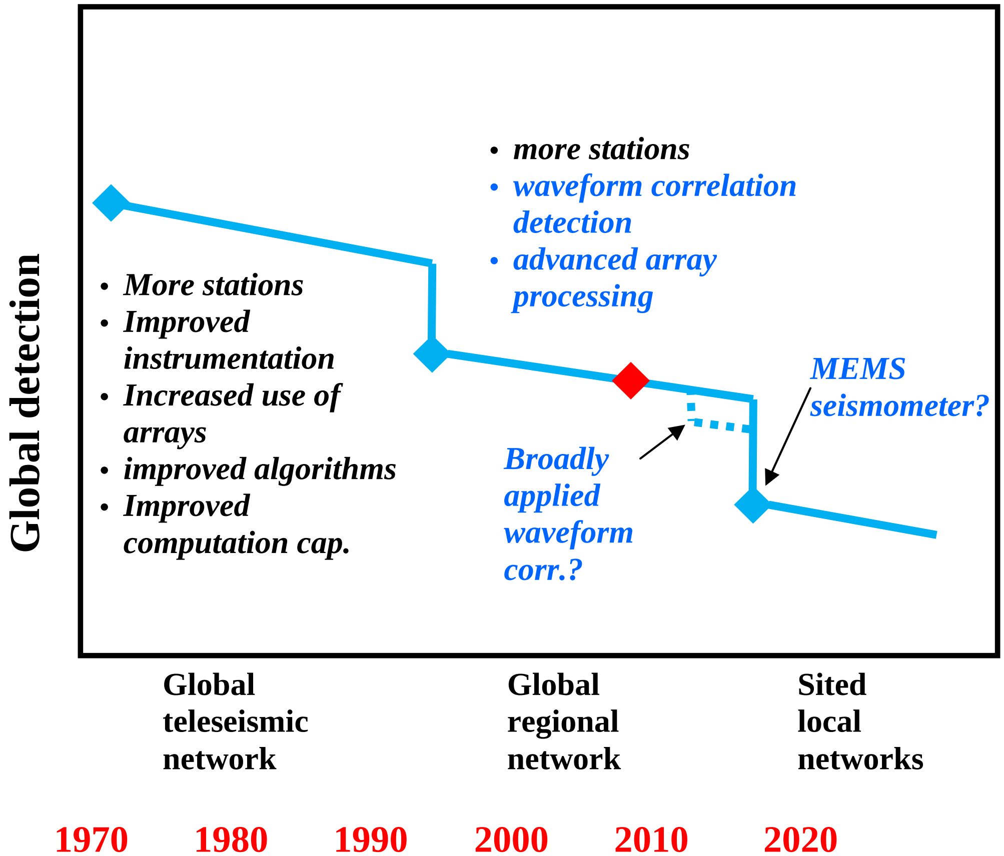

Figure 2. Progress in GNEM R&D detection metric is shown from 1970s to 2020. Detection improvements are a function of several factors the major being to add more stations closer to where you want to monitor. Improved instrumentation, algorithms, and analyses methods have made a difference.

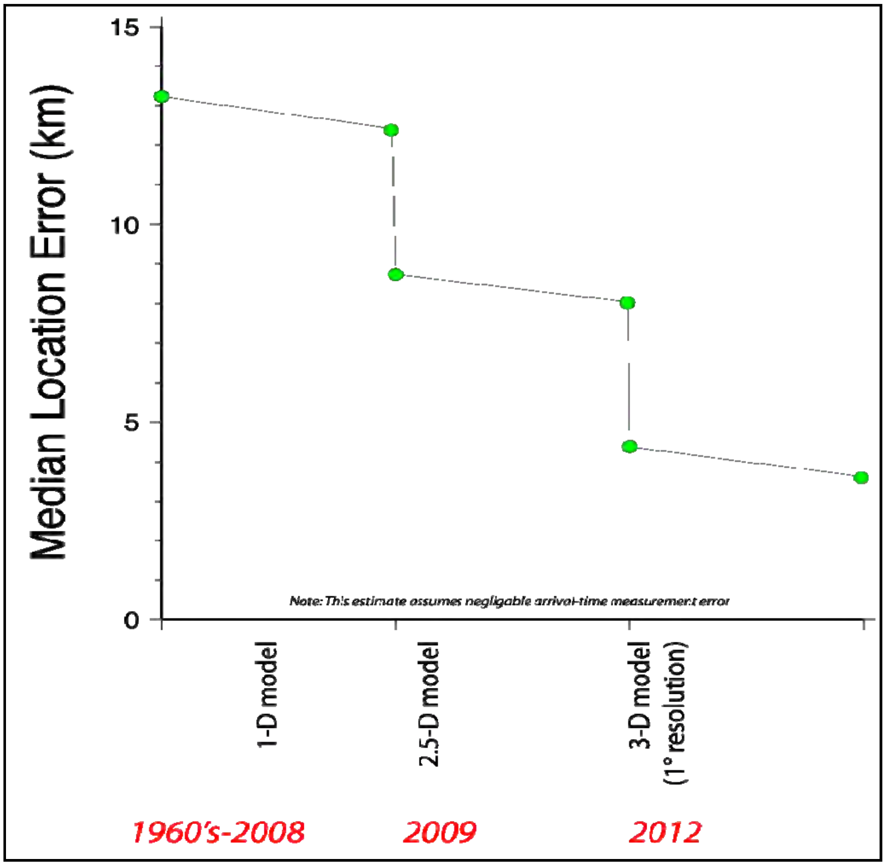

Figure 3. Location past, present and future progress chart. These results are applicable only for small tests (<~4.5) in broad tectonic regional discrimination.

