Networked Gamma Radiation Detection System for Tactical Deployment

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ABSTRACT

A networked gamma radiation detection system with directional sensitivity and energy spectral data acquisition capability is being developed by the National Security Technologies, LLC, Remote Sensing Laboratory to support the close and intense tactical engagement of law enforcement who carry out counterterrorism missions. In the proposed design, three clusters of 2″ × 4″ × 16″ sodium iodide crystals (4 each) with digiBASE-E (for list mode data collection) would be placed on the passenger side of a minivan. To enhance localization and facilitate rapid identification of isotopes, advanced smart real-time localization and radioisotope identification algorithms like WAVRAD (wavelet-assisted variance reduction for anomaly detection) and NSCRAD (nuisance-rejection spectral comparison ratio anomaly detection) will be incorporated. We will test a collection of algorithms and analysis that centers on the problem of radiation detection with a distributed sensor network. We will study the basic characteristics of a radiation sensor network and focus on the trade-offs between false positive alarm rates, true positive alarm rates, and time to detect multiple radiation sources in a large area. Empirical and simulation analyses of critical system parameters, such as number of sensors, sensor placement, and sensor response functions, will be examined. This networked system will provide an integrated radiation detection architecture and framework with (i) a large nationally recognized search database equivalent that would help generate a common operational picture in a major radiological crisis; (ii) a robust reach back connectivity for search data to be evaluated by home teams; and, finally, (iii) a possibility of integrating search data from multi-agency responders.

Key words: Networked detectors, tactical engagement, false positive alarm rate, system parameters, radioisotope identification.

1. BACKGROUND

This two-year engineering research effort is part of a rapid prototyping project to develop a networked gamma radiation detection system with directional sensitivity and gamma energy spectral data acquisition capability for the close and intense tactical engagement of the law enforcement elements in carrying out their conduct of operations and rules of engagement for counterterrorism and other activities. At completion we expect to be able to test the system in a controlled radiological environment. Three clusters of 2″ × 4″ × 16″ sodium iodide crystals (4 each) with digiBASE (for list mode data collection) would be placed along the passenger side of a vehicle (in our case a minivan). The clusters are 60 cm apart, lined up against the vehicle wall. At the center of these clusters will be 2″ × 36″ (2 each) cylindrical ^{3}He tubes at a pressure of 2.7 atmospheres; the tubes will run in a proportional counter mode to provide high-efficiency neutron counting. The currently deployed mobile detection system consists of 2″ × 4″ × 16″ sodium iodide crystals (4 each) and is known as Mobile Search System, version III (MSS III). The newer networked detection system provides 3 times the gamma sensitivity of the MSS III. Each cluster individually would indicate the general direction of the location of the source by exploiting self-occlusion of gamma rays by thallium-

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doped sodium iodide (NaI:Tl) crystals whose expected angular resolution is ~3º. A pictorial description of the pieces of hardware consisting of the (left to right) new package casing, single sodium iodide crystal with a low-power multichannel analyzer and package design for the 4-unit quad module of detectors is shown in Figure 1. The figure also shows the packaging of a smaller dual pack (right bottom) of 2″ × 4″ × 16″sodium iodide crystals (hereafter called gamma logs).

The spectral data will be written in list mode, but only relevant regions of interest, as required by the embedded analysis software nuisance-rejection spectral comparison ratio anomaly detection (NSCRAD), will be written. Multiple search algorithms running simultaneously will reduce the false alarm rate in this data-starved situation. Special situational awareness tools based on GIS capabilities will be developed that will facilitate nighttime operations and provide real-time escape routes, and nearest emergency services. The mapping system would incorporate National Atmospheric Release Advisory Commission (NARAC) plume plots and other plots (evacuation and sheltering) according to the environmental guidance plan for a smooth transition from pre- to post-detonation situations, should they occur. We are incorporating expert search techniques into sensor data acquisition and analysis systems by utilizing the fast acquisition times (0.5 seconds). These expert search techniques process sudden changes in the gamma fields to provide a means to localize and track anomalies, so the prototype system will deliver advanced real-time algorithms and data visualization for vehicular search with directional systems coupled to commercial off-the-shelf (COTS) component technologies that improve the ability to localize and track effectively. This approach leverages the emerging capabilities inherent in embedded processors, smart phones, or tablets. The goal is to enhance detector components with improved capabilities with a priority on localization and source tracking with COTS acquisition system components.

