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MODELING OF COMPOSITE SCENES USING WIRES, PLATES AND DIELECTRIC PARALLELIZED (WIPL-DP)

Electromagnetic Techniques, Inc.

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AFRL Project Engineer: Carl Thomas, SNRT, Carl.Thomas@rl.af.mil

14. ABSTRACT
WIPL-DP was developed to speed the solution of the commercially available electromagnetics modeling and simulation program WIPL-D. To utilize WIPL-DP, a model is defined with WIPL-D, and then exported to a parallel processor machine to accelerate the solution time. The resultant data is then imported back to WIPL-D for display and analysis. Utilizing parallel processor machines Allow the problem to be split into parts and distributed for a faster solution. The model integrity is not compromised in comparison to solving the problem with WIPL-D. Work performed under this contract has been reported in a number of papers previously presented at conferences; copies of these papers comprise the final report for the contract.

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This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

AFRL-SN-RS-TR-2006-209 has been reviewed and is approved for publication

APPROVED: /s/

CARL R. THOMAS
Project Engineer

FOR THE DIRECTOR: /s/

RICHARD G. SHAUGHNESSY
Chief, Rome Operations Office
Sensors Directorate

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Introduction

AFRL has sponsored the development of an electromagnetics modeling and simulation program known as *Wires, Plates, and Dielectrics Parallelized (WIPL-DP)*. WIPL-DP is a parallelized version of the commercial modeling program Wires, Plates and Dielecrtrics (WIPL-D) marketed by OHRN Enterprises, Inc.

WIPL-DP substitutes the model solution routines of WIPL-D to utilize parallel processing computers. In practice, an engineer uses a version of WIPL-D to develop the model of the system to be analyzed. This model is then solved using the WIPL-DP program. The parallel solution provides designers two advantages over WIPL-D. First, a higher number of unknowns can be solved, corresponding to larger more complex designs. Second, the solution time is reduced. The solution is then imported back to the WIPL-D program for display.

Under this contract, the WIPL-D code was used to Model and Simulate (M&S) a variety of computationally intensive numerical problems in a number of different situations. WIPL-DP was then used to solve the simulations capitalizing on the higher Number of Unknowns and faster solution speeds available.

One of the main problems covered under this effort was the design of large, low-frequency, broadband antennas over a lossy half-space using WIPL-D. These models simulate the transmitting and receiving antennas used in Ground Penetrating Radar (GPR) experiments, which use 2D Synthetic Aperture Radar (SAR) techniques to image buried objects. In addition, several aircraft antennas were designed using WIPL-D. WIPL-D was also applied to the problem of designing passive Frequency Selective Surfaces (FSSs) and to analyze and design several patch antennas for use in wireless systems.

Papers Presented

The following papers were presented under this contract:

1) “WIPL-D Modeling and Simulation (M&S)”
Norgard
GPR Review
AFRL/RRS

2) “Surveillance of Strategic Sub-Surface Sanctuaries”
Norgard, Musselman, Bracken, Brown, Genello, Lynch, VanDamme, Wicks
Tenth International Conference on Ground Penetrating Radar
21-24 JUN 04
Delft, The Netherlands

3) “System Survey of Deep Penetrating Radar”
Brown, Genello, Lynch, Musselman, Norgard, Wicks
Tenth International Conference on Ground Penetrating Radar
21-24 JUN 04
Delft, The Netherlands

4) “Waveform Diversity in Ground Penetrating Radar (GPR) Applications”
Wicks, Norgard, Musselman
Waveform Diversity and Design Conference
8-10 NOV 04
Edinburgh, Scotland

5) “Ground Penetrating Radar (GPR) Sub-Surface Radiators and Receivers”
Norgard, Wicks, Musselman
Tri-Service Radar Conference
Huntsville

6) Deep Ground Penetrating Radar (GPR) – WILP-D Models of Buried Sub-Surface Radiators”
Norgard, Wicks, Musselman
ACES 2005 Symposium
4 APR 05
Hawaii

WIPL-D Special Session

7) “Radar Cross Sections (RCS) of Aircraft using HPC/CEM Hybrid Codes”
Norgard, Musselman
PIERS 2005 Symposium
22-26 AUG 2005
Hangzhou Zhejiang, China

8) “Surveillance of Sub-Surface Sanctuaries using Earth-Penetrating Radiators”
Norgard, Musselman
PIERS 2005 Symposium
22-26 AUG 2005
Hangzhou Zhejiang, China

Reprints of the abstracts and papers listed above summarize the work competed on this project.

