SAND2011-9053P

DTRA FY12 Technical Call Focus Area 4: Standoff Detection

1.0 Project Narrative

Existing radiation sensors for monitoring and identification of Special Nuclear materials (SNM) are suitable only for short-range application, less than 100 meters. To address the problem of radiation detection at long standoff, 100 meters and beyond, an approach based on radio-frequency (RF) probing of the low-density plasma generated in the atmosphere due to ionizing radiation emitted from the SNM is sought. SNM emits various types of ionizing radiation that can be detected in principle if not attenuated by surrounding materials. High-energy gamma rays and neutrons can penetrate some surrounding materials and can create sufficient ionization of the surrounding atmosphere to create a phase shift in a RF beam. Increased atmospheric ionization and therefore an increased RF phase shift can be achieved if SNM is actively interrogated by an external source of gamma rays or neutrons. The RF phase shift resulting from passing through a low-density plasma can be detected using an appropriate RF antenna coupled to signal processing electronics and sensitive interferometry. Initial calculations on the most limiting case, natural gamma ray emissions from bare, metallic HEU, indicate a phase shift of approximately 3 degrees that could be detected from a 100 m standoff distance. If active interrogation is assumed, the expected phase shift is even greater. The availability of a system that can detect SNM from a distance greater than 100 meters will enable monitoring and detection of SNM from aircraft or ground based platforms, filling the security gap in unmonitored areas of concern.

1.1 Problem Statement

The current sensors and systems operate either in passive or active mode. Passive or active detection modes involve the use of gas, liquid, or solid radiation sensitive materials to record signatures from radiation in the form of particles or photons emitted from SNM. Unlike the passive mode, the active mode utilizes interrogating or probing radiation like neutrons, gamma-rays or electromagnetic waveforms to generate detectable signals from the SNM. In both the passive and active systems, the radiation intensity from SNM decreases as a function of distance with the well-known inverse square law. Additionally, the air mass between the SNM and sensors attenuate the radiation emitted, making it practically impossible to detect any radiation signature at long standoff distances. We propose to develop a long standoff (at least 100 m) detection system that is based on RF probing of low-density plasmas produced as a result of radiation emission from SNM materials. This ground- or airborne-platform based system integrates radar to probe the low-density plasma, a radio frequency interferometer and associated signal processing electronics to detect reflected radio waves, and analysis software for detection and identification of SNM. The proposed RF system development will directly address the capability gap for long range standoff detection systems.

1.2 Creative and Innovative Nature

SNM and other radioactive materials monitoring is dependent on established passive or active traditional techniques that are based on the detection of emitted radiation and are limited to less than 100 meters range. While the use of RF and other frequency waveforms for plasma electron density measurements is a well established laboratory procedure [2], their use for long range standoff detection of SNM materials or radioactivity is nonexistent. Although the use for detection of radionuclide effluents from nuclear reactors was suggested in the past, it has never been implemented for the purpose. The RF approach proposed herein will be the first of its kind for monitoring of SNM and other nuclear materials for long-range standoff detection.

2.0 Objectives

The overall goal of the present project is to address the need for long range standoff SNM detection by developing and for the first time demonstrating the feasibility of a long range standoff detection system using RF probing. The following major objectives have been established toward reaching this goal.

1 Development of RF based technique for detection of SNM materials using modeling and simulation. Develop the theory behind the detection of SNM materials using low density plasma generated in different atmospheric conditions.

2 Development of the RF system based on phase shift measurement for monitoring and detection of SNM at greater than 100 meter distance.

3 Demonstration of the long range standoff detection system prototype for SNM monitoring and detection at distances greater than 100 meters.