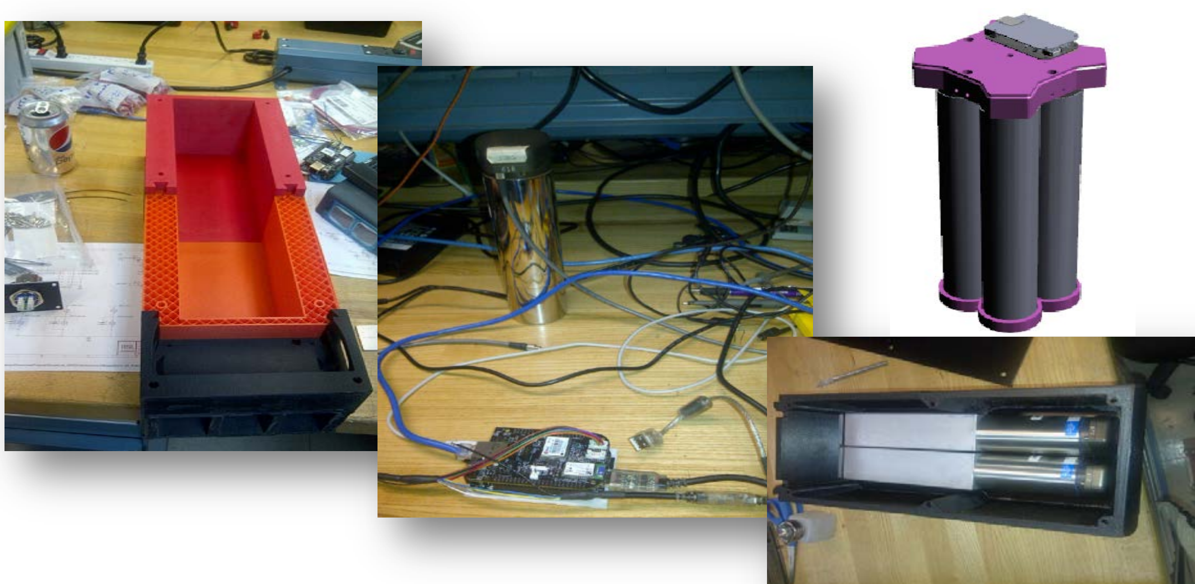


Fig. 1. An assorted variety of detectors of various sizes and configurations were custom designed to be used in the field operations of search and localization of radioactive materials.

Another goal of this project is to improve existing algorithms that detect, locate, and associate with visual observables and signatures. These algorithms have not matched the development of computational capabilities contained within low-cost COTS systems such as the smartphones, tablets, and other embedded processors used today for detection and data acquisition. Improvements in processing algorithms that may effectively leverage these computational platforms and associated sensors (i.e., GPS, cellular/Wi-Fi/Bluetooth communication, display, and micro-electro-mechanical system (MEMS)–based accelerometers) are being explored; our focus is to develop user search techniques to acquire and analyze data so that detection, location, and then tracking of sources can happen quickly. Multiple rapid decision-making algorithms will run simultaneously to reduce false alarm rates. Advanced low statistics detection of spectral anomalies will be included in these expert search techniques.

The mobile vehicle would maintain its own ad hoc mesh networking with other deployed vehicles on the mission. A cradle point using three (AT&T, Verizon, and Sprint) air cards would provide seamless cell-net service for data telemetry and networking. The search data from each vehicle would be uploaded to the search management dashboard in the mobile technical operation center for decision making.

2. SIMULATION OF A LARGE VEHICLE-MOUNTED DETECTION SYSTEM

The Monte Carlo N-Particle Transport Code MCNP5[1] developed at Los Alamos National Laboratory was used to simulate the sensitivity and angular response of the two mobile systems, the MSS III with 4 gamma logs and the new system with 3 clusters of 4 gamma logs. Figure 2 shows the gamma count rates from the two systems: (i) 4 gamma logs as used in MSS III and (ii) 12 gamma logs in three clusters spaced 60 cm apart. The count rates are shown as a function of the central distance between the gamma-emitting source and the detector. The source used is a combination of ^{241}Am, ^{137}Cs, and ^{60}Co (common industrial radioisotopes) each 0.25 mCi placed at various distances from the detector center with zero vertical offset.

