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Detection of Underground Tunnels with a Synchronized Electromagnetic Wave Gradiometer

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ABSTRACT

Cross-border tunnels have been used by drug, people smugglers and terrorist organizations for clandestine entry or exit and transportation of contraband materials under the borders. The ability to detect these tunnels is paramount to successful border control. The Synchronized Electromagnetic Gradiometer uses the enhanced conductivity associated with tunnels, as compared to the surrounding medium, to detect the tunnels. A low-frequency electromagnetic (EM) signal is used to illuminate the area of interest. This signal, in turn, induces current flow in any conductors within the tunnel that generate secondary EM fields observable at a distance from the tunnel. The magnitude of the secondary wave can be orders of magnitude less than the illuminating signal. An efficient detection system has been achieved by using a gradiometer design that suppresses the illuminating signal by more than 70 dB while maximizing the secondary signal with a narrow bandwidth (BW = 1 Hz) synchronized receiver. This paper describes the performance of the Synchronized Electromagnetic Wave Gradiometer during several field studies and demonstrations including the Otay Mesa cross-border tunnel near San Diego, California.

Keywords: electromagnetic gradiometer, tunnel detection, gradiometry, synchronization receiver, perimeter defense

1. INTRODUCTION

Engineering studies, along with supporting field tests, have shown that the electromagnetic wave gradiometer can locate and map underground passages in real time. The burial depth and orientation of an underground passage can be estimated from single traverses over a tunnel. Field tests have demonstrated that the high signal-to-noise ratio in the measured gradient data eliminates the need for extensive post-processing to identify simple target structures like a single tunnel. For more complex passages, the responses from multiple conductors within the underground facility would have to be de-convolved from the acquired data in order to provide a detailed characterization of the facility.

The high signal to noise ratio are achieved through evolution in gradiometer receiver design which has been sponsored by the Air Force Research Laboratory High Frequency Active Auroral Research Program (HAARP). A synchronization receiver channel was added to the design so that the gradiometer receiver could be synchronized to the primary wave illuminating the structure, thus maximizing the gradiometer receiver threshold sensitivity. The advantage of synchronization is that the gradiometer can be used with standoff transmitters with no physical connection to a remote transmitter. The EM gradiometer, in various versions, has been used in the detection of a known border-crossing tunnel near San Diego, California, railroad tunnels near Raton, New Mexico, and a mine complex in Alaska.

2. BRIEF HISTORY

Since early history, people have attempted to avoid detection through underground activity. In the Roman siege on Fidenae (435 BC), the 1864 Union siege of Petersburg, and on through Vietnam, Bosnia and Afghanistan, tunnels have been used effectively to hide both offensive and defensive military operations. As surface activity has become vulnerable to detection along the nations borders, "coyotes" and drug smugglers have also found tunnels to be

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protective cover for their activities. Detection and imaging of underground passages has proven to be a difficult problem often resolved only by chance discovery or with human intelligence. It is not, however, an intractable problem.

The EM Gradiometer concept was developed for the US Army Fort Belvoir Research, Development, and Engineering (RD&E) activities in support of the Korean Demilitarization Zone (DMZ) tunnel-detection campaign in the late 1980s. During this effort every geophysics technology thought to have potential for tunnel detection was evaluated and the most promising concepts were tested in field data acquisition and ground truth studies. Although intelligence was the major driver in the detection of the DMZ crossing tunnels, this effort closed in 1991 with the detection of the fourth DMZ tunnel with cross-hole electromagnetic (EM) instrumentation.

The discovery, based on human intelligence, of the Otay Mesa, California, drug-smuggling tunnel in 1991 provided an opportunity for detection technologies to be evaluated against a known underground target [1, 2]. For this particular site, it was demonstrated that active low-frequency EM survey, using a surface gradiometer and cross-well instrumentation, could detected the tunnel. Since these tests, the gradiometer design has been enhanced in work sponsored by the Air Force Research Laboratory in an effort to improve the sensitivity of the sensor system and to allow operation with remote transmitters. Several test sites were identified for demonstration of improved gradiometer receiver which provided a wide range of geologic conditions. The present DeltaEM gradiometer instrumentation has been shown to provide rapid, real-time, surface-based data collection and interpretation.

