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TRIPWIRE: Multi-Modal Distributed Sensing for Repository Verification

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ABSTRACT

Underground geological repositories for storing used nuclear fuel are being planned and developed around the world. Research is being performed to understand technical aspects of sealing entombed materials and underground repositories to ensure the radiological and nuclear materials remain contained. To support safeguards verification for these facilities research at Idaho National Laboratory (INL) is underway to develop and demonstrate a multi-modal sensor system, TRIPWIRE, for containment verification in inaccessible radiological and nuclear waste repositories. The TRIPWIRE system will continuously monitor ionizing radiation and electromagnetic fields in the vicinity of emplaced nuclear materials buried in a repository, reporting on disturbances with a real-time alarm control station. The system will use long-length scintillating fiber bundles (SFBs) to perform area radiation monitoring; these will be coupled to kilometer-scale multimodal optical communication fibers – all light sensors and electronic components used with this system will be located above ground. Electromagnetic fields, and changes in local dielectric conditions caused by intrusion and soil movement, will be monitored using commercial grade, ported "leaky" coaxial cables (PCCs), with control electronics also located above ground. Tamper-indicating self-diagnostic assessments will be done using optical and electronic time domain reflectometry in the SFBs and PCCs, respectively. The result will be a long, kilometer-scale multi-modal SFB-PCC system. Simulation and modeling are being used to inform the work and a demonstration of the system's utility is planned at a nuclear storage facility in the future.

INTRODUCTION

Many countries are making progress towards building and commissioning underground used nuclear fuel repositories. TRIPWIRE aims produce the first passive underground sensors system suitable for long-term deployment and use within underground geological repositories during both loading operations and in post-operation entombment/closure. Since the TRIPWIRE concept uses below-ground components and keeps all electronics and data processing computers in above ground, accessible areas, it has the potential for extremely long-term deployed operations. If/when photon and electronic measurement equipment fails it can be easily replaced. As new advances are made in instrumentation and computers the entire data acquisition system can easily be upgraded and replaced. Also, since the system serves as a real-time process monitor, the data streams from the emplaced sensors may find use, when integrated with other types of data, within a larger data-analytics architecture supporting machine learning and big data science.

This capability will allow detection of undeclared access to a sealed underground repository; detection of non-natural activity in the vicinity of nuclear storage containers including casks, metal drums, and large metal boxes; and detection of the movement or removal of radioactive and nuclear materials from the repository. To achieve this, system will continuously monitor ionizing radiation and electromagnetic fields in the vicinity of emplaced nuclear materials buried in a repository. An illustration of the distributed sensors with notional locations is shown in Figure 1. The electromagnetic sensors are shown in green and the radiation sensors in red. An additional vibration sensor is shown in yellow.