These papers, which were presented at numerous conferences and symposia, cover the following topics:

I. Waveform Diversity
a. Spatial Diversity
b. Velocity (Doppler) Diversity
II. Antennas Immersed in a Lossy Medium
III. Optimum Transmitter Heights above a Lossy Material Half-Space
IV. Imbedded Transmitters in the Earth
V. SAR Image Formation
VI. Earth Focusing Factors
VII. Experimental Sub-Surface Imaging Models
VIII. Bradys Bend Test Results
a. Predictions
b. Validations
IX. Antenna Patterns
a. Gain
b. Directivity
c. Beam Width
d. Side-Lobe Levels
e. Input Impedance
f. Bandwidth
X. Broadband Antenna Design
a. Microstrip Antenna Arrays
b. Frequency Selective Surfaces (FSS)

All reports and abstracts are printed with acknowledgement that they were first printed in the proceedings for the given conferences.

Preliminary Problems

WIPL-D was used to model

i) GPR antennas
ii) passive FSS models
iii) wireless antenna arrays
iv) aircraft antennas

Preliminary Applications

These models were applied to the development of GPR antennas for shallow surface probing (for personnel and tank mines) and for deeper penetration (for tunnels and bunkers). These antennas were integrated into the experiments for imaging buried objects using GPR/SAR techniques. In addition, passive FSS filters were designed to cover large phased array antennas. The filters were designed to reject certain frequency bands while, at the some time, pass other frequency bands. Also, several patch antenna arrays were designed to provide broadband diversity to wireless networks. Finally, several antenna arrays were designed for use on the F16, on the F-22 Stealth Fighter, and on the Joint Strike Fighter (JSF).

WIPL-D Models

MATLAB Pre-Processors were written to write large WIPL-D IWP (Input WIPL) input geometry files. These files contain the defined nodes, the connecting wires and plates, the selected sources (and their associated types and parameters), and the definitions of the different dielectric/metallic domains (and their associated parameters).

Similarly, MATLAB Post-Processors were also written to collect the WIPL-D.OWP (Output WIPL) results. These files are very large and contain the output data for induced currents, near fields, far-fields, input impedances, etc.

WIPL-D (M&S): 1. GPR Antennas

WIPL-D was used to design small, broadband HF/VHF antennas. These antennas are being used in the GPR experiments that concentrate on searching for deeply buried objects, such as tunnels and bunkers.

WIPL-D was also used to study the effects of embedding the GPR antennas, either the transmitting antenna or the receiving antenna, in the ground. Significant improvement in the signal-to-noise ratio (SNR) at the receiver was found using WIPL-D algorithms. Experimental tests at the Bradys Bend test site in Pennsylvania were performed to verify the enhanced signal level in the detected signal. WIPL-D was used to model multiple tunnels and shielded doors.

WIPL-D was also used to predict the effects of the earth/air interface on the radiation characteristics of the transmitting and receiving antennas. The distortions in the far-field radiation patterns were determined, as well as the effects on the near-field energy distributions. The input impedance of the transmitting antenna was calculated as a function of frequency. The resulting usable bandwidth of the transmitting antenna was thereby determined.

WIPL-D was used to verify the antenna pattern distortion, the effects of disturbed soil in the area of the buried antenna or the target, the effects of covering the antenna above ground, the perturbing effects of a bore-hole, and the effects of stratified layers (a continuing effort in progress), using the depth profiles of the earth's dielectric constant and conductivity.