3. METHODOLOGY

3.1 Physical Basis of System

The EM gradiometer method is based upon the long wavelength scattering limit of mathematical physics [3]. In a very simplified form, the method is illustrated in Figure 1. The primary EM wave from a remote EM source may be resolved into vertical (E_Z) and horizontal (E_X) components at the earth's surface overlying the underground target. The horizontally polarized E_X and H_Y fields are responsible for the primary wave traveling vertically downward into the earth. Wait's recursive formula described how EM wave energy travels vertically into the layered earth [4]. When the downward traveling EM wave interacts with a subsurface scatterer, a secondary wave forms and travels back to the surface. At the surface, the wave sums with the primary wave to form the total field, with horizontal components, E_o and H_o, the observables on the surface. If the tunnel or underground facility contains an electrical conductor, then the analysis by Harrington of the scattering problem for the limiting case of a thin electrical conductor illuminated by a uniform EM wave applies to the problem [5].

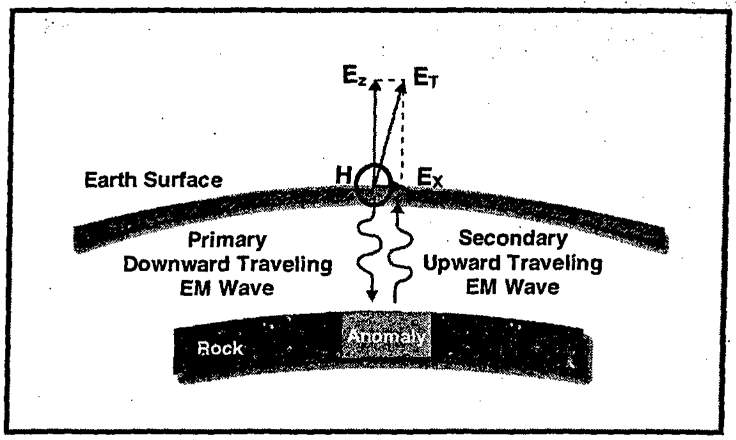

Figure 1: Traveling electric field components illustrate the tilt in the vertical electric field component

Even in the case where no apparent conductor, such as wiring, is present, detection is still possible using the EM gradiometer. This comes from the fact that the humidity in underground facilities approaches 100% and water condenses on the walls and pools on the floor. Surface water also leaches through the overlying soil or rock, bringing along dissolved salts. These salts are deposited into the micro-fractures in the void floor. The underlying floor rock (soil) electrical conductivity has been measured with in-situ cross-hole EM methods and found to increase by at least a factor of three and a factor of 10 is not uncommon. Ground control techniques, such as reinforced concrete and wire mesh, also increase electrical conductivity of rock (soil) surrounding the void. The increased electrical conductivity causes the induced current to be "channeled" along the long axis of the underground structure.

The data in Figure 2 illustrates the increase in electrical conductivity in a tunnel resulting from natural conditions in a tunnel. The in-situ cross-hole electrical conductivity measured at the Otay Mesa test site is shown in the figure as the solid curve with boxes. The corresponding linear approximation of the conductivity is also shown in the graph with diamonds. The anomaly in the conductivity at 58 ft occurs at the depth of the tunnel.

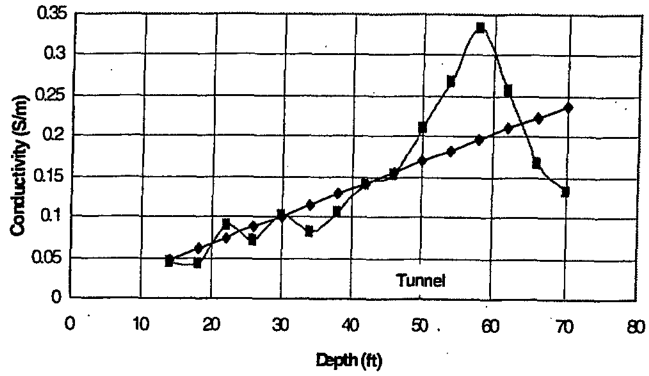

Figure 2: Dissolved salts in ground water and condensation on tunnel walls increases floor conductivity

Detection of the tunnel, the scatterer, can be achieved by finding a way to suppress the primary field so that the secondary field, which can be orders of magnitude less than the primary in amplitude, is measurable . The simplest method to achieve this suppression is gradiometry.