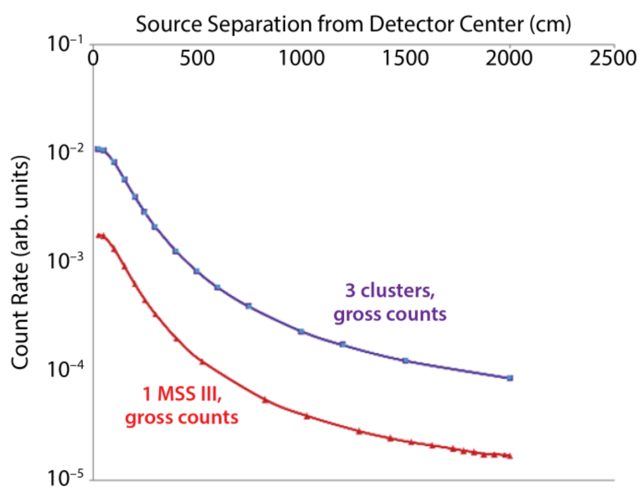


Fig. 2. MCNP5 simulated count rate comparison between the MSS III (current system) and the proposed detector array. Gross count rates between the gamma energy ranges of 30 keV to 3000 keV are calculated from simulated spectral response. A full width half maximum energy resolution of 7.5% at 662 keV was assumed.

An asymmetry (A_y) of counts was calculated as per Equation 1 for different angular position (Θ) of the source as

$$A_y(\Theta) = \frac{N_1 - N_4}{N_1 + N_2 + N_3 + N_4}, \qquad \text{Eq. 1}$$

where N_1 and N_4 are the counts from detectors facing the source (left and right respectively) and N_2 and N_3 are the counts from detectors in the back (left and right respectively). This asymmetry function varies linearly with the angle of source position with respect to the center of the detector array. Knowing the instantaneous value of the asymmetry one can determine the angular position of the source with a high degree of accuracy. Figure 3 shows the linear relationship between the asymmetry function, characteristics of the detector array, and the angular position of the detector arrays. As there were three clusters of detectors available, three different asymmetries were plotted, and they all seem to show the same linear variation. A least square linear fit of the general variation of asymmetry with angle is obtained as

$$\Theta = 114.77\, A_y(\Theta) + 0.0246\,. \qquad \text{Eq. 2}$$

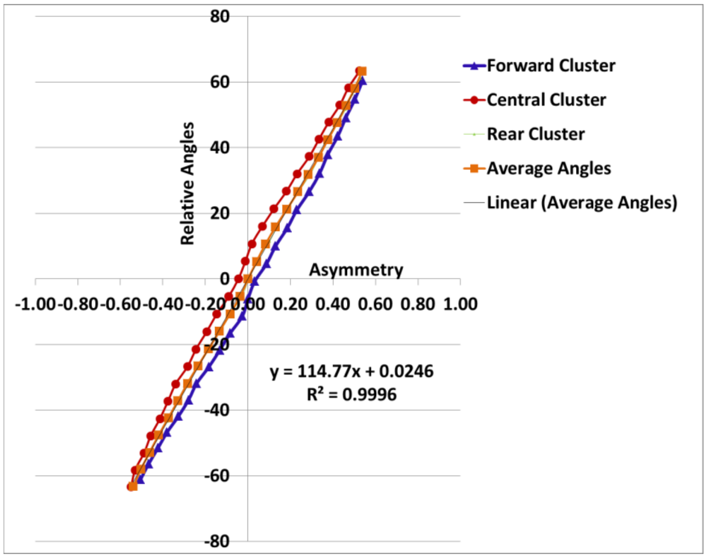


Fig. 3. Asymmetry functions for three different clusters are shown as a function of angular position of the source over the range of field of view of ±60°. This method provides a quick way to determine the instantaneous angular position of the source and is independent of background variation. The error in angle measured is less than 3°.

