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System Survey of Deep Penetrating Radar

Russell Brown, Jerry Genello, Douglas Lynch,
John Norgard[*], Michael Wicks
Air Force Research Laboratory
Rome Research Site
Rome, NY USA

[*]US Air Force Academy, Colorado Springs, CO

Robert Kapfer, Vincent Amuso
Rochester Institute of Technology
Rochester, NY USA

Abstract— In this paper, trade-offs associated with critical issues involved with ground penetrating radar (GPR) techniques are addressed. The proliferation of sub-surface sanctuaries has increased the need for remote sensing techniques providing for the accurate detection and identification of deeply buried objects. A new concept is proposed to use a sub-surface radiator, delivered as an earth penetrating non-explosive, electronic "e-bomb", as the source of transmission for GPR experiments using ground contact or airborne receivers. The goal is to achieve improved sub-surface surveillance characteristics of buried objects. Three-dimensional imaging techniques for deeply buried targets are developed based on two-dimensional synthetic aperture radar (SAR) data collection techniques.

Keywords- deep-penetrating radar, sub-surface radiators, buried-objects, buried facilities, SAR, GPR, RCS, system survey

I. INTRODUCTION

In this paper, trade-offs associated with critical issues involved with GPR techniques are addressed. The proliferation of sub-surface structures used as command posts and storage sites for conventional or nuclear weapons has increased the need for remote sensing technologies providing for the accurate detection and identification of deeply buried objects. HF radiation is required for deep penetration. Remote sensing using an elevated GPR system, which provides a safe stand-off distance, reduces the surface penetration of the transmitted wave and radar resolution. Ground foliage and the mismatch at the earth/air interface further reduce the transmitted energy available in the wave propagating in the earth. Therefore, a new concept is proposed to use a sub-surface radiator, delivered as an earth penetrating non-explosive, electronic bomb (e-bomb), for the source of the transmission and ground contact or airborne receivers. The goal is to achieve improved sub-surface surveillance of buried objects, target detection and identification, wide-area surveillance, targeting, battle damage assessment, and buried facility parameters (lateral location, depth, size, shape, and portals). This technique will improve the detection process of locating deeply buried objects. Three-dimensional imaging techniques for deeply buried targets are developed based on two-dimensional SAR data collection techniques. Near-field focusing is performed digitally to combine the 2D data collected over a planar grid of equally-spaced sample points to form a 3D image of sub-surface features.

II. GROUND PENETRATING RADARS

Commercially viable GPR typically fall into two categories, shallow penetrating systems operating to depths of five feet or less and very deep penetrating systems operating to depth of hundreds or even thousands of feet. Numerous manufacturers produce both impulse and spread spectrum shallow penetrating radars [1] designed to look for pipes or similar objects near the surface, and literature is widely available on the internet, while a limited number of very deep penetrating radars have been built. These very deep penetrating radar systems, custom built for oil and gas exploration, operated below the AM broadcast band. Due to antenna constraints, they operate with tuned antennas [2] and large time-bandwidth products, so that the transmitting antenna can be continuously tuned to each new frequency component as the frequency synthesizer steps or sweeps through the band. This paper addresses a third, even more difficult category of ground penetrating radar, one designed to operate to depths of several hundred feet, yet with operational constraints that demand rapid mobility, preferably mounted on an airborne platform, and without the long "stationary" dwell at each location that would permit use of tunable antennas. Here, a combination of airborne sensors operating in conjunction with a buried or subsurface radiator offers the only practical solution to a very difficult design problem. This concept is described heuristically herein, and posed as a challenge problem with engineering solutions systematically under investigation by the authors.

III. SUB-SURFACE RADIATORS

Earth penetrating munitions, such as the laser guided GBU-28 "Bunker Buster", emerged in the early 1990s. Sled tests verified that the bomb could penetrate over 20’ of concrete, while earlier flight tests proved that the bomb could penetrate more than 100’ of earth. About the same time, the "smart bomb" or the e-bomb became available. Then, came the advent of the earth penetrating radiator, that is, the underground e-bomb, which can penetrate the earth without blowing up prematurely or destroying itself on impact.

It is proposed to replace the "explosives" in the e-bomb with "electronics" to produce an underground earth penetrating non-explosive, electronic radiator. This earth penetrating e-bomb can provide a sub-surface transmitter (radiating source) for GPR experiments used with ground contract or airborne receivers. One important application is to surface contact synthetic aperture radar (SAR).