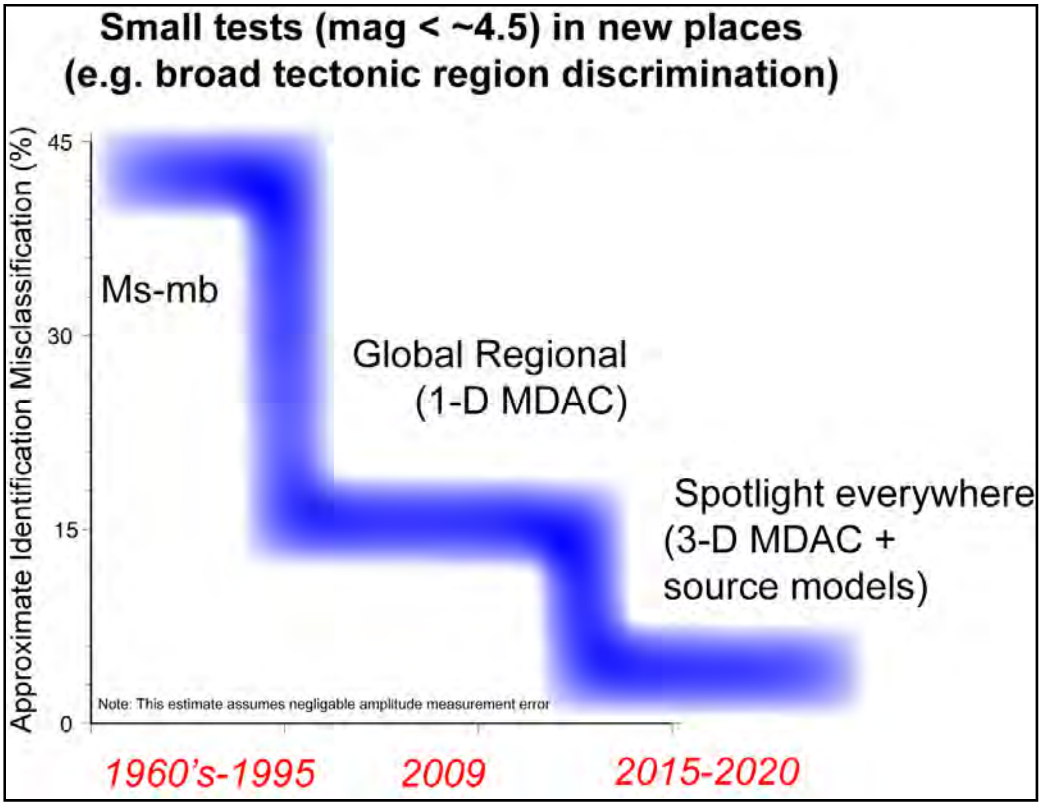

Figure 4. Identification past, present and future progress chart. Applicable only for small tests (<~4.5) in broad tectonic regional discrimination.

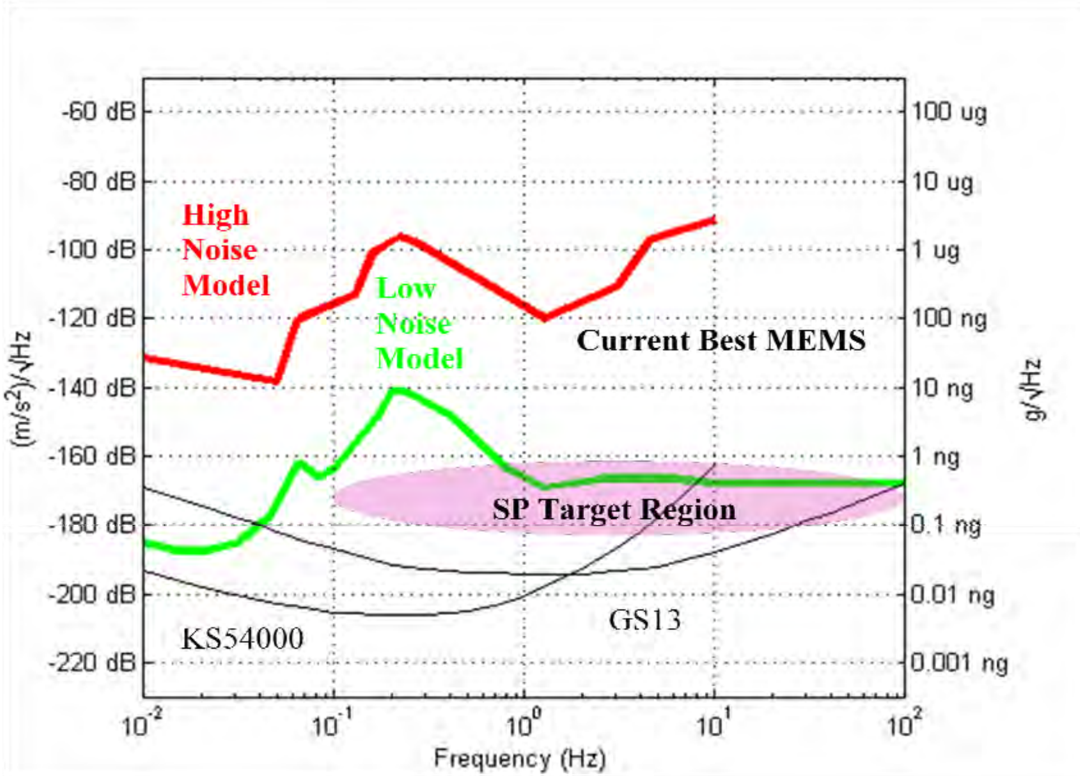

Figure 5. Seismometer R&D is directed and constrained by Earth noise. USGS High Noise (red) and Low Noise (green) models are shown with current capabilities and future targets.

Table 1. MEMS weak motion accelerometers requirements.

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