3.0 Application

The proposed RF approach is for monitoring of SNM in difficult locations where deployment of radiation detectors is limited. The approach could be either in the form of ground or air- based platforms. The ground-based platform may involve the detection of RF in a transmission mode. This requires an RF transmitter and receiver located on either side of the suspicious object to be monitored. The ground based system may be an unmanned system with RF transmitter and receiver posts equipped with electronics and networks for remote data accessibility and handling. An air borne platform on the other hand will require the measurement of the probing RF in a reflection mode. The RF source will act as a transmitter and receiver for the detection of the SNM material. Reflection of the RF is achieved from background surfaces, such as truck beds where the suspicious nuclear material is loaded or possibly from the SNM or nuclear material container surface. The airborne platform may also be unmanned and equipped with electronics and network capability for remote data accessibility and handling. The proposed RF system has a clear advantage over the current state-of-the-art detectors in that it allows detection of SNM and nuclear material from a long standoff ranges. It is anticipated to detect materials that will result in an elevated magnitude of ion density in the nearby atmosphere. However, the proposed system design and extent will not allow the identification of radio nuclides as with some radiation detection techniques. But we strongly believe that identifying a source of radiation from a 100 meters standoff detection is a significant milestone and will be complementary to on-going research in the development of standoff active interrogation radiation sources.

It is anticipated that by the end of the project, Sandia will have developed the proposed standoff detection system to TRL4.

3.1 Key R&D Goals and Project Milestones

Goal/Milestones	Completion Date
Design and develop of the RF technique	
1. Carryout detailed modeling of atmospheric ionization of SNM from different active interrogation schemes	06/30/2012
2. Analyze atmospheric conditions with regard to ion density dispersion, recombination, etc., that may have significance in the observed RF phase shift.	09/30/2012
3. Estimate the minimum detectable phase shift for modeled conditions taking into account fluctuations in measurements. Communicate Results	12/30/2012
Develop the RF system for SNM monitoring and detection	
1. Design the RF system based on COTS components and using Sanidia's internal capabilities	03/30/2013
2. Design and fabricate RF antennas appropriate for the system	09/30/2013
3. Acquire components and integrate for testing of the RF system	12/30/2013
4. Develop the software for data acquisition and analysis Communicate results	12/30/2013
Test and Demonstrate the developed RF system	
1. Test the integrated system at either the Gamma Irradiation Facility (GIF) or High-Energy Radiation Megavolt Electron Source (HERMES) at Sandia	03/30/2014
2. Establish minimum detectable ion density	04/30/2014
3. Investigate sensitivity enhancement techniques	06/30/2014
4. Implement enhancement techniques	09/30/2014
5. Demonstrate SNM detection using radiation sources for different source strength	11/30/2014
Final Report	12/30/2014

4.0 Prior Work

Currently there are no known state-of-the-art detectors that are used for standoff detection beyond 100 meters. All known state-of-the-art SNM detection system rely on detection of radiation emitted either in a passive or active mode in less than 100 meters standoff distance. That the radiation flux diminishes due to attenuation and as the inverse square of the distance between the emitting source and the detector makes it impossible to achieve adequate signal-to-background, excluding anti-neutrinos, at distances of 100 meters and beyond. Although anti-neutrinos are an exception, the detection of this particle requires long data acquisition time and significant investment.

There have been analytical and theoretical efforts for long range (100 meters) detection of nuclear fallouts and radioactive material emissions from nuclear plants and facilities. Work by Peurrung [3], Didenko et al. [4], and Elokhin et al. [5] describe these studies in greater detail. In all these efforts, authors address the approach of RF reflection from low-density plasma for long range standoff detection of radioactive plume emission. However these studies were focused on reflection of RF from a plasma mass that happens at critical ion or electron densities. Reflection of RF from plasma is a well established phenomenon and is the basis for radio signal propagation through the ionosphere [6], allowing radio communication around the globe. RF reflection has been also reported in the detection of Gamma Ray Burst (GRB) from the outer space [7]. Effluent emissions from reactors, however, were found to be less than the critical electron density for reflection of RF waveforms. Unlike these studies of RF reflection from the plasma mass, our proposal relies either on transmission of RF through the plasma mass and detection of the RF at the opposite side of the RF source or reflection of RF from background surfaces where SNM or nuclear material is localized and detection at the same side as the RF source. The transmitted or reflected waveform will undergo a phase shift due to a refractive index change caused by the ion density generated in the surround atmosphere from SNM radiation. This phase shift will be the key in our proposal for long range standoff SNM detection.