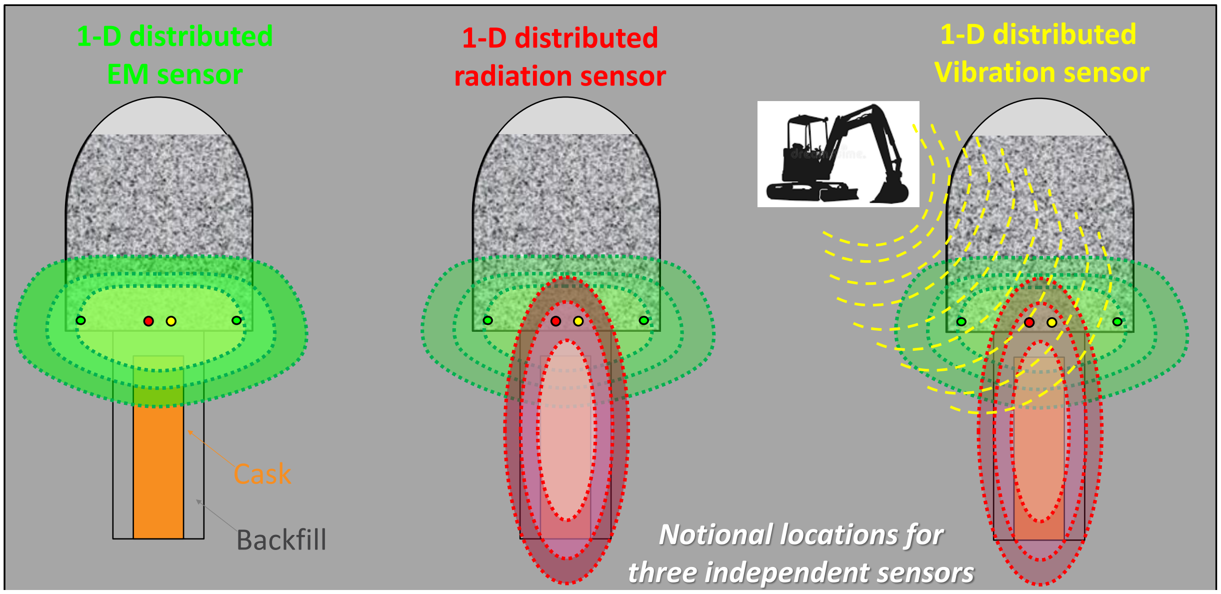

Figure 1. Illustration of three independent 1-dimensional distributed sensors with notional locations.

RADIATION SENSING

Small-diameter, organic scintillating fibers were studied previously at INL, being applied as one-dimensional linear sensors to monitor and characterize ionizing radiation fields over long distances or over large areas [1]. As the fiber's core material is polystyrene, which has a low-Z value, their main mechanisms for radiation interaction are photelectric absorption and Compton scattering. In both cases electrons deposit energy in the fiber leading to photon generation which is then scattered as it travels to the photomultiplier tube (PMT) where it is detected and measured.

Background

Commercial plastic scintillating fibers are usually fabricated in cylindrical shapes with a core of polystyrene and fluor in which the scintillating light is generated through interaction of the incident radiation. The core is surrounded by a thin cladding material which is typically acrylic, more specifically polymethylmethyacrylate. Light rays that arrive at the core-cladding interface with an angle of incidence that is greater than the critical angle for total internal reflection are "piped" down the length of the fiber. To achieve maximum light yield in small (tenths of a millimeter to several millimeter) diameters, a high fluor concentration of several percent is typically used. Other fibers may contain a wavelength shifter which is used to absorb the primary scintillation fluorescence and re-emit it at a longer wavelength [2].

Preliminary Testing

Preliminary laboratory testing with a short-length scintillating fiber was conducted to establish the initial modeling framework. This experimental set-up consisted of a 2.72-m, single BCF-10 scintillating fiber inside a stainless-steel, flexible conduit tube covered by a light-tight sleeve. The tubing and sleeve are combined commercial furcation tubing with a black coating (Thor Labs Inc.)

The fiber was extended over a stainless-steel table and a 3D printed holder was used to move the sources down the length of the fiber. The fiber was connected to a Hamamatsu (H10580) photomultiplier tube (PMT) and biased at +1570 volts. Upon passing through an amplifier, a shaping time of 0.5 microseconds was applied and connected to the multichannel analyzer (MCA). The MCA data was recorded using ORTEC's Maestro software. Measurements were conducted in 20-cm increments along the length of the fiber. A photograph of the set-up can be seen in Figure 2. Inside the 3D printed holder, four Cs-137 sources were placed at the same distance from the center of the fiber; information about the sources used and their location is found in Table 1. The holder was used to slide the sources along the fiber without changing their orientation.

Table 1. Sources used inside the 3D printed holder with their position relative to the holder.