Of practical concern when operating with a buried receiver, is the issue of data communications. Here, the problem of data transmission to the war fighter is compounded by the effects of propagation attenuation in the ground, and air-earth mismatch losses. A low-cost, light-weight transponder could aid in the communications concept of operations.

Alternately, for extended battery life, the transmitter can be above-ground, and the receiver below-ground. In addition, due to the attenuation of signals by the earth, there is less interference with a sensitive buried receiver from intentional/unintentional sources of radiation. Also, due to the dielectric constant and finite conductivity of the lossy earth, the intrinsic wavelength of the radiated waves in the earth is smaller than that in the air. Therefore, the sub-surface antenna can be smaller than one in the air above-ground.

The advantages of a sub-surface radiator over the conventional above-ground radiator include the elimination of the "ground bounce", the large reflection off the mismatch from the earth/air interface and ground foliage, and refraction into the earth, reduced beam distortion (ground focusing/defocusing), dissipation and signal attenuation, signal distortion, etc. resulting in significantly more power delivered into the ground, improved signal-to-noise ratio (SNR), better control over the radiated beam from the antenna, and simple performance predictions.

IV. HISTORY

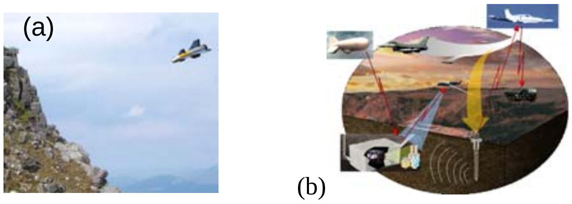

Figure 1: (a) incoming e-bomb missile (b) ground penetrated/embedded e-bomb operating in close proximity to potential threat target sub-surface facility.

V. EXPECTED GAIN IMPROVEMENTS

1) Radiation Efficiency

An improvement in radiation efficiency is expected due to the shorter wavelength and increased apparent length of the subsurface radiator compared to an above-ground antenna. This effect varies with the square root of the dielectric constant, which for a relative dielectric constant example of $\varepsilon_r = 16$, would shorten the wavelength by a factor of 4. Since the size of the radiator is limited in practice, an expected improvement in radiation efficiency from 20% with the above ground antenna to 80% with the subsurface radiator could typically result.

2) Loss Through Ground

The subsurface radiator is deployed in close proximity to the target of interest. Thus, the propagation loss through the earth medium will be reduced compared to a radiator positioned on the surface. In a typical case, where the propagation loss through the ground is 0.25dB/ft, and the surface antenna is 100 ft from the target, while the subsurface radiator is located 40 ft away, we would expect a 15dB improvement in favor of the subsurface radiator.

3) Air-Earth Interface

A loss is typically incurred when incident radiation penetrates the ground from the air, due to the mismatch in dielectric constant and conductivity. An improvement of approximately 3dB is expected for the subsurface radiator by elimination of this loss effect.

4) Antenna Lobing

Lobes in the radiation pattern of an antenna sited on the surface of the ground have been observed and documented. These lobes can favor or attenuate the returns from desired targets by up to +/-10dB, depending on their location and the geometry of the bistatic path from transmitter to target, and to the receiver. Much less (if any) such variability is expected for the subsurface radiator.

5) Performance Summary

Surface	Subsurface	Radiator	Improvement
Radiation Efficiency	20%	80%	6 dB
Loss through Ground	25dB	10 dB	15 dB
Air Earth Interface	-3dB	0dB	3 dB
Antenna Lobing	+/- 10 dB	0 dB	+/- 10 dB
TOTAL IMPROVEMENT			14 – 34 dB

VI. CRITICAL ISSUES: CLUTTER/MISMATCH

Two critical issues are addressed with the application of the sub-surface e-bomb transmitter. First and foremost is the additional energy on target achieved due to the elimination of the air-earth mismatch loss. Of equal importance is the significant reduction in surface clutter backscatter to the airborne receiver platform. As such, not only is the signal-to-thermal-noise enhanced, but so is the signal-to-clutter.