Wondwosen Mengesha has previous experience in RF phase shift measurements and plasma analysis using Network Analyzers. He has led several projects as a Principal Investigator (PI) and Project Manager (PM) in past. **Billy C. Brock** has over 34 years of experience in the fields of RF antennas, propagation, and electromagnetic analysis. His expertise includes broad-bandwidth antenna design, phased-array antenna analysis, polarimetric radar, radar-cross-section measurement and analysis, ionospheric propagation, electromagnetic propagation in magnetoplasma, and electromagnetic propagation in soil. **Nathalie Le Galloudec** has experience in experimental high energy density plasma research on high intensity laser target interactions with flat and conical targets, electron transport, optical diagnostics, particle and x-ray emission to optimize target and laser for applications. **Isaac Shokair** has 25 years experience in physics modeling and development of data analysis methods and detection algorithms. Currently he is involved with data analysis methods and gamma spectroscopy in several projects.

5.0 Proposed work and Scientific Basis

5.1 Proposed Task

The objectives of the proposed project will be accomplished through the performance of the following tasks.

Task 1 — Develop the RF technique and approach for monitoring and detection of SNM at a distance greater than 100 meters (**Objectives 1, 2**). Detailed study and simulation of ion generation in the atmosphere due to terrestrial, cosmic sources, and other sources including SNM will be conducted.

Task 2 Model typical ambient atmospheric conditions, including turbulence, wind, and humidity (**Objectives 1, 2**). Investigate the atmospheric impact in the ion mass or low-density plasma surrounding SNM materials.

Task3 Estimate system sensitivity required for monitoring and detection of SNM at greater than 100 meter distances. Investigate and evaluate transmitted and reflected radio wave intensity under varying ionization conditions involving a spectrum of gamma energies from SNM. The GIF and HERMES at Sandia National Laboratories (SNL) will be used for active interrogation of Highly Enriched Uranium (HEU) (**Objective 3**).

Task 4 Investigate the impact of background radio signals that can be a deterrent to the proposed system functionality (**Objectives 2, 3**).

Task 5 Appropriate data analysis techniques, including FFT and pattern recognition, will be investigated to enhance signal-to-noise ratio (SNR) of the system (Objectives 3).

Task 6 Demonstrate feasibility of the proposed RF system. A prototype will be developed to effectively demonstrate SNM detection at a distance of at least 100 meters. (**Objective 4**).

5.2 Technical Approach and Scientific Basis

SNM detection at distances greater than 100 meters using the RF approach exploits the fact that SNM materials emit energetic photons that travel past the container unabsorbed. The photons, or gamma rays, upon interaction with the surrounding air mass produce ionization. The ionization is a continuous process and creates a low-density plasma mass surrounding the SNM. The energetic photons from SNM materials have a mean free path given by:

$$MFP = \frac{\int_0^\infty r e^{-\mu r} dr}{\int_0^\infty e^{-\mu r} dr} = \frac{1}{\mu} \tag{1}$$

where μ is the energy dependent linear attenuation coefficient in air (ρ_{air} = 1.2754 kg/m^3 at standard temperature and pressure (STP)), r is the radial distance travelled by gamma rays from the source location. The MFP for a range of energy calculated is shown on Figure 1. A gamma ray of 1 MeV energy, that is one of the signature energy from SNM material, can have an average MFP reaching to 100 meters.