Source	**Activity (µCi)**	**Position relative to the holder**
Cs-137	20.53	Left
Cs-137	20.04	Top
Cs-137	20.85	Right
Cs-137	20.17	Bottom

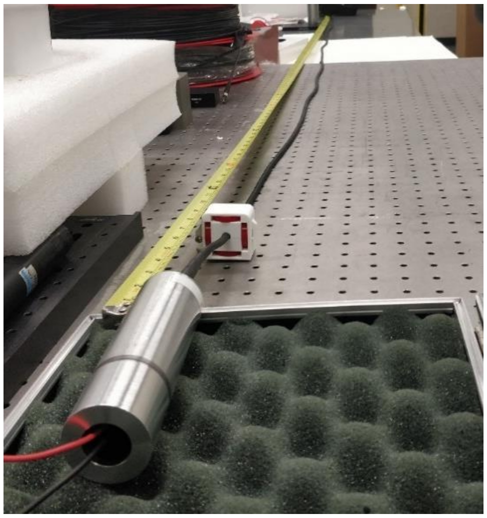

Figure 2. Experimental setup of the short-length scintillating fiber using multiple Cs-137 sources inside the 3D printed holder.

Measurements were recorded with a minimum of 100,000 counts between channels 0 to 500. The background subtracted data can be seen in Figure 3 for all the measured distances. The separation between events undergoing less light scattering at closer distances and the opposite at further distances is clearly seen. The same data with a reduced number of measurements, to help illustrate the trends, is shown in Figure 4.

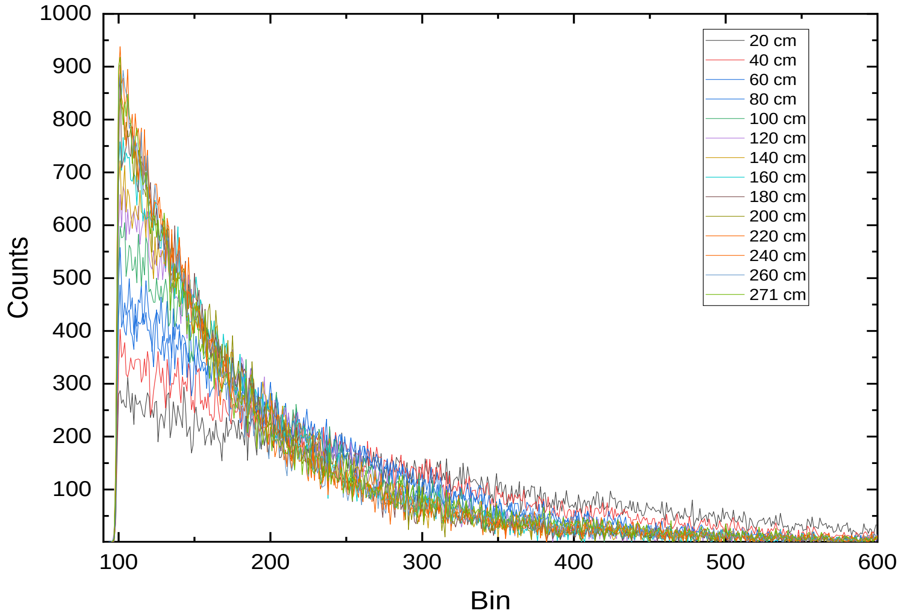

Figure 3. Experimental data for all distances along the fiber length.