3.2 Theoretical Response

The secondary field, H_S, is of much lower magnitude than the illuminating primary magnetic field, H_P. The total magnetic field signature of a tunnel is the sum of these two fields and the response for the special case of non-uniform illumination of a short electrical conductor, as derived by Hill [6], is shown in the upper set of curves in Figure 3. These curves represent the fields for a conductor located at the surface axis origin, pointed into the page, and 15 meters below the sensor level. In this example, a frequency of 100 kHz was used for the primary illuminating wave although the shapes of the curves are frequency independent. These response curves illustrate the limitation in the total field EM detection method. As the primary field is much larger than the secondary field, the total field changes by only a small percent when the survey line crosses over a significant anomaly. The relatively low amplitude, spatially broad anomaly in the total field signal would be difficult to detect in normal measurement noise.

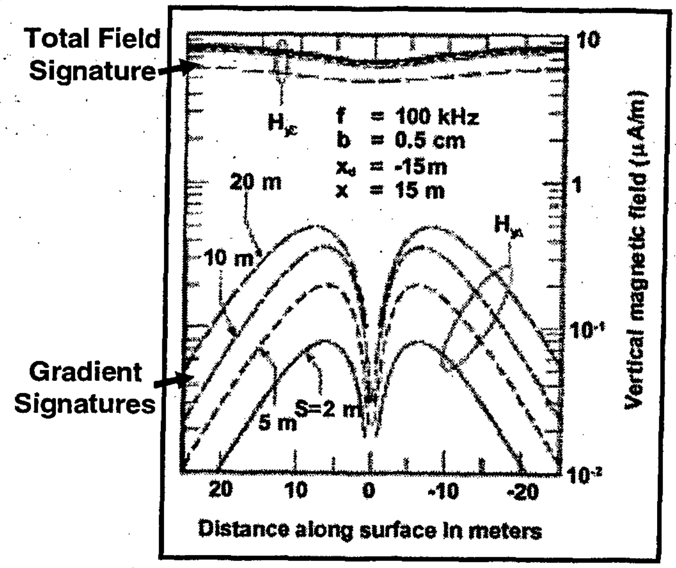

Figure 3: Surface EM total field and gradient signature responses over a conductor

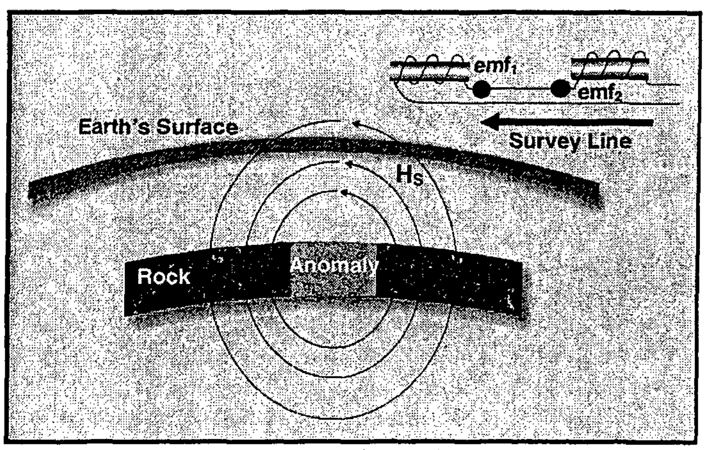

Figure 4: Secondary magnetic fields from geologic anomalies

The lower sets of curves, for an EM gradiometer, however, show a much more definitive signature for the conductor though at much lower amplitude. An EM gradiometer is simply two oppositely wound coils on ferrite rods separated by some small distance (Figure 4) forming a magnetic dipole antenna array [7]. Output signal is the voltage given by

$$emf_0 = emf_1 - emf_2 \qquad (1)$$

As the separation distance is small compared to the wavelength of the primary signal both antennas can be assumed to see it equally and differencing removes the primary field. As is seen in Figure 3, when the center point of the gradiometer is directly over the conductor, the two antennas will see fields of equal strength and the differenced output will be a null. At any other location, the closer dipole will detect a stronger field and will produce a non-zero output signal for the gradiometer. The signature is not very sensitive to dipole separation. The gradiometer response for various magnetic dipole separation distances, S, is also illustrated in Figure 3, taken from Hill [6]. A ten-fold increase in separation distances increases the response by less than an order of magnitude. While increased separation does help, it is not a significant factor in system design.