3. QUICK MAPPING WITH LARGE MOBILE DETECTORS

Background and with-source gamma ray gross counts data and spectral data were collected from a vehicle-mounted system in a parking lot across from a Joint Base Andrews (JBA) movie theatre. A complete RSL mobile system (hereafter called MSS III with gamma sensors only, no neutron detector was used) collected gamma data using (i) NaI-based detectors and (ii) a high-purity germanium (HPGe) array of four detective-class detectors. The sensors moved in a well-defined grid pattern and the sources were stationary at a few locations. Gamma-emitting radiation sources had a varied energy signature covering a large range of gamma ray energy to test sensitivity of localization parameters on incident gamma energy. The sources were maintained at fixed points within the test area inside a government-owned vehicle by a trained source user (Figure 4).

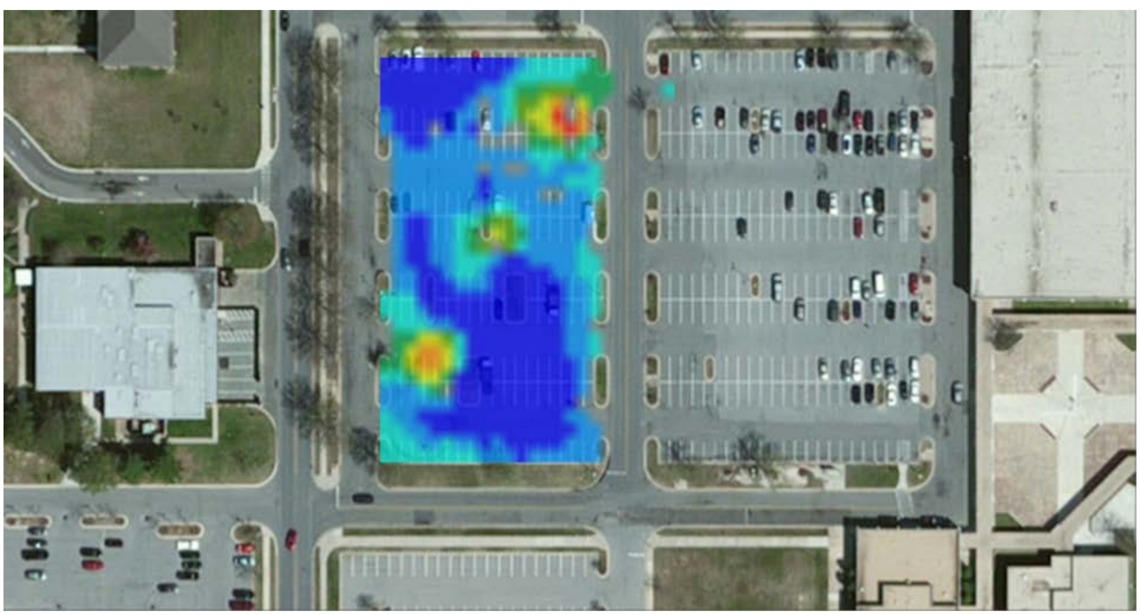


Fig. 4. Contoured map of collected gamma gross counts by a traditional mobile system with 4 each 4″ × 2″ × 16″ NaI crystals. The point-like sources (^{133}Ba, ^{137}Cs and ^{232}Th) were placed at a height of 50 cm above ground along a diagonal in the parking lot.

The primary objectives of this series of measurements were to provide proof of concept for deployment of a large number of HPGe sensors for mobile search and to establish the associated benefits from it. For this set of measurements, data were collected using a traditional mobile system for gamma ray measurements with different sets of sensors. We hope to prove that the application of HPGes can improve localization and better define the probability density function for the source. The collected data, when analyzed, will provide better understanding of detection efficiency for two different sets of sensor arrays in a mobile environment.

4. NETWORK DESCRIPTION

The field-deployed detector(s) are networked to provide a comprehensive real-time radiological snap shot of a given area under surveillance remotely or in situ for law enforcement to make quick decisions. The web-based toolset can be operated in a deployed forward position with a laptop computer, wireless broadband air card, and reach-back to a home component for support during small-scale responses and in the early stages of a real-time deployment. The field-collected data are monitored from the deployed command center, as shown in Figure 5. The system collects data from handheld search units via cellular net; the broadband backbone resides at the Remote Sensing Laboratory Nellis Operations. The radiological data from a moving vehicle are shipped out using a standalone IP router (Cradle Point). The aerial platforms use Global Star satellite communication systems to provide real-time radiological data to the decision makers. In addition, the new network features a server-enhanced emergency communications network satellite kit that replicates all telemetered data to a local server system, as well as wired and wireless satellite internet access. The extended network is capable of classified communications.