WIPL-D (M&S): 2. Passive FSS Models

WIPL-D was used to model modern radome materials containing embedded FSS filters. The band-pass and band-reject frequencies were adjusted to produce on-resonance and off-resonance effects, which were switched on and off through an open-circuit or a closed-circuit load to the FSS. The switching between resonance and non-resonant states produces a variable radar cross section (RCS) for the filter, as a function of frequency.

The pass-band was designed between 9-10 GHz as desired. This was achieved by using a symmetric two-layer FSS. The top layer was active, being switched between open and short circuit conditions with a bias circuit. The bottom layer was passive, being open-circuited and fixed.
The difference between the absorption coefficient in the 9-10 GHz range and the reflection coefficient in the 9-10 GHz range was predicted by WIPL-D to be greater than 20 dB, at normal incidence. The case of oblique incidence was also modeled with WIPL-D.

In addition, an optimal thickness of the FFS filter was determined with WIPL-D to be 5mm.

WIPL-D (M&S): 3. Wireless Patch Antennas

A single inverted "F" antenna (IFA) was designed by WIPL-D for wireless applications. The center frequency of the antenna was designed at 2.45 GHz, with a 50 Ohm input impedance over a 10% bandwidth. A four element IFA array (2x2, square array) was also designed to meet the same specifications. In both the single IFA and IFA array designs, all feed line details were modeled. It was found that the mutual coupling between the antenna and the feed lines was very important (for agreement between the theory and the measurements). In particular, the attachment points of the feed line to the antenna were critical. The coax length, size, shape, dielectric constant, and extrusion length were also important parameters in the design model.

The IFA antenna was used in a laptop diversity circuit. The circuit controls the access point (AP) gain and directivity of the network. The built-in laptop IFA antenna provides increased range at lower power and, subsequent longer battery life.

WIPL-D (M&S): 4. Phased Array Aircraft Antennas

WIPL-D was used to model antennas on advanced aircraft. The F-16, the F22, and the JSF were modeled (on going effort in progress). The radiation patterns of the antennas in the presence of the aircraft were determined. The scattering cross-sections of the aircraft with the antennas in position were also determined, as a function of frequency, angle-of-incidence, and polarization.

One problem of interest is the design of large phased array antennas which are conformal to the aircraft fuselage. The antennas are covered with radomes built with inhomogeneous and anisotropic materials. The interaction of the antenna with the aircraft platform, the interaction between the antenna and the radome, and the mutual coupling between nearby arrays must be included in the design equations in order to properly design radar absorbing materials (RAM) and to produce stealth aircraft.

Several simple canonical structures were modeled to compare the theory with the code predictions. Non-canonical structures (modern advanced airframes) and experiments to validate the code predictions were planned.

Conclusions

The WIPL-DP High Performance Computing tool was used to model complicated computational electromagnetic (CEM) problems. WIPL-DP was validated against other numerical codes and with experimental measurements.

WIPL-DP was applied to the solution of the following computationally intense electromagnetic problems, as summarized above:

v) GPR antennas
vi) passive FSS models
vii) wireless antenna arrays
viii) aircraft antennas

Several papers and presentation were made on the results of this effort. Several reports were also prepared.

Papers/Abstracts

The following papers were presented under this contract:

"WIPL-D Modeling and Simulation (M&S)"
Norgard
GPR Review
AFRL/RRS

"Surveillance of Strategic Sub-Surface Sanctuaries"
Norgard, Musselman, Bracken, Brown, Genello, Lynch, VanDamme, Wicks
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"Ground Penetrating Radar (GPR) Sub-Surface Radiators and Receivers"
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"Surveillance of Sub-Surface Sanctuaries using Earth-Penetrating Radiators"
Norgard, Musselman
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Surveillance of Sub-Surface Sanctuaries

John Norgard, Randall Musellman
Air Force Academy
Colorado Springs, CO USA
john.norgard@usafa.af.mil

Justin Bracken, Russel Brown, Jerry Genello
Douglas Lynch, Jim VanDamme, Michael Wicks
Air Force Research Laboratory
Sensors Directorate
Rome, NY USA

***Abstract*— Electromagnetic (EM) imaging techniques are being developed to survey strategic sub-surface sanctuaries. The overall goal of this study is to develop and demonstrate techniques for sub-surface profiling from ground based and/or airborne (or even space) platforms.**

This surveillance scheme combines and utilizes bistatic RCS measurement techniques, broadband GPR antenna technologies, and far-field SAR remote sensing techniques. The combined RCS/GPR/SAR surveillance technique is used to extract target signatures concealed in measured RCS data and to remove thermal nose and ground clutter at the earth/air interface from the SAR data.