The general form of this gradiometer output curve is "M"-shaped with two peaks offset to either side of the conductor. The peak-to-peak separation is proportional to the depth of the anomaly. Kelly has shown that the burial depth (*D*) can be approximated by

$$D = \frac{\sqrt{3}}{2} S \tag{2}$$

where S = peak-to-peak distance [8]. Further, it can be shown that if the peaks are not of equal amplitude, they are an indicator of a non-orthogonal crossing over the conductor and of the crossing angle over the conductor.

4. TEST SITES

Figure 5: EM Gradiometer in use at Otay Mesa

Over the past six years, the EM gradiometer has undergone extensive development to improve system sensitivity and to allow the use of stand-off transmitters as illuminating sources (Figure 5). Various models of the man-portable EM gradiometer instrument have been used for detection of tunnels and passageways in a wide variety of geologic settings, ranging from thick ash fall tuffs nears San Diego, California, to sedimentary rocks in New Mexico and to granitic, and permafrost formations in Alaska. The technology has been shown to work without regard to the geologic setting. In the following discussion, we will look at the results of three tunnel surveys conducted at Otay Mesa near San Diego, a railroad tunnel near Raton, New Mexico, and over a hard-rock tunnel complex in Alaskan.

4.1 Otay Mesa

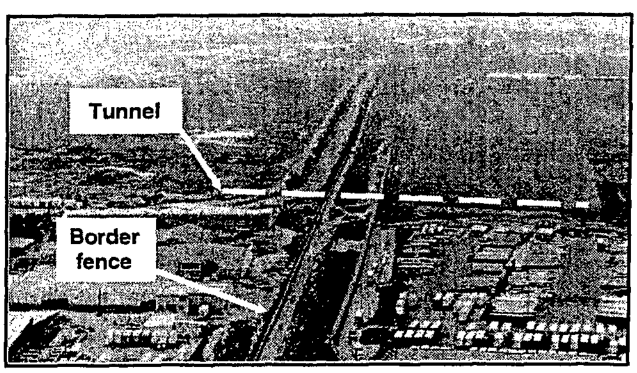

Figure 6. Otay Mesa Border Crossing Tunnel

One of the earliest test sites for the man-portable EM gradiometer was the Otay Mesa border crossing tunnel located just east of San Diego, California. Figure 6 is an aerial photograph of the crossing site. The tunnel was assumed to be developed for either drug or human smuggling and was dug from the Mexican side of the border towards an unfinished warehouse on the U.S. side. It is located in an ash fall tuff. As can be seen in Figure 7, the tunnel was well constructed and included three phase electrical power cable on the left-hand wall and ventilation tubing was hung by the straps in the upper right hand wall of the tunnel and removed at some point after discovery. The tunnel depth ranged from approximately 55 feet at the border crossing to about 40 feet at the near northern end.

Multiple traverses of the tunnel were made in the field north of the boarder fence at walking speed. Due to the high signal to noise ratio of the EM gradiometer, no post-processing of the data is required and the system response was displayed as the data was collected. In Figure 8, the data from the traverses are plotted against the centerline of the tunnel. It is apparent from this plot that the EM gradiometer has unambiguously detected the tunnel. Note that the signature of the tunnel becomes less pronounced at the traverses near the ends of the tunnel. This is an anticipated effect due to lower coupling of the illuminating signal with the finite length conductor near its end points. From the data displayed in Figure 8, using the peak separation distance formula given in Equation (2), estimated depths followed the trend of the tunnel. Depth estimate errors were typically of the order of several feet but errors as great as 17 feet were observed when the signature "M" curve broadened and the peaks were harder to define.