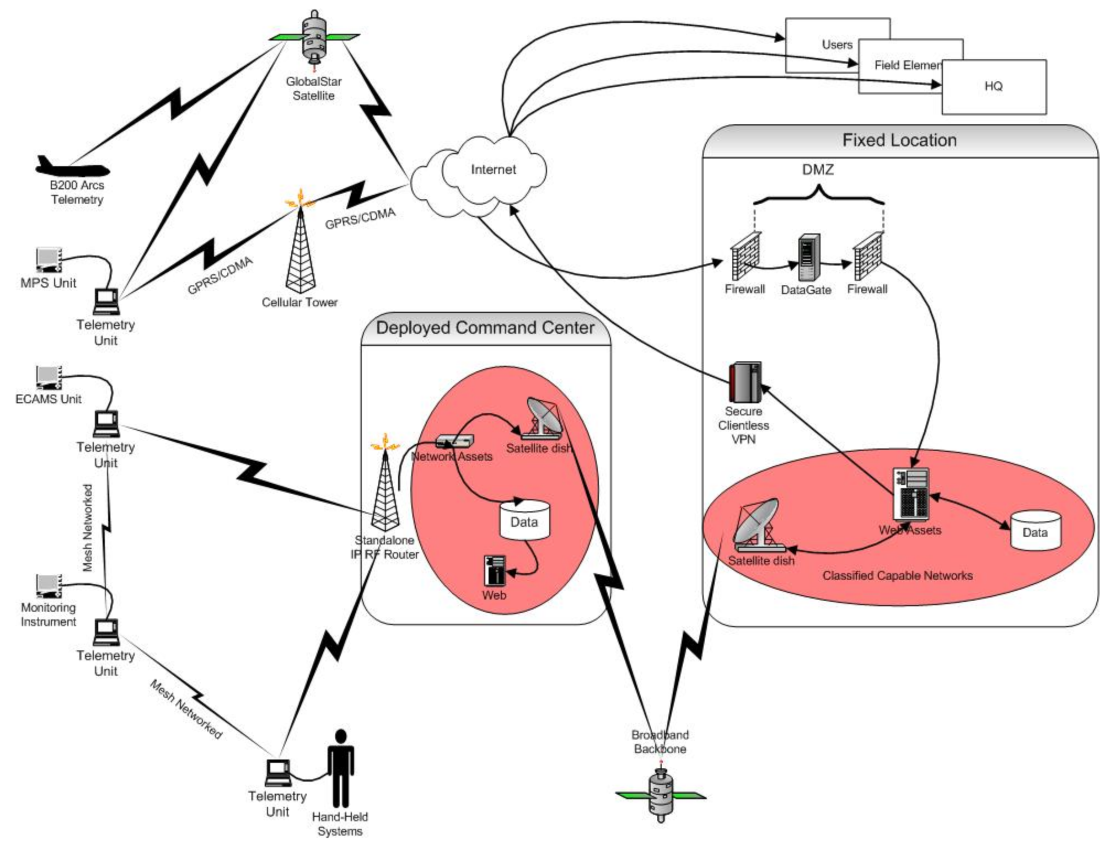
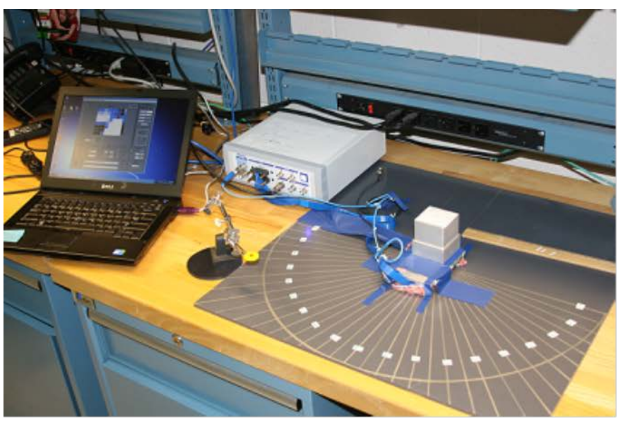


Fig. 5. Hardware layers for the deployed monitoring network. There are three basic components to the overall structure. The fixed server (classified capable network) stays behind firewalls at Nellis Air Force base (shown on the right). It can be reached by virtual private network (VPN) from outside. The deployed command center could be located at the forward point of a deployment with a deployable smaller-sized data server. Typically, vehicle or rooftop-mounted satellite dishes are used for the deployed command center. The third group of components are the mobile or fixed field elements—handheld devices using cell net or other radiation-monitoring devices on a mesh network.