The combined RCS/GPR/SAR surveillance process utilizes ground contact and airborne transmitting (TX) and receiving (RX) antennas. Small, but efficient, ultra-wideband (100:1 bandwidth) conformable GPR antennas are being designed and developed to operate over the HF/VHF bands.

Planar wire-grid bowtie antennas are being developed as broadband GPR radar antennas. These antennas are 2D approximations to frequency independent, i.e., ultra-wideband, 3D solid biconical antennas. The antennas are truncated to finite lengths, which reduce the bandwidth to a finite range that is adjusted to cover the HF/VHF bands. 2D cross-sectional versions of the bowtie antennas were built and tested at the AFRL/RRS sub-surface antenna range and were compared to an adjustable standard-gain half-wave dipole antenna.

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 subsurface 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 overall goal is to achieve improved subsurface 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.

Keywords- sub-surface sancturaries, buried-objects, SAR, GPR, RCS, planar bowtie antennas

Introduction

The theory of antenna radiation in the presence of a material half-space has been the subject of investigation for many years [1-11]. In this paper, the theory is applied to develop electromagnetic (EM) imaging techniques to survey strategic sub-surface sanctuaries, such as underground voids (caves, crevasses, tunnels, mine drifts, etc.) and/or buried objects (cellars, bunkers, munitions, landmines, oil/gas fields, etc.). Techniques for sub-surface profiling from ground based and/or airborne (or even space) platforms are being developed and demonstrated.

Surveillance Scheme

This surveillance scheme combines and utilizes the following radar techniques:

i) bistatic RCS measurement techniques
ii) broadband GPR antenna technologies
iii) far-field SAR remote sensing techniques

The combined RCS/GPR/SAR surveillance technique is used to extract target signatures concealed in measured RCS data and to remove thermal nose and ground clutter at the earth/air interface from the SAR data. EM beams from 3 to 30 MHz (HF band) are utilized for deep penetration into the earth for varying soil moisture conditions from dry to wet; EM beams from 30 to100 MHz (VHF band) are utilized for shallow objects to enhance the spatial resolution of the imagery data.

Tomographic Images

High-resolution 3D tomographic images of the earth's strata are produced from the scanned 2D SAR data. These images are used to map the earth's strata and to detect embedded objects and/or empty voids in the ground and to determine their sizes, shapes, and locations, e.g., lateral positions and depths, below the surface of the earth.

Ground/Air Surveillance Scenarios

The combined processes utilize ground contact and airborne transmitting (TX) and receiving (RX) antennas. Therefore, small, but efficient, ultra-wideband (100:1 bandwidth) conformable GPR antennas are being designed and developed to operate over the HF/VHF bands.

Broadand Antenaas

This paper concentrates on the initial ground contact scenario with the synthetic aperture on or near the surface of the ground. A planar wire-grid bowtie antenna is being developed as a broadband GPR radar antenna. This antenna is a 2D approximation to a frequency independent, i.e., ultra-wideband, 3D solid biconical antenna. The antenna is truncated to a finite length, which reduces the bandwidth to a finite range that is adjusted to cover the HF/VHF bands. A 2D cross-sectional version of the bowtie antenna was built and tested at the AFRL/RRS sub-surface antenna range and was compared to an adjustable standard-gain half-wave dipole antenna. For portability and weight reduction, the standard 2D "metal plate" bowtie was realized as a "wire grid" frame model and as a simple, flexible "tape and tarp" antenna.

Soil Parameters

The constitutive parameters (μ,ε,σ) of the top layer of the soil (assumed homogeneous throughout) were measured at the test site using a capacitive probe inserted into the ground.