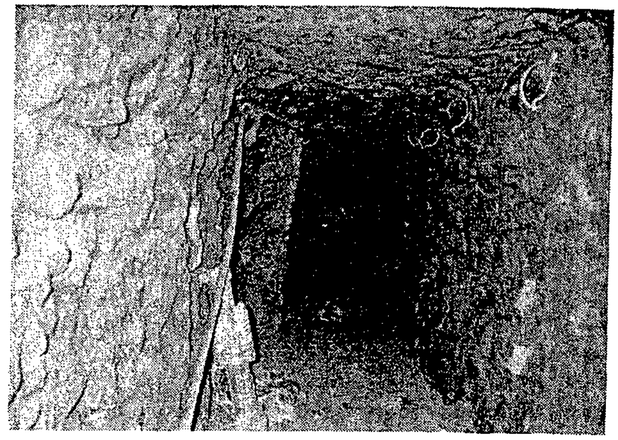

Figure 7: Otay Mesa Tunnel Construction

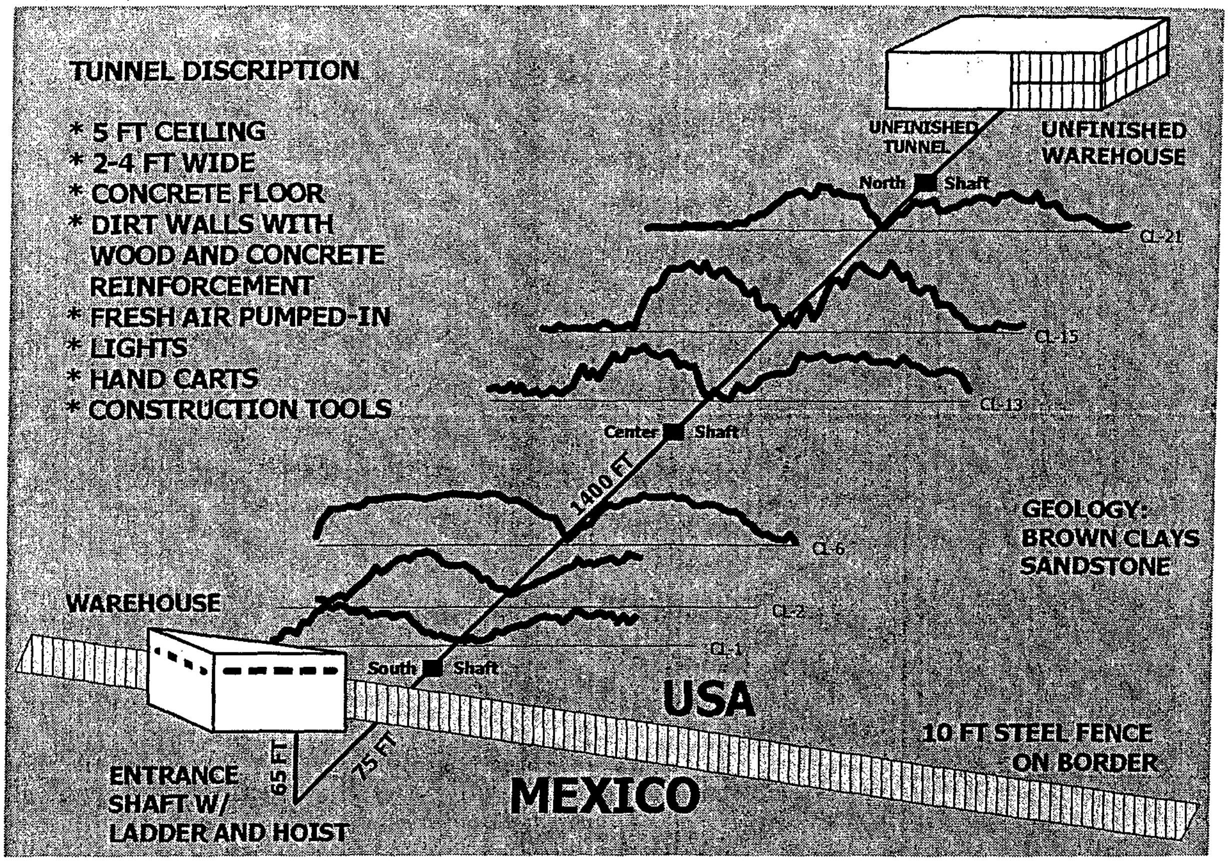

Figure 8: EM Gradiometer Traverses of Otay Mesa Tunnel

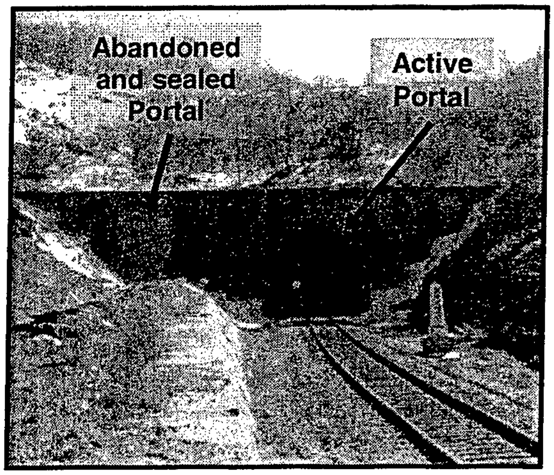

Figure 9: Santa Fe Railroad tunnel adits

4.1 Railroad Tunnel

A unique field demonstration site has been identified on Raton Pass near Raton, New Mexico. The original Santa Fe railroad tunnel was developed in 1881 and was abandoned when a larger diameter tunnel was developed to the west of the original tunnel. The original tunnel track has been removed and represents an empty tunnel without rail or cable. The surface tomography provides a tunnel depth ranging from 50 feet to 150 feet. A photograph of the Santa Fe railroad tunnels is shown in Figure 9.

The measured survey data acquired over survey lines crossing the tunnels is illustrated in Figure 10. The survey was conducted at 20 kHz with a local transmitter. The estimated depth is 78 feet compared to the actual depth of approximately 70 feet. The null point on the left is the abandoned tunnel centerline approximately 40 feet away.