5. SMALL HANDHELD DEVICE RESULTS

We, in collaboration with Vertilon Corporation, have developed a small handheld direction-sensitive gamma ray spectrometer that would work very well as a radioisotope identification device (RIID). The handheld detection system uses a sodium-doped cesium iodide (CsI:Na) segmented scintillator assembly consisting of four 1″ × 1″ × 1.5″ thick CsI:Na crystals arranged in a 2 × 2 array. Crystals are packaged in a thin-walled aluminum container with a flange for a hermetically sealed optical/mechanical connection to a Hamamatsu H8500 photomultiplier tube (PMT) assembly. The emission maximum of CsI:Na peaks at 420 nm and is well matched to the photocathode sensitivity of a bialkali PMT. The photoelectron yield for gamma rays amounts to 85% of that of an equivalent NaI:Tl crystal. The decay time of CsI:Na at 630 ns is less than that of thallium-doped cesium iodide CsI:TlCist. The Hamamatsu H8500 flat-panel PMT has features particularly suited for this work: it is position-sensitive, extremely compact (12 mm height), and has a 49 × 49 mm effective area and a minimal peripheral dead zone (mm). The H8500 PMT's metal channel dynode is used for charge multiplication in an 8 × 8 anode array used for charge collection and position calculation. MCPNX simulation of the sensor performance and measured angular resolution data from small gamma ray sources are presented for near-field measurements (~3 meters from the source).

The 4-element spectrometer was used to measure the angular position of single point-like gamma-emitting source. A combination of gamma radiation sources of ^{241}Am, ^{137}Cs, and ^{60}Co were placed at a distance of 25 cm from the center of the detector and gamma energy spectra were collected from each of the four crystals independently for a period of 300 seconds. The measured spectrum for source angular position at 30° is shown in Figure 6. Gamma count rates per second were calculated from the spectral data; these counts were done in two ways: (1) gross count rate measurement and (2) full photo-peak (at ^{137}Cs peak of gamma energy value 661.6 keV) count rate. The asymmetry parameter Ay (Θ) as defined in Equation 1 was plotted as a function of the source angle Θ subtended at the center of the detector. A linear relationship exists between these two quantities, viz., Θ and Ay (Θ). The resultant plot is shown in Figure 6.



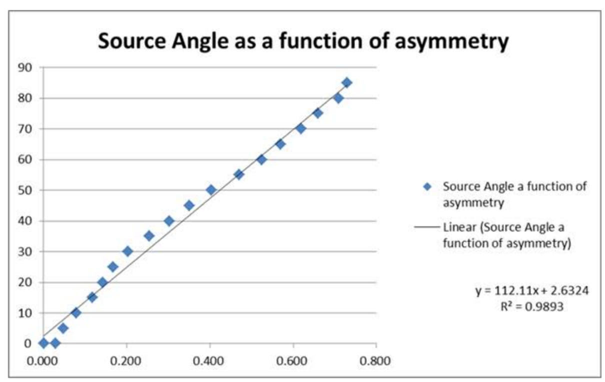


Fig. 6. (left) A handheld spectrometer with 4-segment detection elements made of sodium-doped cesium iodide (CsI:Na) scintillator crystals was used with a position-sensitive multi-anode PMT to determine the angular position of a combination gamma source. (right) The known angular positions of the gamma-emitting source were plotted against the asymmetry function calculated from count rates in individual detector (as per Equation 1). The plot establishes a linear relation between the observed angle and measured asymmetry and leads to determination of instantaneous angular position of a source from the knowledge of count rates in individual detector.