Earth/Air Interface

The TX and RX antennas are matched to their transmission lines and are designed to efficiently launch waves into the ground though an earth/air interface covered with foliage. The optimum heights of the TX and RX antennas above the earth/air interface have been determined for deep penetration into the ground. In addition, the optimum angles of incidence and return at the Brewster angles have been determined to reduce the "ground bounce" at the earth/air interface (for parallel polarization).

Computer Modeling & Simulation Algorithms

A computer program for the "Surveillance of Strategic Sub-Surface Sanctuaries" S^5 is being developed to model and simulate the combined RCS/GPR/SAR image process and to aid in the analysis and design of small, low-frequency, efficient, broadband antennas for use in the sub-surface target detection process.

Low-Frequency Broadband Antennas

In this paper, the electrical characteristics of a planar bow-tie antenna over an earth/air interface are studied to improve the broadband transmission and reception properties of the antenna at low-frequencies (HF Band). The design parameters to be considered and varied in a parametric study are the height of the antenna above the ground, the overall length and the width of the antenna, and the flare angle of the antenna.

Earth/Air Interface Geometry

The antenna is located at a height h in air over a planar earth interface. The constitutive parameters of the earth are $(\mu_e, \varepsilon_e, \sigma_e)$ where $\mu_e = \mu_o$ (non-magnetic) and $\varepsilon_e = \varepsilon_o \varepsilon_r$. The dielectric constant and conductivity of the earth vary dramatically with the moisture content of the soil. Typical values are:

$$\varepsilon_r = \begin{cases} 1 & air \\ 4 & dry \\ 16 & loamy \\ 25 & wet \\ 81 & saturated \end{cases}$$

with

$\sigma = 0.001$ low loss soil

Plane-Wave Expansions

The radiated field of the antenna over the half-space is decomposed into a spectrum of plane waves. The individual plane waves are reflected off the interface and transmitted into the earth. The integral expansions representing the superposition of the plane waves for the incident, reflected and transmitted waves are evaluated asymptotically in the far field of the antenna.

Reflection/Transmission Coefficients

The refection coefficients and transmission coefficients for perpendicular and parallel polarizations of the individual planes waves (relative to the plane formed by the normal to the interface and the incident propagation vector) are determined from Snell's and Fresnel's Laws and are used to determine the strength of the reflected wave in the air and the transmitted wave into the ground as a function of the operating frequency of the antenna and the height of the antenna over the earth/air interface.

Asymptotic Expansions (Far Fields)

These "geometrical optics" approximations to the fields are then used to determine the antenna patterns and the directivities (gains for a lossy earth) of the antenna over the earth/air interface. This analysis is performed for different heights of the antenna over the earth at selected frequencies over the operating band of the antenna to determine the optimum height of the antenna over the interface as a function of frequency.

Electric/Magnetic Dipoles

Theoretical results are presented for infinitely small electric and magnetic dipoles horizontally oriented over the earth/air interface. The theory for infinitesimal dipoles explains the directive properties of finite length resonant dipoles and electrically small broadband antennas. Resonant dipoles and broadband antennas were also modeled and simulated numerically and experimental tests were performed to verify the theory. A large resonant dipole antenna with an adjustable length over the HF band was compared to the infinitesimally small dipole results. Later, a planar bowtie antenna was constructed from 1 inch metal tubing and the electrical characteristics were compared to the dipole results.

Note that a "fat" dipole has a resonant length slightly shorter than a "thin" dipole. A one-inch conduit would be considered thin at these frequencies, producing an input impedance of approximately 73 ohms at resonance.

The resulting structure can be encapsulated in plastic tubing to keep the dipole off the ground and to prevent the losses in the ground from shorting out the fields. Supporting legs are also used for stand-off purposes.

Directivity/Gain

Electric/Magnetic Dipoles (Horizontal Wires/Loops)

The directivities of electric and magnetic dipoles as a function of height above the earth/air interface are shown in figures 1 and 2 with the dielectric constant of the earth as a parameter.

