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TITLE:

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Modeling the Electromagnetic Detection of Buried Cylindrical Conductors⁺

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Abstract -- The remote detection of buried structures and tunnels is important to the mining, construction, and defense industries. It is often desirable to identify underground power lines, pipe lines, and utility tunnels which have unique electromagnetic cross sections. A computational model for the electromagnetic detection of buried conducting cylinders is described in this paper. The source of electromagnetic radiation is either current injection into the soil or a surface based magnetic dipole with possible extensions to airborne platforms. Frequency ranges from a few kHz to 100kHz are considered. The target conductor is a cylinder buried directly in the soil or placed inside an insulating pipe. The receiver is a magnetic gradiometer held 1m above the ground, separate from the transmitter. Data are taken widely over the terrain under investigation. Cases where the target conductor is grounded at both ends, one end, or not at all are modeled. The scattered field and field gradient are computed at or above ground level and compared in magnitude and phase with the transmitted signal. Calculated results are compared with experimental tests. Essential factors affecting detection performance are frequency optimization, dynamic range of reception and proper data processing.

INTRODUCTION

The central physics issues in the "visualization" of underground structures and tunnels are attenuation, scattering, and clutter. The commonly addressed techniques, such as electromagnetic, dc magnetic, seismic and gravitational, are impacted to varying degrees by these three factors. Only electromagnetic scattering (EMS) techniques are considered here.

Local conditions cause the electrical conductivity of soils to vary from place to place by several orders of magnitude, leading to significant variations in radiation skin depth, $\delta = \sqrt{2/(\mu_0 \sigma \omega)}$, where σ is the electrical conductivity of the soil and ω is the angular frequency of the wave, $\omega = 2\pi\nu$. At low frequencies, an oscillatory plane wave attenuates by one factor of e for each skin

depth it travels. If the target were a buried conducting sphere, the total scattering cross section is approximately proportional to $k^4 a^6$ where the radius of the sphere is a , the wave number in earth, k , is related to the wave length, λ , by $k = 2\pi/\lambda$, and it is assumed that $ka \ll 1$. One may reduce attenuation by reducing the operating frequency, but the corresponding reductions in cross section will eventually overcome the improvements in attenuation.

In addition to attenuation and electromagnetic scattering by the target, the phenomenon of geologic noise or "clutter" is a major factor in underground detection. When natural variations in σ and dielectric constant, κ , introduce signal fluctuations comparable to the target scattering, accurate detection is impaired.

The work in this paper combines two realities inherent to the applications and physics of underground detection technology. First, many of the "targets" typical of underground detection applications are in long tunnels: pipelines, power lines, communications, and clandestine transportation. Second, the scattering cross sections for long conductors are significantly greater than for smaller objects such as storage bunkers and tanks.

PHYSICS MODELING

The physics issues described above are well known, [1]-[3]. The objective of this work is to combine the physics representations of the transmitter, target scattering, and receiver into one computational model capable of predicting system performance and enhancing system optimization. The computational modeling has been done with *Mathematica* in MKS units.

The systems concepts in this paper are largely drawn from the work of Dr. L. Stolarczyk of Raton Technology Research (RTR) in Raton, NM [4]. The base case is illustrated in Fig. 1. In this example, the transmission is current injection into the ground by means of an ac power supply connected to ground points approximately 100m apart. An alternative transmitter used by L. Stolarczyk and collaborators at RTR and Sandia National Laboratory, Albuquerque (SNLA) is a horizontal

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Fig. 1. Conceptualization of current injection, field propagation and gradiometer reception.

magnetic dipole. The far fields of the current injection and the horizontal magnetic dipole are similar.

The subterranean electric field for an infinitely long wire on the surface is derived in [2] and [3]. An approximation for a grounded wire of finite length was derived and incorporated into the present model to compute both E and B at and above the target conductor. The transmitter to target separation, R , is assumed to be long compared to the skin depth of the earth, δ , but short compared to the wavelength in air, λ_a . These assumptions enable one to treat the vertical and horizontal dependencies of the fields as separable. The E and B fields are computed two different ways and checked for self consistency.

The target is taken to be a conducting wire or pipe of radius a inside an insulated tunnel of radius b . The conductor may be grounded at both ends, one end or neither end. It is also possible to have the conductor be a part of the tunnel wall and in contact with the ground all along its length.

The E field of the transmitter drives a current in a target conductor of finite length. This was computed using a Green's function technique presented by Hill [5], and it was checked against an independent Fourier expansion model derived by R.W.M.