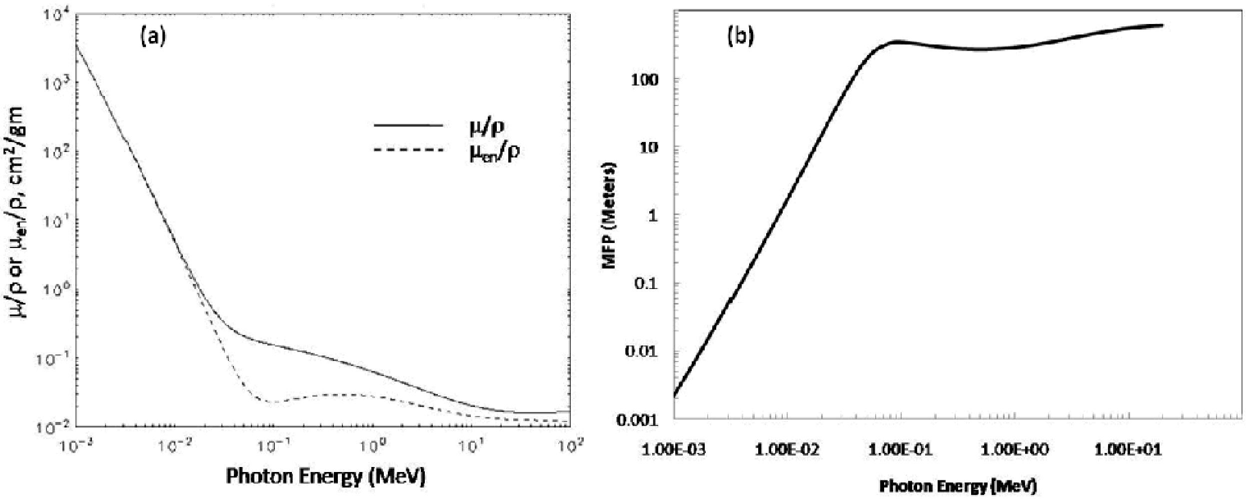

Figure 1 (a) Mass and Energy absorption coefficients in air as a function of photon energy. (b)Calculated mean free path for a range of gamma ray energies. Dry air at STP was assumed in the calculation of the MFP [8].

5.2.1 Background radiation caused ion density

The background ion content in air is due to cosmic and terrestrial. The equilibrium ion density, d_I, in air is given by the simple formula[3]:

$$d_I = \sqrt{\frac{q}{\alpha}} \ , \qquad (2)$$

where q represents the ionization rate and α is the recombination rate in air. The existence of radiation sources, such as SNM, tends to elevate the ion density within a volume of air determined by the gamma energy mean free path (MFP). The MFP may vary for different energy gamma rays in accordance with the mass attenuation coefficient for the particular energy (Figure 1(b)). Knowledge of typical ionization density in air from the different background sources is vital in designing of the proposed RF system for SNM detection and monitoring. Study made by Daling et al. [9] gives some idea on possible ion density as a result of background radiation in air. However their data may or may not encompass all levels at other areas. Daling et al. reported measured dose rates at one meter from the surface of the ground for control and areas of elevated levels of background radiation. Based on their measured dose rate data, respective ion densities were calculated as shown in Figure 2(a) and 2(b) for control and high background radiation area measurements respectively. For comparison with the background radiation produced ion density, a crude calculation of 1 kilo-gram (kg) of U-235 (186 keV) and Pu-239 (413 keV) (both on the order of milli Curies) were made. Since the calculation was meant to give a rough estimate, no account was made for internal absorption, shielding, cascade emissions, and may not reflect an accurate figure for all smuggling scenarios. Detailed work on the expected ion densities from these materials taking into account all the factors including atmospheric attributes will be made in the initial stage of the proposed project. But one can see from those figures shown in Figure 2, that ion densities from SNM materials can be significantly higher than those from natural background radiation to allow effective detection of SNM signatures. Under active interrogation, the ion density expected from SNM should exceed these values.