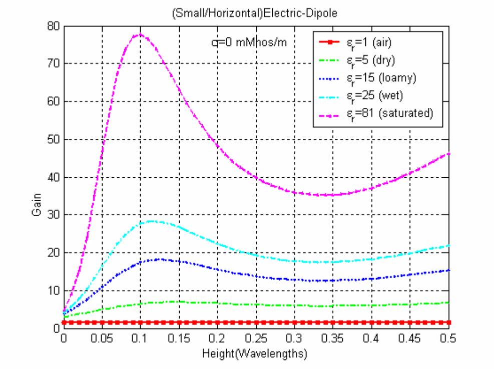


Figure 1. Gain (Electric Dipole) – Lossless Earth

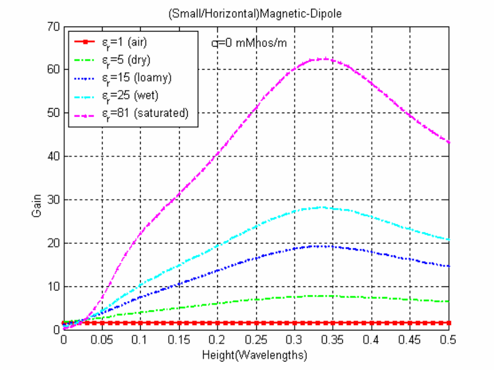
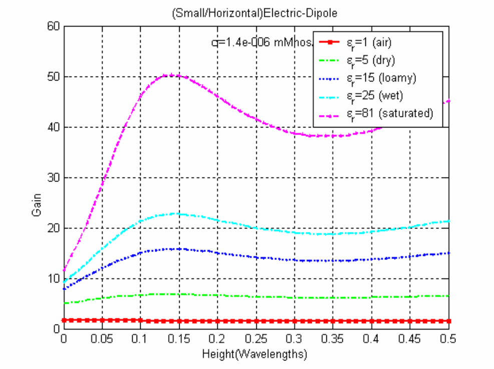


Figure 2. Gain (Magnetic Dipole) – Lossless Earth

As shown in figures 1 and 2, the resonant frequencies of electric dipoles occur at distances lower to the ground that for magnetic dipoles. Therefore, for the initial ground contact measurements, the electric dipole results were used to design a broadband bowtie antenna. As shown in figure 3, when losses are added to the earth, the resonant frequencies of electric dipoles shift to longer wavelengths and the peak gains are reduced.



This work was supported by the AFOSR

Figure 3. Gain (Electric Dipole) – Lossy Earth

Antenna patterns

The antenna patterns in the E-plane of an electric dipole at various heights above the earth/air interface are shown in figures 4-9, for cuts at φ=0° (figures 4-6) and for cuts at φ=90° (figures 7-9).