6. DETECTION OF FISSION AND FISSILE MATERIALS

The capability for detection of threat quantities (~2 lb) of special nuclear materials (SNM) is of utmost importance for any modern identification equipment. The fission properties of SNM are exploited for their passive detection. Shielded SNMs are even harder to detect using passive sensors. Special identification algorithms are used to determine if fissile materials are present. We tested a newly developed HPGe system, the DX-200 manufactured by Ortec Coproration.[2] The system features an 85 mm diameter, 30 mm long, cylindrical HPGe crystal used as a planar detector with very high resolution at low energy (consistent with SNM energies). We measured the response of the DX-200 towards minute amounts of SNM under the laboratory conditions, comparing it to the coaxial HPGe Detective-EX-100T (another system manufactured by Ortec Corporation). The two sources were (1) a bare, highly enriched uranium (HEU) ^{235}U source, 6.02 μCi, 3 g that is a combination of two equal smaller sources); and (2) an aged plutonium source, ^{239}Pu, 61.97 mCi, 1 g, that has a lot of ingrown ^{241}Am. To reduce the gamma ray intensity from ^{241}Am, this source is used with a 1/16″ sheet of cadmium as shielding. Table 1 presents the results of the lab tests. No false positive identification occurred. In the case of the ^{239}Pu source, even with the cadmium sheet in place, the alarm from ^{241}Am would be reported long before ^{239}Pu is identified. A man-portable backpack will have a maximum useable range of 2 meters for 500 gm of HEU, whereas a Detective-EX-100T will be able to detect the source at 5 meters within 60 seconds.

Table 1. Maximum detectable distances and time to identify sources

Equipment	Source	Max. Distance (ft)	Time of Response (sec)
EX-100T	^{235}U	10	582
DX-200	^{235}U	12	407
EX-100T	^{239}Pu	15	765
DX-200	^{239}Pu	16	428

Figure 7 depicts the time characteristics of the performances of DX-200 compared to the EX-100T. The DX-200, having an enhanced SNM detection algorithm, is a better performer and would be very useful for field deployment.

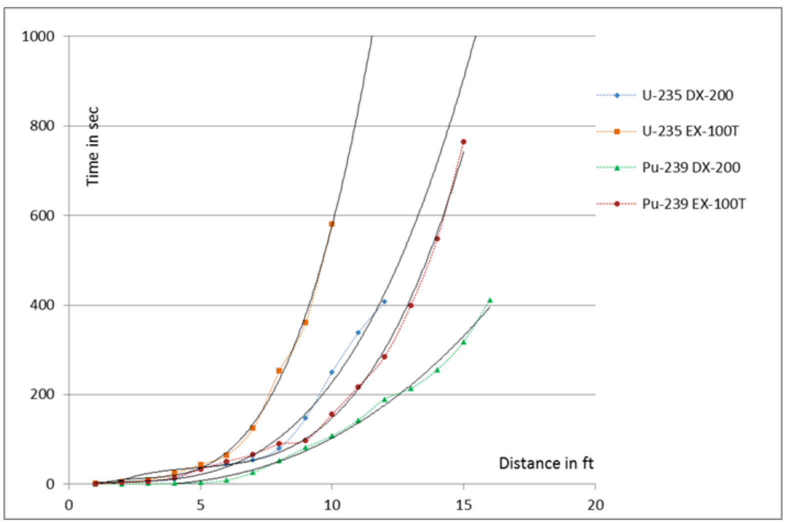


Fig. 7. Times in seconds taken by the spectrometers DX-200 and EX-100T to identify ^{235}U and ^{239}Pu sources as a function of source-to-detector distances are shown. The DX-200 performed better than the EX-100T. With larger quantities (actual threat quantities) of SNM, the identification time will be much shorter.

6.1 Feynman Variance (Y2F) Measurement for Fissile Material Detection

A high-speed field-programmable gate array (FPGA), SBRIO-9602, manufactured by Nuclear Instruments Inc., has been used to exploit the time correlations between neutrons from different sources. For example, cosmic or background neutrons in a maritime environment are only mildly correlated, primarily because of the high rates of spallation neutrons created by cosmic interactions. Neutrons from (α, n) channels are completely uncorrelated, and neutrons from fission, particularly when multiplications are taking place following spontaneous or induced fission, are very highly correlated. By following the detected neutron counting distributions with very narrow time gates ranging from 1 to 512 μs, one can partition between fission and cosmic neutrons within a very short time, on the order of 10 minutes. This approach provides a unique solution to discriminate against cosmic neutrons in a maritime search environment (in real time) and enables effective measurement of a neutron source on the ground from a large standoff distance.