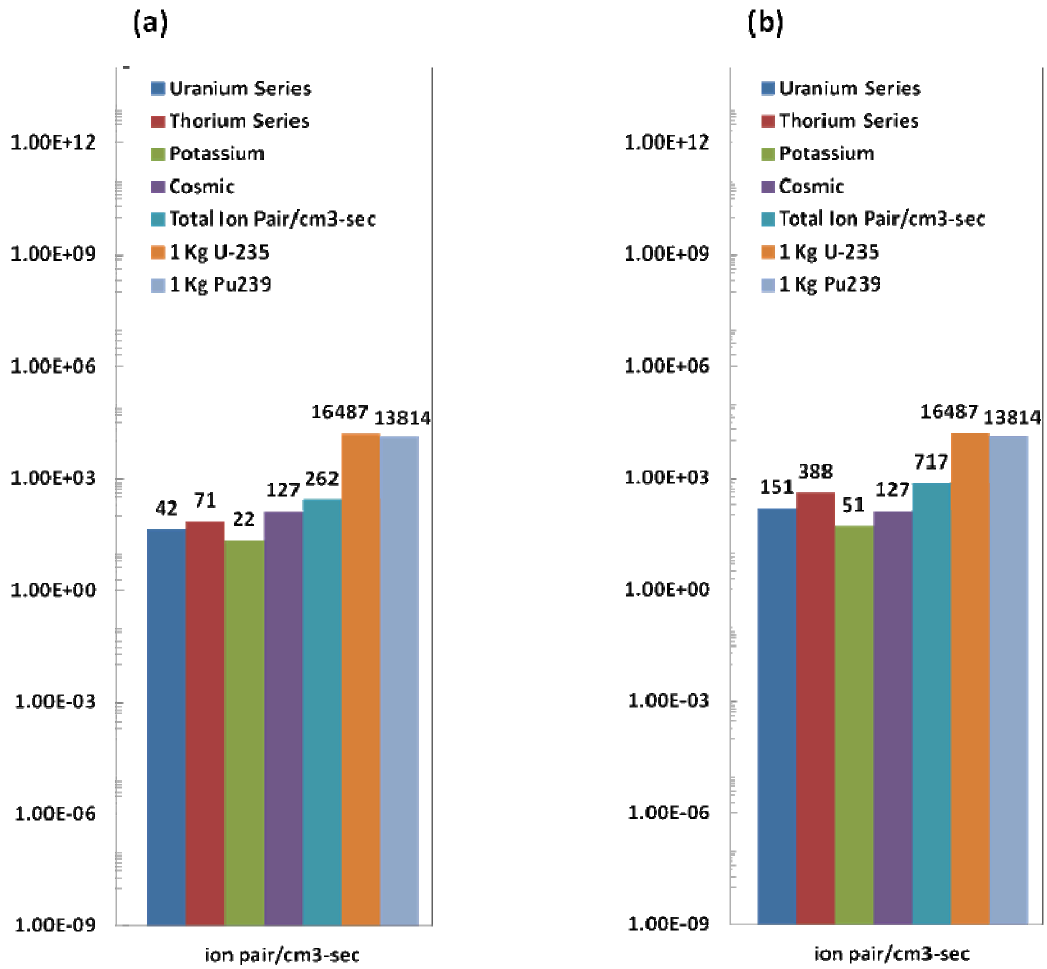

Figure 2 (a) Calculated average ion density for controlled area measurement. (b) Calculated average ion density for high background area measurements [9].

5.2.2 Electromagnetic wave propagation in Plasma

Equation describing propagation of electromagnetic waves in plasmas is derived using Maxwell equations:

$$\Delta\vec{E} - \frac{\varepsilon}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = 0 \; , \; \Delta\vec{H} - \frac{\varepsilon}{c^2}\frac{\partial^2\vec{H}}{\partial t^2} = 0 \qquad (3)$$

where c is the speed of light and ε, the dielectric constant.

For non-magnetized plasma, the key factors governing the propagation of electromagnetic (EM) wave in plasma are the plasma conductivity and dielectric constant [10]. Solving for the one-dimensional electron motion in the electric field of EM wave with frequency ω results in the dielectric constant that is given by real and imaginary parts as:

$$\varepsilon = \varepsilon_\omega + i\frac{\sigma_\omega}{\varepsilon_0\omega} , \tag{4}$$

where ω is the EM wave frequency, σ_ω is the plasma conductivity, and ε_ω is the real part given by:

$$\varepsilon_\omega = 1 - \frac{\omega_p^2}{\omega^2 + \nu_{en}^2} , \tag{5}$$

,

where υ_{en} is the electron neutral collision frequency and ω_p is the electron plasma frequency. The plasma conductivity is also given by the expression:

$$\sigma_\omega = \frac{n_e e^2 \nu_{en}}{m(\omega^2 + \nu_{en}^2)} , \tag{6}$$

For collision less plasma, the previous equation may reduce to:

$$\sigma_\omega = \frac{n_e e^2 \nu_{en}}{m\omega^2} , \quad \varepsilon_\omega = 1 - \frac{\omega_p^2}{\omega^2} , \tag{7}$$

If the plasma conductivity is not high, $\sigma_\omega << \omega\varepsilon_0|\varepsilon|$, and EM waves propagate easily for sufficiently high frequency. However when the frequency decreases, the dielectric permittivity, ε_ω, becomes negative and the electromagnetic wave is unable to propagate. Negative values of ε_ω make the refractive index ($n = \sqrt{\varepsilon}$) equal to zero and the attenuation coefficient, $\kappa \sim \sqrt{|\varepsilon|}$. In this case, the depth, l, of EM wave penetration in plasma is given by:

$$l = \frac{\lambda_0}{2\pi\sqrt{|\varepsilon_\omega|}} = \frac{\lambda_0}{2\pi}\left|1 - \frac{\omega_p^2}{\omega^2}\right|^{-1/2} , \tag{8}$$

where λ_0 is the EM wavelength at the critical frequency.