A. E-Plane Cuts (at *φ*=0°) - Horizontal Electric Dipoles

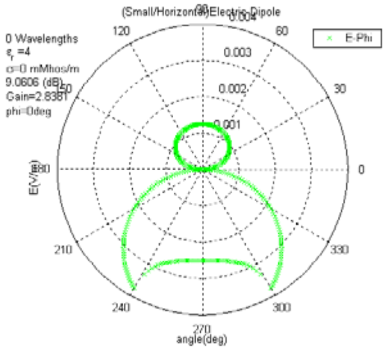


Figure 4. E-Plane Cut (at φ=0°) – Electric Dipole at h=0λ

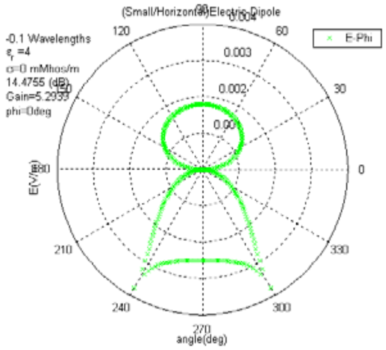


Figure 5. E-Plane Cut (at φ=0°) – Electric Dipole at h=λ/10

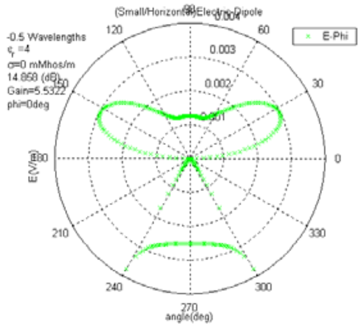


Figure 6. E-Plane Cut (at φ=0°) – Electric Dipole at h=λ/2

B. E-Plane Cuts (at *φ*=90°) - Horizontal Electric Dipoles

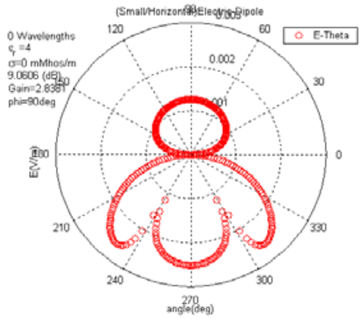


Figure 7. E-Plane Cut (at φ=90°) – Electric Dipole at h=0λ

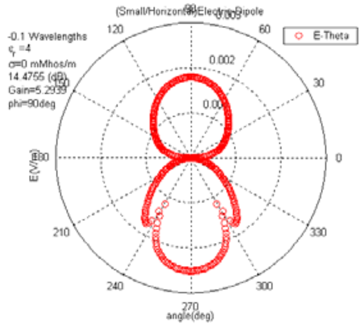


Figure 8. E-Plane Cut (at φ=90°) – Electric Dipole at h=λ/10

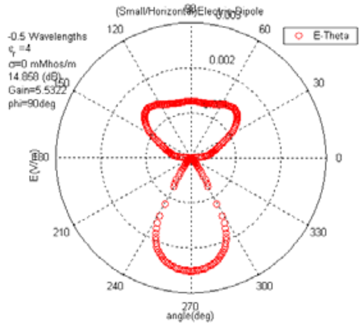


Figure 9. E-Plane Cut (at φ=90°) – Electric Dipole at h=λ/2

Band Width

Electric Dipoles (Horizontal Wires)

The measured bandwidth of the bowtie antenna is shown in figure 10.

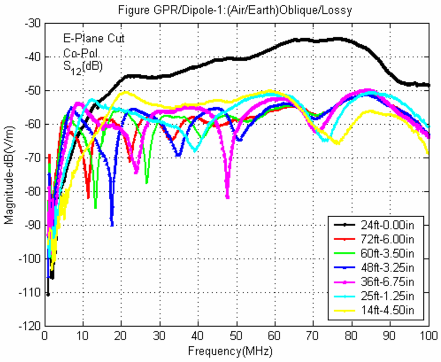


Figure 10: Bowtie/Dipole Bandwidth Comparisons

As shown in figure 10, the bowtie antenna has a gain of 10 to 20 dB better than resonant dipoles tuned across the HF and VHF bands.

References

[1] Sommerfeld, “Uber die Ausbreitung der Wellen in der drahtlosen Telegraphie”, Ann. Physik, Vol. 28, pp. 665-737, 1909.

[2] L.M. Brekhovskikh, Waves in Layered Media, NY Academic, 1980, pp. 225-285.

[3] S.A. Schelkunoff, “Anatomy of surface waves”, IRE Trans. Antennas Propagat., Vol. AP-7, pp. S133-S139, Dec 1959.

[4] K.A. Norton, “The propagaiton of radio waves over the surface of the earth and in the upper atmosphere”, Parts I and II, Proc. IRE, Vol. 24, pp.1367-1387, Oct. 1936; and Proc IRE, Vol. 25, pp. 1203-1236, Sept, 1937.

[5] R.W.P. King, Theory of Linear Antennas, Cambridge, MA: Harvard, 1956, Ch 7.“

[6] J.R. Wait, “Electromagentic Surface Waves”, in Advances in Radio research, Vol. 1, J.A. Saxton, Ed. NY: Academic, 1964, pp.157-217.

[7] A. Banos, Jr. Dipole Radiaiton in the Presence of a Conductng Half-Space. NY: Pergamon, 1966.