The choice of a magnetic gradiometer for the receiver is drawn from experience at RTR. For a bistatic transmitter - receiver arrangement, ∇B of the scatterer stands out in greater proportion to ∇B of the transmitter than does B of the scatterer versus B of the transmitter.

RESULTS

Sandia National Laboratory buried wire tests A series of tests were carried out by LANL, RTR, and SNLA at

SNLA during 1995. The target was a #14 gauge wire drawn through a 4" diameter plastic pipe. The pipe was ~100m long and the central 50m were buried to a depth of ~10m. Various transmitter configurations were used including current injection from a 100m line parallel to the target and 100m away from it. Also a horizontal magnetic dipole was placed directly over one end of the buried wire.

The Sandia tests showed a distinct horizontal magnetic gradient as the gradiometer was taken across the buried grounded wire. These results are illustrated in Fig. 2 where the transmitter was a magnetic dipole operating at 100kHz and moved across the wire in tandem with the receiver to reduce transmitter interference.

To model the Sandia experiments, the characteristics of the earth were taken to be $\kappa = 10$ and $\sigma = 0.03 \text{ mho/m}$. The results computed using the model described above are shown in Fig. 2. Both sets of results are shown with arbitrary normalization. The shapes of the gradiometric amplitudes are similar except the two peaks of amplitude are more widely separated for the computation than in the experimental results. Perhaps the actual conductivity of the soil was higher than the $\sigma = 0.03 \text{ mho/m}$ used in the computation. When the wire is not grounded, the computations predict the driven current to be reduced by a factor of ~80. The reduction is ~20 if only one end is grounded. The experimental tests of open ended conductors were inconclusive.

Yucca Mountain tests A series of tests by LANL, RTR, and SNLA is underway at the Yucca Mountain site in Nevada. In this case, a 3.6m diameter tunnel ~ 40m under ground is being surveyed. A variety of transmitter configurations are planned: ranging from a rectangular loop, 100m×200m, placed to the side of the tunnel to horizontal magnetic dipoles at various positions around the tunnel. The operating frequencies are $\nu = 5, 10, 30, 60$, and 100kHz.

The model presented above has been used to predict the gradiometric signals to be expected when the large rectangular loop, carrying 1Amp, is placed with its

Fig. 2. Experimental (solid) and theoretical (dashed) normalized values of horizontal magnetic field gradient for the SNLA tests at 100kHz over a grounded wire 10m deep.

nearest edge 150m away from the center line of the tunnel. The soil parameters are taken to be $\kappa = 12$ and $\sigma = 0.002\text{mho/m}$. The computed gradients of the horizontal and vertical magnetic field are plotted as a functions of horizontal position in Fig. 3a and 3b respectively for a 3.6m diameter conducting tunnel. In segments of the tunnel which are not reinforced with metal walls, the primary scattering conductor is probably in the railroad tracks along the tunnel. Estimating these as equivalent to a conducting cylinder 10cm in diameter gives the scattering shown in Fig 3c.

Although there is a scattered signal present for all five

Fig. 2. Computed magnetic field gradient for the Yucca Mountain tests at 5, 10, 30, 60, and 100kHz. (solid-short dashed-long dashed respectively) over a 3.6m diameter tunnel ~40m deep at $x = 0$; showing (a) horizontal field gradient and (b) vertical field gradient for a conducting walled tunnel, and (c) vertical field gradient for an open tunnel containing small conductors such as railroad tracks.

frequencies, it only shows the characteristic point of inflection for the lowest two or three frequencies. The large tunnel with insulated walls scatters three to four times more in amplitude than the 10cm diameter conductor in an insulated tunnel.

The present results indicate that even when operating with field gradients, the transmitter signals may mask out the scattered signals. By accurately modeling the transmitter fields, fully recording the amplitude and phase of the received signal, and assuring an adequate dynamic range of the receiver, it should be possible to extract conductor locations using image analysis techniques.

CONCLUSIONS

The performance of sub-surface detection is enhanced by adapting the wavelength and orientation of the probing radiation to the configuration of the underground structure and to the soil characteristics. This paper provides a demonstration of how a bistatic transmitter and receiver can be arranged to locate subterranean conductors. Experimental-theoretical agreement has been achieved in the shape of the scattered signal for a wire buried at 10m depth in tests at SNLA. Theoretical predictions indicate that a tunnel at the Yucca Mountain facility should be locatable by visual examination of gradiometric data versus position for frequencies in the 5-30kHz range. Assuming the dynamic range of the receiver is sufficient, data processing may reveal the tunnel location with higher frequencies.

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