In this particular case of interest, the EM depth of penetration does not depend on the conductivity and is not related to energy dissipation. Such node dissipative stopping of EM is the phenomenon of total EM wave reflection from the plasma. The total reflection of electromagnetic waves takes place when the electron density in the plasma reaches the critical value, when $\omega = \omega_p$ and is given by:

$$n_e^{critical} = \frac{\varepsilon_0 m \omega^2}{e^2} \quad , n_e(cm^{-3}) = 1.24 \times 10^4 \times [\nu(MHz)]^2 . \tag{9}$$

However in present proposal context, such critical ion/electron density is not achievable with SNM material of interest. The expected ion density is far lower than the critical density requirements for RF reflection. RF propagation through this low ion density plasma is maintained and with an expected RF phase shift due to change in refractive index of the medium.

5.2.3 Phase Shift in RF waveform propagating through low density plasma

The phase change for an RF going through the low density plasma mass is given as [11]:

$$\varphi = \int k dl = \int N \frac{\omega}{c} dl \tag{10}$$

where k is the wave number, ω is the angular frequency, N is the refractive index, and c is the speed of light. The phase shift is then determined using a reference RF without a plasma mass, k_0, and with plasma k as in the case of interferometry measurement.

$$\Delta\varphi = \int (k - k_0) dl = \int (N-1) \frac{\omega}{c} dl \tag{11}$$

where $N^2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c}$, n_e is the electron density, ω_p is the electron plasma frequency, and n_c is the critical density at which the wave stops propagating (equation (9)).

For $n_e \ll n_c$

$$\Delta\varphi = \frac{\omega}{c} \int \left[\left(1 - \frac{n_e}{n_c}\right)^{1/2} - 1 \right] dl, \quad where \left(1 - \frac{n_e}{n_c}\right)^{1/2} = N \approx 1 - \frac{n_e}{2n_c}$$

$$\Delta\varphi = \frac{-\omega}{2cn_c} \int n_e dl \tag{12}$$

Using the above formulation for the phase shift, for varying electron density, one calculates the phase shift as shown in Figure 3. A uniform electron density through the path of integration is assumed, which might not be a realistic case. A reference electron density for assessing feasibility of the idea would be in the range 10^4-10^5/cm^3. Looking to the Figure 3 the phase shift for such electron densities is possibly measurable provided that one implements an interferometry technique with enhanced sensitivity and devise means for sensitively handling the fluctuation in the ion density and address background radiation caused ion density.