Y2F, defined as excess of variance of neutron counts over that of a Poisson's distribution, is calculated from measured neutron counts and shown in Figure 8 for a fissioning ^{252}Cf source (with multiplicity value ~3.76) for different neutron count rates. A simple linear correlation exists between the Y2F value and the count rates measured by a commercial fission meter manufactured by Advanced Measurement Technology (AMETEK) Corp. The slope of the line depicting linear correlation between Y2F and count rate is positive. Strikingly, for a non-fissioning Am-Be neutron source the slope is negative. This is an easy way to determine whether fissile materials are present. Figure 9 shows the negative correlation of Y2F vs neutron count rates for a non-fissioning neutron source.

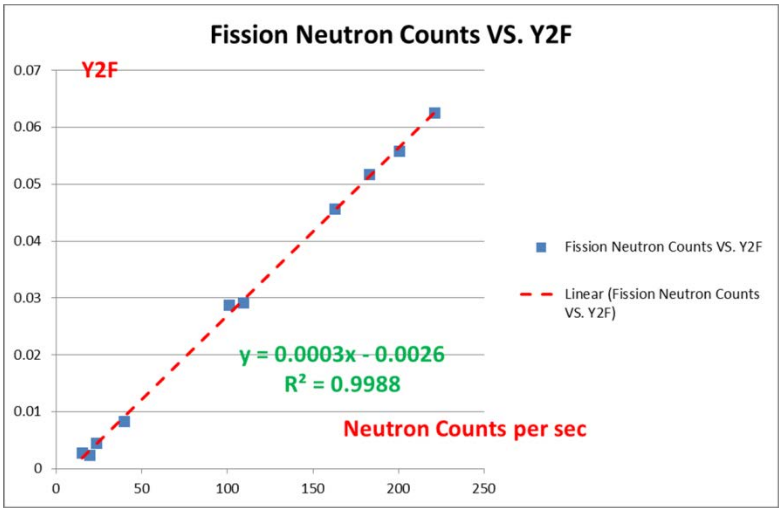


Fig. 8. Instantaneous Y2F (Feynman variance) is plotted as a function of neutron count rates, indicating that Y2F increases linearly with the neutron count rates for a fission source (^{252}Cf).

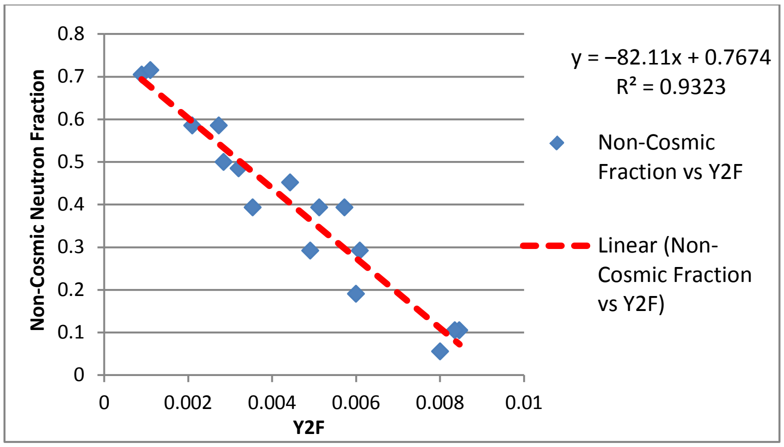


Fig. 9. Low count rates from Am-Be (non-cosmic fraction as determined by the fission meter) are plotted for corresponding instantaneous Y2F values; the count rate decreases with the Y2F value's decrease, showing and exactly opposite trend from Figure 8. Following the slope of the Y2F vs count rate, one can quickly determine the presence of fissile materials.

7. CONCLUSION

Gamma radiation detectors with directional sensitivity and different sizes and configurations have been built and networked following IEEE 802.11 protocol for media access control and physical layer specifications, providing wireless local area networking. Fast sub-second GPS and data acquisition times have been used to provide rapid actionable intelligence for search, localization, and identification operations in a radiological emergency. All detectors are tracked by a robust reach back system to develop a common operating picture in case of a large operation like national special security events. One of the most important features of the mobile detection system is its ultra-low false alarm rate. The system exploits data collected by all sensors in the network to build continuous local area radiation background profile so that small excess in gamma ray counts above background (small signal-to-noise domain) could potentially indicate the presence of smaller sources, increasing the sensitivity and selectivity at the same time.

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