VII. CRITICAL PHYSICAL PHENOMENA

Point electromagnetic sources at long distances provide for a nearly planar radiation wave front, which is ideal for wide area surveillance radar under a variety of conditions. This is especially true for the detection and tracking of airborne threat targets from airborne radars. In ground penetrating radar, we attempt to place the transmitter and/or receiver as close to the target area as possible. This is due to range equation power limitations. With such close proximity to the subsurface target of interest, we violate the plane wave assumption and compound the signal processing requirements.

A confluence of factors compound the problems associated the operation of ground penetrating radars for the detection of hardened and deeply buried targets, and our ability to automatically discern returns from natural structures and sub-surface targets. Most obvious among these factors is the dielectric mismatch loss at the air earth interface. As such, the energy on target is significantly reduced.

Snell's Law and Fresnel's Law may be used to describe the transmitted and reflected energy at the air-earth interface. Two significant physical phenomena occur here. First, the relative dielectric constant of the earth ε_{re} (dry earth being 4 or greater, with 15 typical for moist soil) and the angle of incidence determines the bending of the rays of incident energy upon transversing the interface, while the ratio of the energy transmitted to reflected is $4/\left(1-\sqrt{1/\varepsilon_{re}}\right)^2$ for non-magnetic materials. Furthermore, the plane wave impinging upon the air-earth interface is distorted to be co-sinusoidal with respect to the normal.

An additional problem arises due to the fact that surface reflections from strong scatterers such as buildings, automobiles, and trucks will cohere and mask subsurface returns. Furthermore, receiver dynamic range is ultimately limited by these scattered returns from surface clutter. Direct path leakage between the transmitter and receiver may easily be mitigated via classical side-lobe cancellation, which offers in excess of 20dB in interference reduction. Ultimately, surface clutter reflections remain and ultimately mask weak target returns or even cause receiver saturations. Beyond that, the radar range equation is dramatically altered to include a dielectric constant propagation attenuation factor in addition to R^4 range attenuation. This attenuation is exponential and measured in dB per unit depth. For moderate depths of penetration, the dielectric constant propagation attenuation factor could be orders of magnitude greater than the R^4 range attenuation. In numerous ground penetrating radars, surface contact antennas are employed to increase energy coupling into the ground. To further improve performance, these antennas would have to be buried.

Figure 2 presents a pictorial view of experiments conducted at Gouvernour, NY. Two bowtie antennas are used to collect data over a grid containing 121 points on the surface. The transmitter remained stationary while the receiver was moved to cover 121 equally spaced points on the ground. A manmade drift (mine) 150-160 feet below the surface was detected and imaged using an experimental apparatus described by Lynch [4] and Brown [5], and presented in the Figure. Most notable is the extensive unfocused clutter spanning from 20 to 40 feet below the ground. Using a subsurface e-bomb transmitter, the unfocused clutter at or near the air-earth interface would be significant reduced. Burying the transmit antenna is not always practical, especially in a warfare environment.

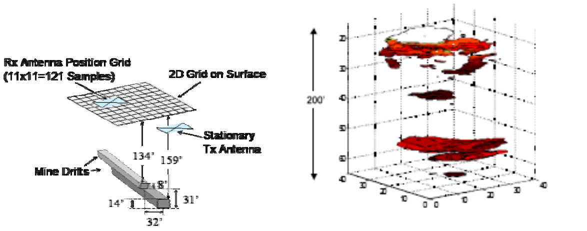

Figure 2: Early work on deep penetrating radar utilized surface contact antennas operating bistatically to detect natural and manmade objects to a depth of 200 feet. [3].

A simple scenario has airborne sensors operating to detect likely hardened and deeply buried targets. Then, a sub-surface radiator missile is launched, buries itself in the ground between 20 and 100 feet, and begins to radiate. This is illustrated in Figure 3. Here, we have a combination elevated/airborne transmitter/receiver pair operating in conjunction with a sub-surface transmitter for precision engagement. In figure 4, a long term goal includes airborne UAV based transmitter and receiver pairs. This may be impractical given the difficult environments in which sub-surface facilities may be built.

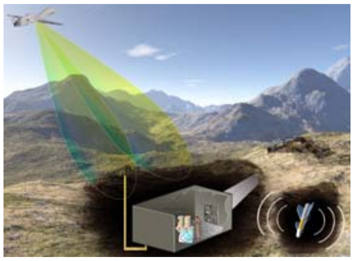

Figure 3: Realistic scene with an elevated (aerostat) airborne receiver, and a sub-surface radiator to facilitate precision engagement.