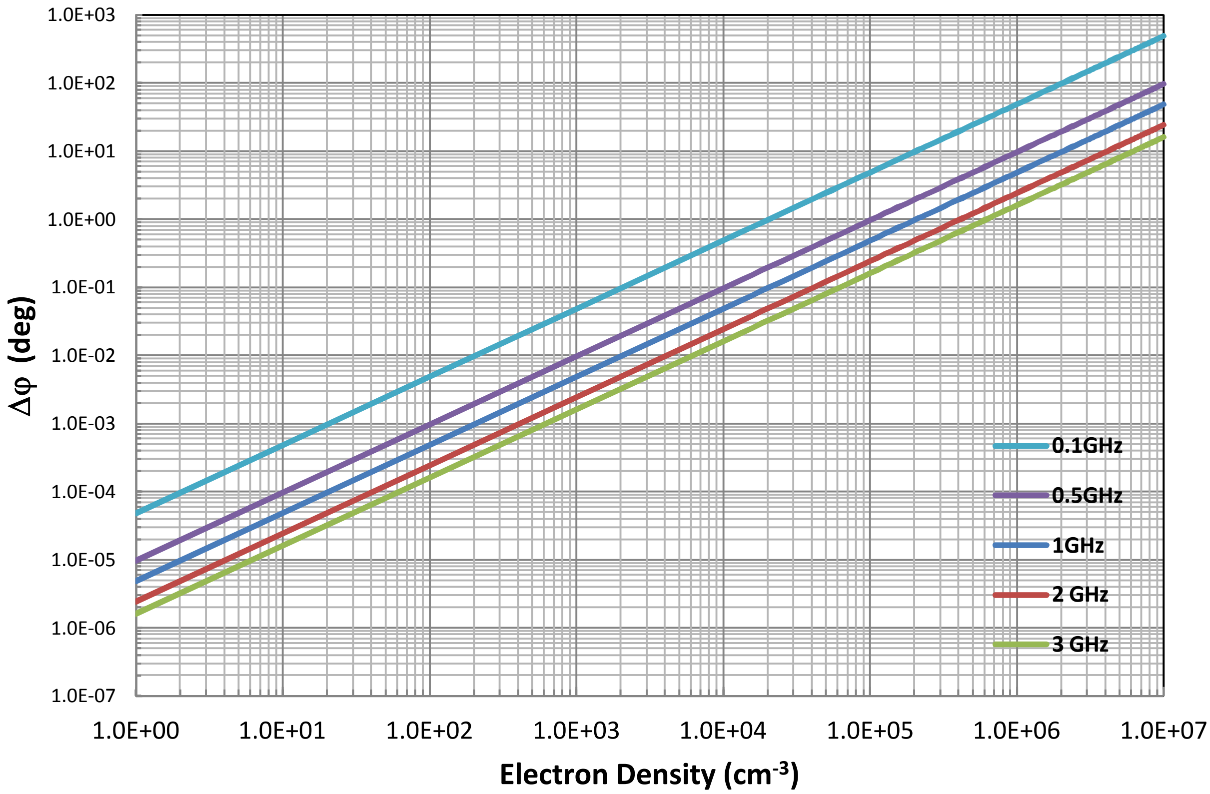

Figure 3. Phase shift as a function of electron density.

5.2.4 Atmospheric Dispersion Modeling

Ionized air near an SNM is not static and is subjected to turbulence, humidity, and motion, based on temperature, pressure, wind, and other environmental factors. The MFP estimated in Section 5.2 is for an ideal STP and static atmospheric condition. The ionized mass of air besides the continuous generation and recombination processes is dependent on the atmospheric factors and on the exact volume and size of ionized air. Modeling and simulation are instrumental and can give some picture of the ionized air mass dynamics. Meteorological data and the atmospheric modeling tool will assist in studying the extent of ionized mass dispersion around SNM and its impact on the analysis RF phase shift due to propagation in SNM created low density plasma.

5.2.5 Fast Fourier Transform (FFT) Technique for Reflected or transmitted RF Wave Analysis

The FFT technique will be implemented to analyze known and unknown RF signals. In the present context, the known signals are the transmitted or the reflected signal from the probing RF that has gone through the low-density plasma. The unknown signals may be all those RF signals from the background; these may be considered as noise in the measurements.

6.0 Technical Issues

Several technical issues should be addressed that can be a hurdle in the effective implementation of the proposed technique. These may include:

1. What is the extent of ionization (low-density plasma) in the air surrounding an SNM material? This question involves the creation of ions and their recombination thereafter. The larger the volume and constancy of the ion mass within the air, the better the sensitivity for the radio wave that probes the SNM materials. Modeling and simulation will be carried out under varying detection setups to investigate the state of the low-density plasma.
2. How significant is the ambient weather around the SNM material in obscuring signatures from being detected by the RF approach? Wind, rain, and other parameters might have some impact on the process of the proposed SNM detection. Modeling of air turbulence with varying moisture and other parametric factors will be made in the investigation.
3. What is the extent of ion density from the background radiation signal? The background caused ion density may impact the sensitivity of the proposed approach. Sensitivity of the proposed system for varying background caused ion density will be calculated and measured. Techniques will also be devised to eliminate background caused fluctuation and contribution.
4. Last but not least will be addressing noise from background radio-signals that are ambient in the atmosphere. Appropriate filtering techniques, such as FFT, will be implemented to address such issue.

7.0 Potential users for the proposed RF system

In addition to NNSA and DTRA, other potential users include DOD and DNDO for monitoring of SNMs, illicit radioactive materials, and weapons of mass destruction (WMD). The proposed system can be incorporated by the U.S. Army into the existing Web and network for SNM monitoring, which will benefit from this proposed system. The proposed system may also have significance in the nuclear industry for a number of applications requiring radiation source monitoring.