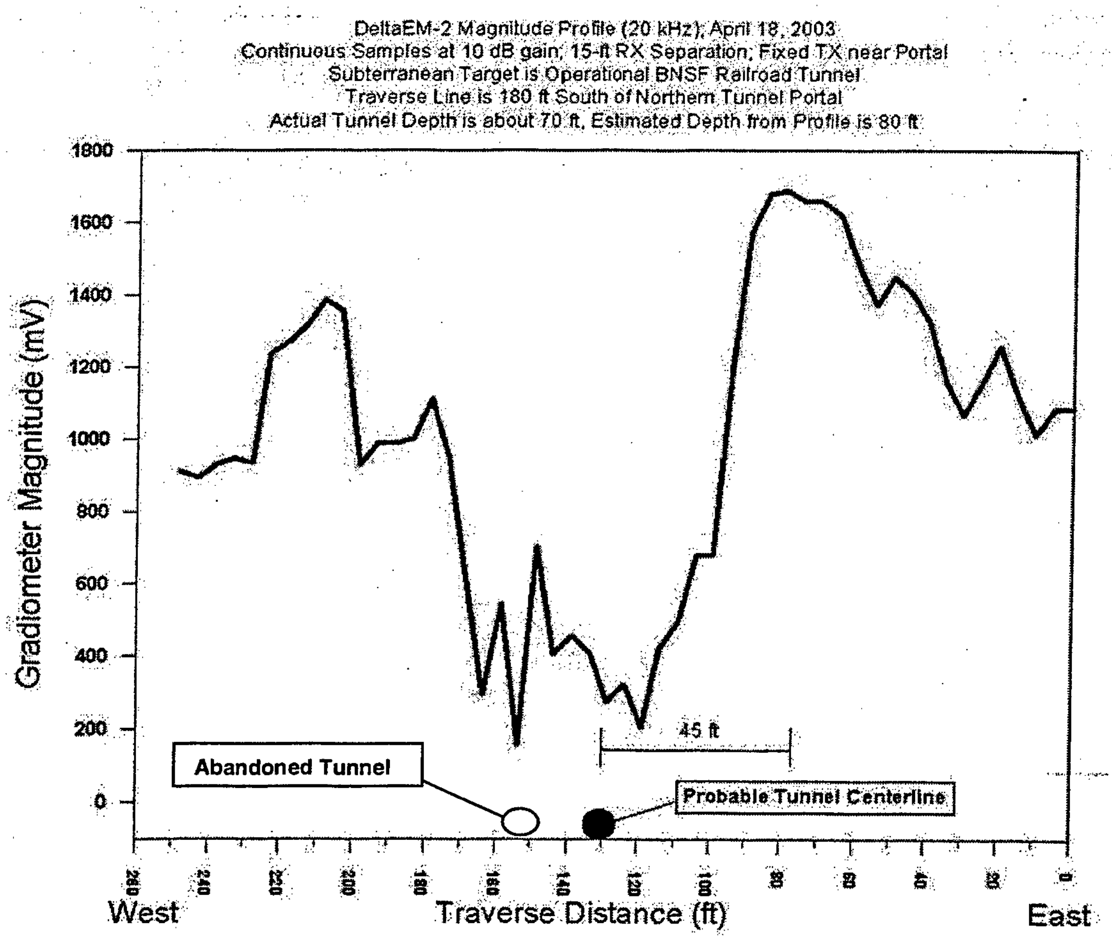

Figure 10: DeltaEM gradiometer response on survey line crossing both Railroad Tunnels

4.2 Alaskan Mine Tunnel

The Delta Mine Training Center is an active hard-rock mining training facility. This site provides very unique opportunities for testing electromagnetic systems with local or remote transmission sources. The HAARP transmitter has demonstrated the ability to modulate the ionospheric electrojet producing ELF/VLF band* signals that couple into the ionosphere-earth waveguide and are easily observed on the surface of the earth. The HAARP program has studied several techniques for the detection of underground structures using ELF/VLF radio waves generated in the ionosphere.

An Alaskan map and a photograph of the Delta Mine portal are shown in Figure 11.