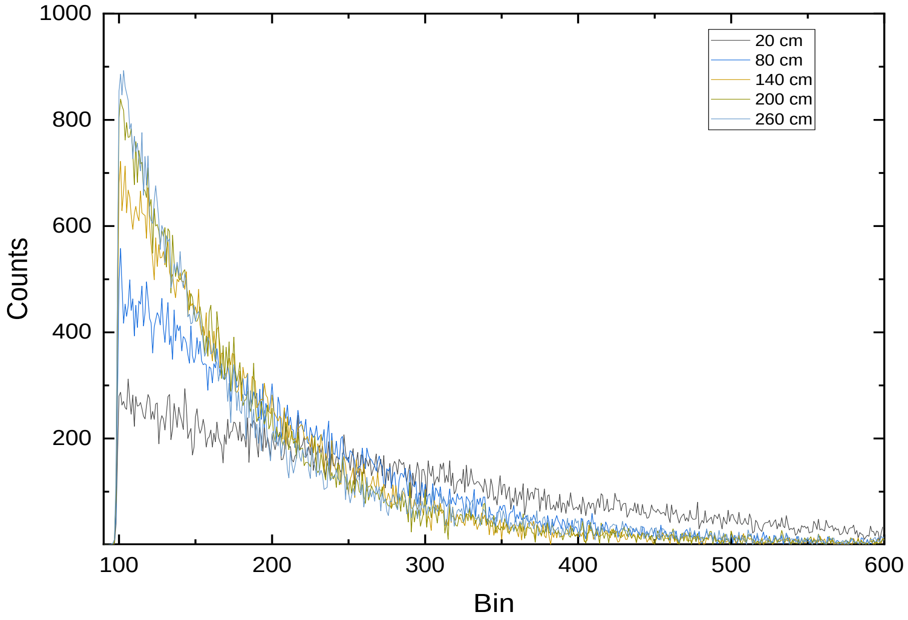

Figure 4. Experimental data for distances 60-cm apart to help illustrate the trends with the change of measurement distance.

ELECTROMAGNETIC SENSING

The current state of the art for the use of ported "leaky" coaxial cables (PCCs) as buried intrusion detection sensors is sophisticated and commercially available as a turn-key product. The basic concept of operation is that a voltage is applied to a long-length 'transmit' cable with poor electromagnetic shielding to produce a pseudo-static electric field in the nearby vicinity of the cable, a second 'receive' cable is then used as an 'antenna' to sense the intensity of this static electric field. If anything alters the dielectric properties near the transmit-receive cable pair (to a range of several meters) the received signal is then altered, resulting in a transient in the steady-state signal; this transient condition is then used as an alarm trigger criterion. In a typical security installation, the cables are buried several inches below grade, as a part of a Perimeter Security Detection System (PIDAS), and detection is based on the field perturbation cause by a human crossing over the cables.

Theory

The signal traveling inside the cable propagates in a normal coaxial model with radial electric field lines and circular magnetic lines between the inner and outer conductor. The inner coaxial cable is a closed wave guide set up between the inner and outer conductor. There is an outer coaxial field produced by the energy which couples through the apertures in the outer conductor causing it to be an open wave. This field decays with radial distance from the cable at a rate which is related to the permittivity and conductivity of the burial medium [3]. The propagation characteristics of coaxial cables have been studied since for this purpose since the 1970s [4][5][6]. According to Fernandes [7], the outer coaxial cable mode can be represented as follows:

Longitudinal field:

$$E_z = A_0 H_0^1(jh_0 r)e^{-\gamma z} \tag{1}$$

Radial field:

$$E_r = A_0 \frac{\gamma}{h_0} H_1^1(jh_0 r)e^{-\gamma z} \tag{2}$$

Coaxial:

$$H_\theta = A_0 \frac{k_0^2}{\omega \mu_0 h_0} H_1^1(jh_0 r)e^{-\gamma z} \tag{3}$$

where r = radial distance

h_0 = transverse wave number $\left({h_0}^2 = \gamma^2 - {k_0}^2\right)$

k_0 = complex wave number $(k_0 = \omega\sqrt{\varepsilon\mu})$

γ = propagation factors

A_0 = a constant to be determined when the normalization of the field is done

H_0^1, H_1^1 = Hankel functions of the first kind for orders zero and one

ε, μ = the complex permittivity and permeability

The arguments of the Hankel functions can be replaced by Modified Bessel functions of the second kind and orders zero to one:

Longitudinal field:

$$E_z = -A_0 \frac{2}{\pi} K_0(h_0 r) \tag{4}$$

Radial field:

$$E_r = -A_0 \frac{2\gamma}{\pi h_0} K_1(h_0 r) \tag{5}$$

Coaxial:

$$H_\theta = -A_0 \frac{2k_0^2}{\pi \omega \mu_0 h_0} K_1(h_0 r) \tag{6}$$

The limiting forms for small arguments are simplified as follows:

$$K_0(h_0 r) \cong -\ln\left(\frac{h_0 r}{2}\right) + 0.5772 \tag{7}$$

$$K_1(h_0 r) \cong \frac{1}{h_0 r} \tag{8}$$

And for large arguments:

$$K_0(h_0 r) = K_1(h_0 r) \cong \sqrt{\frac{\pi}{2h_0 r}}\, e^{-h_0 r} \tag{9}$$

As explained by Blaunstein [8], the propagation constant is directly related to the external surface impedance $\zeta_0(\gamma)$, assuming that the ground is described by a complex wavenumber (k) with permittivity (ε), permeability (μ) and conductivity (σ). According to Wait [9], the surface impedance can be calculated as:

$$\zeta_0(\gamma) = \zeta(\gamma) - \frac{\gamma^2}{\eta(\gamma)} \tag{10}$$

Where the dispersive impedance $\zeta(\gamma)$ and admittance $\eta(\gamma)$ are given by:

$$\zeta(\gamma) = \frac{\mu_0 \omega}{2\pi j} [\Lambda(\gamma) + 2A(\gamma)] \tag{11}$$

$$\eta(\gamma) = \frac{-j 2\pi \varepsilon_0 \omega}{[\Lambda(\gamma) + 2B(\gamma)]} \tag{12}$$

The functions $\Lambda(\gamma), A(\gamma)$ and $B(\gamma)$ have the form:

$$\Lambda(\gamma) = K_0(k_0 a) - K_0\left(k_0 a\sqrt{1 + \frac{4h^2}{a^2}}\right) \tag{13}$$

$$A(\gamma) = \int_0^{\infty} dx\,[u_0(x) + u(x)]^{-1}\cos(ax)\,e^{-2hu_0(x)} \tag{14}$$

$$B(\gamma) = \frac{{k_0}^2}{k^2}\int_0^{\infty} dx\left[u_0(x) + \frac{{k_0}^2}{k^2}u(x)\right]^{-1}\cos(ax)e^{-2hu_0(x)} \tag{15}$$

After a series of approximations detailed by Blaunstein [8] and using the quasi-static limit results in:

$$\gamma_c = jk_0\sqrt{\frac{\ln\left[\left(\frac{2h}{a}\right)\left(1 - \frac{j2}{\rho}\right)\right]}{\ln\left(\frac{2h}{a}\right)}} \tag{16}$$

From equation 10, the solution can be presented as:

$$\gamma = \sqrt{\eta(\gamma)[\zeta(\gamma)] - \zeta_0(\gamma)} \tag{17}$$

Or, in the quasi-static limit:

$$\gamma = \gamma_c\sqrt{1 - \frac{\zeta_0(\gamma)}{\zeta_c}} \tag{18}$$

To calculate the density of power at any point the field values must be related to an arbitrary level. This can be done, for example, assuming that 1 watt is applied to the cable in a lossless condition. By relating it to 1 watt at the source and considering an antenna with 1-m^2 effective aperture, the power density distribution will be quoted in dBW. The radial component of the electric field decays with radial distance *r* relative to the field at distance r_1 as:

$$E_r(r, r_1) = 10\log_{10}\left[\frac{K_1(h_0 r)}{K_1(h_0 r_1)}\right] \tag{11}$$

These solutions can then be used to understand the limitations and thresholds of the PCC system. It can be optimization through data binning, delay compensation, and detailed analysis of the waveform signal.