8.0 Funding Requirements

8.1 Budget breakdown

FY	Total	Labor	Purchases	Travel	Capital
2012	$750K	$630K	$100K	$20K	
2013	$800K	$630K	$150K	$20K	
2014	$850K	$630K	$200K	$20K	

9.0 Key Research Team Members

Wondwosen Mengesha has previous experience in RF phase shift measurements and plasma analysis using network analyzers. He offers a broad-based experience in radiation detection and testing, acquired in academia, in the NNSA national laboratories, and private companies. He was also involved in designing and testing state-of-the-art radiation sensors for Homeland Security applications, optimizing radiation sensors using advanced Monte Carlo tools, including

GEANT4, and developing innovative concepts in radiation detection. He has led several projects as a PI and PM.

Billy C. Brock has over 34 years of experience in the fields of antennas, propagation, and electromagnetic analysis. Brock's expertise includes broad-bandwidth antenna design, phased-array antenna analysis, polarimetric radar, radar-cross-section measurement and analysis, ionospheric propagation, electromagnetic propagation in magnetoplasma, and electromagnetic propagation in soil. Selected plasma related Sandia National Laboratories reports by Brock include:

-Ionospheric effects on a wide-bandwidth, polarimetric, space-based, synthetic-aperture radar, SAND92-1967, January 1993.

-A Method for Transionospheric Electromagnetic-Propagation Analysis for Evaluation of Space-Based Synthetic-Aperture-Radar Performance, SAND95-2436 (Specified Dissemination Only), October 1995

-Modulation of a Microwave Signal by Time-Varying Plasma, SAND99-3148 (Export Controlled Information), December 1999

-Electromagnetic Propagation through Turbulent Boundary-Layer Plasma, SAND2002-3316 (Export Controlled Information), November 2002

Nathalie Le Galloudec has 15 years of experience in plasma physics, more specifically high energy density physics of laser target interactions and z-pinch physics. She has experience in optical, x-ray and particle diagnostics either as self-emission or as a probe in high electromagnetic noise and debris environments.

Isaac Shokair has 25 years experience and worked on a variety of projects including Transport of charged particle beams, ICF, Electromagnetic launcher technology, and Standoff detection using UV-LIF Lidar. Current activities include data mining, spectroscopic data analysis, modeling and simulation for radiation detection applications, and development of detection/discrimination algorithms for spectral detection of targets of interest in complex and unknown environments.

10.0 Facilities

Sandia has several facilities that can help in the effective implementation of the proposed project. Some of the facilities that will be used during the project are briefly described below.

10.1 Gamma Irradiation Facility (GIF)

Gamma **I**rradiation **F**acility (GIF) provides a single structure for performing a wide diversity of gamma irradiation experiments with various test configurations and at different dose and dose rate levels. It is divided into two types of irradiation facilities, in-cell dry and in-pool wet, based on the type of test to be performed.

10.2 High Energy Radiation Megavolt Electron Source (HERMES)

The **H**igh-**E**nergy **R**adiation **M**egavolt **E**lectron **S**ource (HERMES) III accelerator is the world's most powerful gamma simulator, producing 13 TW of power in a 19-MeV, 700-kA, 28-ns electron beam. HERMES uses technology developed by Pulse Sciences, Inc. and Sandia National Laboratories in the joint Defense Special Weapons Agency/Department of Energy Linear Induction Accelerator program, and can provide eight shots per day, four days per week.

10.3 Plasma Materials Test Facility (PMTF)

The **P**lasma **M**aterials **T**est **F**acility (PMTF) at Sandia National Laboratories is a DOE designated user and Work for Others (WFO) Facility. This designation permits outside private companies and universities to either visit and use the facility when no DOE experiments are underway or contract Sandia directly through a work for others agreement to perform testing. Some of the research conducted at the PMTF includes:

1. Modeling of plasma/material behavior and interaction. A fully equipped computer laboratory is housed at the PMTF for analytical and experimental support of high-heat flux experiments.

2. Materials characterization. Materials characterization capabilities at the PMTF include a new high resolution, large area scanning electron microscope (SEM). The SEM has a resolution of 10 nm and is equipped with Energy-dispersive X-ray spectroscopy (EDX) and secondary electron analyses and backscattered electron imaging. Unique features of this SEM are its large vacuum chamber (~1 m dia.) and its large sample platen (25 cm x 25 cm in area).

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