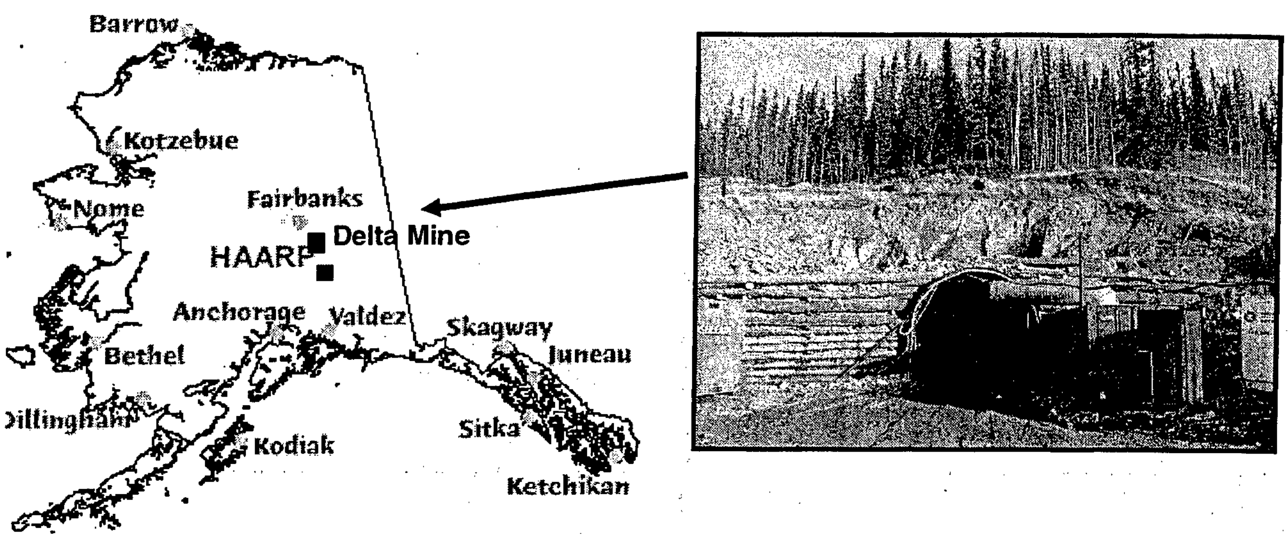

Figure 11: Delta Mine Training Center tunnel adit

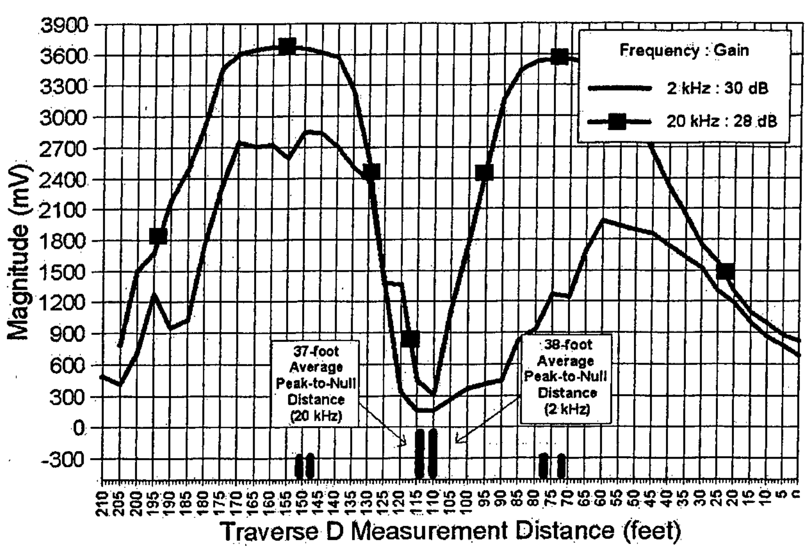

Figure 12: DeltaEM gradiometer response over the Alaskan Mine Tunnel

The DeltaEM gradiometer acquired surveys along different traverse lines over the Delta Mine terrain. The measured survey data acquired over one of the lines is illustrated in Figure 12. The survey was conducted at both 2 kHz and 20 kHz with a local transmitter. The estimated depth is 84 feet compared to the actual depth of approximately 100 feet.

5. CONCLUDING REMARKS

Tunnels have been used throughout history to operate covertly in attacking structures and to conceal illicit activity such as drug smuggling. Securing facilities and borders requires some means of detecting such activity. A hand-carried electromagnetic instrument, using either local or remote ELF/VLF transmissions to illuminate the

* Extremely Low Frequency (ELF) band is 30 to 300 Hz.
Very Low Frequency (VLF) band is 3 to 30 kHz.

target area, now exists for underground passageway detection. The DeltaEM gradiometer receiver design features synchronization with the transmitter source and coherent detection of the scattered secondary field from the passageway. Electric conductivity versus frequency measurements show that the conductivity aries linearly with frequency. The attenuation rate is low at low frequency favoring deep detection capability. The scattering cross section of the conductive object increases as frequency decreases, which increases the detection sensitivity of deeply buried objects. Because of the cylindrically spreading of the secondary EM wave, the detection can occur above the soil surface. Theoretical investigations have found that the secondary EM fields are 20 to 40 dB below that of the primary EM field components. The principal instrument design issue is the detection of the secondary fields in the presence of the much larger primary field components. This has been solved by the careful design of the gradiometer antennas, which achieve 70 dB of primary field suppression. The instrumentation features an electronic design that enables synchronization with the primary field components. Synchronization enables the detection of the smallest possible secondary signal in electrical noise. Radio wave interference from distant sources will be plane waves and suppressed by the gradiometer antennas. The response exhibits a high signal-to-noise ratio—favorable for reducing the false alarm rate.

What has been presented in this paper are data from relatively benign test environments. In more complex environments, typical of urban settings, the EM gradiometer survey method requires field site specific operation and analysis. This comes from the many variables which can be encountered such as overhead wires, which appear as false targets, variations in topography, and subsurface man-made or geologic structure. However, these effects can often be overcome by use of multiple traverses using different frequencies for each traverse.

Of particular note is the fact that EM gradiometry does not require contact with the ground. It is possible to conduct surveys from moving vehicles including from a low-flying, unmanned air vehicle (UAV). Further development of the system is directed at implementing these survey strategies.

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