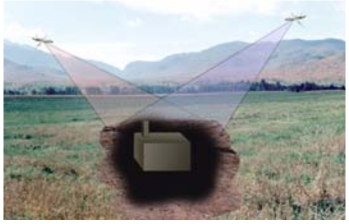

Figure 4: UAV based bistatic GPR for sub-surface facility detection.

Other missiles containing receiver equipment could be launched into the ground, but a more realistic scenario uses the existing airborne sensors to collect and analyze radar data. The goal is to facilitate precision engagement of the hardened and deeply buried targets with bunker buster weapons, or similar munitions. The need for a target image or signal strength estimates becomes secondary.

The goal of imaging a hardened and deeply buried facility is intended to please the human operator. What is ultimately needed is automatic target detection and declaration, which is more in line with the emerging concepts of operations using UAVs and UGVs. As such, freedom to select transmit and receive geometries favorable to the binary hypothesis “target present / target absent” is desired. Imaging for discrimination is secondary to this goal, and only used when marginal test statistics are available from the analysis of measurement data.

VIII. MODELING AND SIMULATION

Comparisons have been made between underground and above ground transmitters. The target model incorporates both specular and diffuse scattering phenomena along with path attenuation. The composite reflection is calculated using a Bidirectional Reflectance Distribution Function which incorporates specular/diffuse scatterers within an anisotropic scenario [6]. A perfectly conducting target was examined according to the target, transmitter and receiver location geometry illustrated in Figure 5.

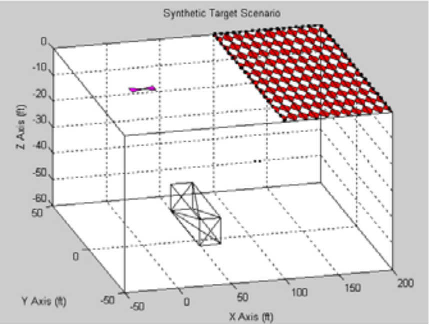

Figure 5. SAR Geometry

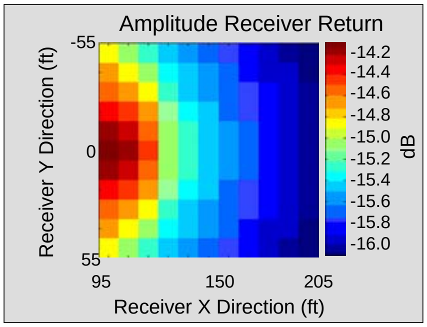

Figure 6. Received amplitudes (transmitter above ground).

The first experiment (see Figure 6) placed the transmitter 6” above the ground and measured the returns at each receiver in the receiving grid. The second experiment (see Figure 7) placed the transmitter 6” below the ground and measured the returns at each receiver in the receiving grid.

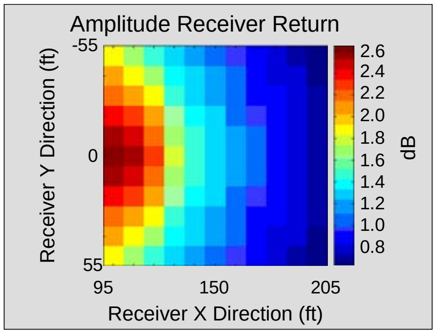

Figure 7. Received amplitudes (transmitter below ground).

All outputs are in terms of integrated power at each receiver location. The simulator does not incorporate the three-dimensional image generation and does not include direct path, however direct path can be evaluated within the simulator. Direct path clutter can be considerably reduced through the use of a high pass filter within the three-dimensional imaging routine.

IX. CONCLUSIONS

These results indicates that by embedding the transmitter only 6” into the ground results in a greater than 10dB improvement in received power.

Additional concerns with “e-bomb” surface penetrating radiators arise. Most notable among these is the transmission of receiver data to the user. An unattended ground station (UGS) attached to the e-bomb via fiber optic is easily deployed upon surface impact. This UGS relays subsurface receiver data directly to the UAV borne transmitter platform for use in image formation and solves the data communications problem. The ability to perform subsurface imaging to depths of 200’ have already been demonstrated by Brown in [3] and presented in Figure 2 above. Furthermore, reference [3] presents thinned array below ground images with data collected in patterns characteristic to loitering UAV platforms.

REFERENCES

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