Equipment

After a series of conversations with multiple electromagnetic intrusion detection system commercial vendors, a down selection for a purchase was made in March 2020. The chosen ported-coaxial cable detection system is the OmniTrax by Senstar. The system is advertised as capable of detecting and locating perimeter intrusions over a distance of up to 800 m per sensor processor and pinpointing intrusion to within one meter. OmniTrax uses digital circuitry to collect and process the signals using a field-programmable gate array housed in the processing unit, shown in Figure 5.

Figure 5. OmniTrax processor with 4 receive and transmit ports inside the enclosure.

The PCC system has been assembled and operational testing has begun. Photographs of this set-up are shown in Figure 6. The PCC system is on the laboratory bench on the first floor while the transmitting and receiving lines extend through the ceiling to the floor above. This set-up allows the system to be characterized through controlled alarms in separate sections along the floor.

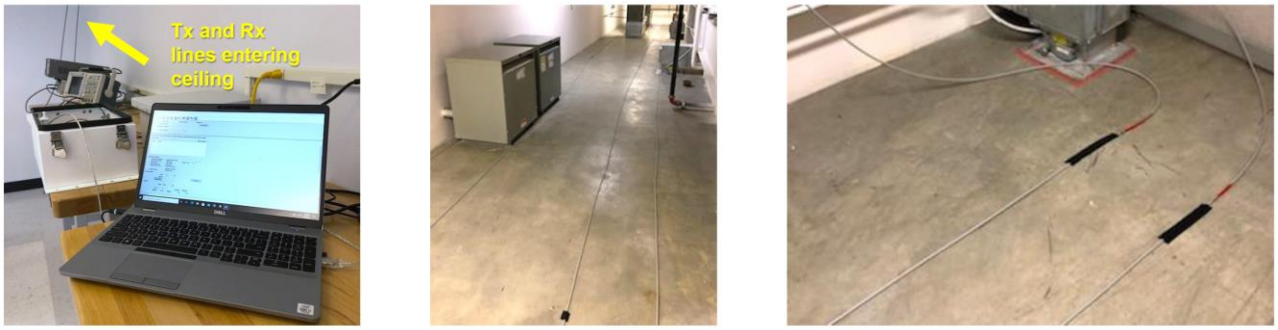

Figure 6. Photographs of the PCC system on the lab bench with transmitting and receiving lines.

ALGORITHMS AND ALARMING

Given the expected amount of data from the scintillating fibers and the PCC, machine learning (ML) is ideal to incorporate the TRIPWIRE multi-modal data streams. Using the current experimental data, ML techniques for signal processing are being explored. These techniques will also apply to data filtering, alarm thresholds, sensitivity, system-health, and tamper-indication diagnostics. Laboratory data will be key to understand the data trends as mentioned earlier and will serve as the first step towards creating a set of algorithms for these data streams. This data will also aid ML by helping train the model and increase its robustness.

One of the primary challenges is the need to monitor nominally constant signals/rates that slowly changes due to drifts in their data acquisitions chains. These include thermal drift at diurnal and annual times scales, component ageing over multi-year times scales, and signal changes due to radioactive decay, potential container degradation/breech

CONCLUSION

Research is underway to develop and demonstrate a multi-modal sensor system for containment verification in inaccessible radiological and nuclear waste repositories. The TRIPWIRE system will continuously monitor ionizing radiation and electromagnetic fields in the vicinity of emplaced nuclear materials buried in a repository, reporting on disturbances with a real-time alarm control station. The system will use long-length scintillating fiber bundles to perform area radiation monitoring. These scintillating fibers have been characterized up to several meters to understand the signal to noise ratio along the fiber. For electromagnetic sensing, the system will use PCCs which produce an alarm based on its electromagnetic field perturbation. Experimental work continues with the scintillating fibers to understand the radiation detection capabilities in 10 and 50-m fibers. The PCC and vibration commercial systems continue to be assessed to create a custom framework and inclusive control system.

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