[8] R.W.P. King and G.S. Smith. “Antennas in Matter; Fundamentals, Theory, and Applications. Cambridge, MA: MIT, 1981, Ch 11.

[9] D.L. Moffatt and R.J. Puskar, “A subsurface electromagnetic pulse radar”, Geophys., Vol. 41, pp. 506-518, June 1976.

[10] L.H. An and G.S. Smith, “The horizontal circular-loop antenna near a planar interface, “Radio Sci., Vol. 18, pp. 483-502, May-June 1982.

[11] G.S. Smith and L.N. An, “ Loop antennas for directive tranmission into a material half-space”, Radio Sci., Vol. 18, pp.664-674, Sept-Oct 1883.

[12] Glenn Smith, “Directive Properties of Antennas for Transmission into a Material Half-Space”, IEEE Transacations on Antennas and Propagation, Vol. AP-32, No.3, March, 1984.

System Survey of Deep Penetrating Radar

Russell Brown, Jerry Genello, Douglas Lynch,
Randy Musselman*, 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 subsurface 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 subsurface 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 subsurface 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, subsurface 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 subsurface 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 subsurface 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 subsurface 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 subsurface 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, operate 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. Subsurface 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 subsurface 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 radiator, 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 is being developed.

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, the intrinsic wavelength of the radiated waves in the lossy earth is smaller than that in the air. Therefore, the subsurface antenna can be smaller than one in the air.

The advantages of a subsurface 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

Typical e-bomb operations are shown Figures 1-2.

Figure 1: Incoming/penetrating/transmitting e-bomb missile

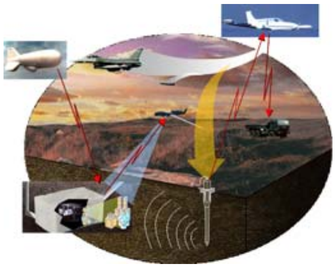


Figure 2: Ground embedded e-bomb operating in close proximity to potential threat target subsurface facility.

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 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
Ground Losses	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 subsurface 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 with 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 subsurface 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 3 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 setup described by Lynch [4] and Brown [5], as shown in Figure 3. 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.

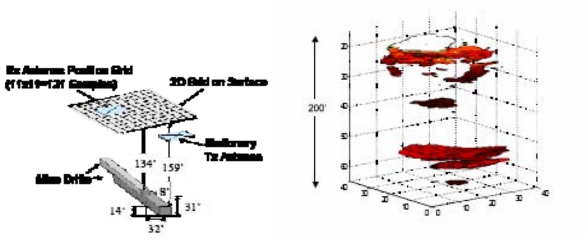


Figure 3: Early work on deep penetrating radar utilized surface contact antennas operating bistatically to detect natural and manmade objects to a depth of 200 feet.

A simple scenario has airborne sensors operating to detect likely hardened and deeply buried targets. Then, a subsurface radiator missile is launched, buries itself in the ground between 20 and 100 feet, and begins to radiate. This is illustrated in Figure 4. Here, we have a combination elevated/airborne transmitter/receiver pair operating in conjunction with a subsurface transmitter for precision engagement. In figure 5, a long term goal includes airborne UAV based transmitter and receiver pairs. This may be impractical given the difficult environments in which subsurface facilities may be built.

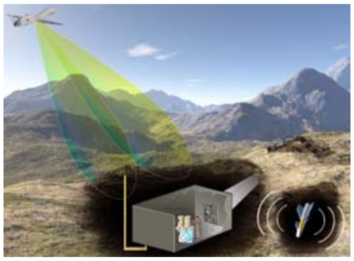


Figure 4: Realistic scene with an elevated (aerostat) airborne receiver, and a subsurface radiator to facilitate precision engagement.

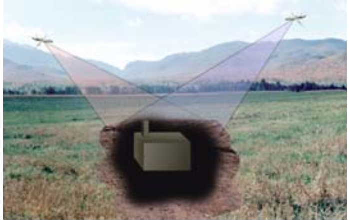


Figure 5: UAV based bistatic GPR for subsurface facility detection.

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 incorporates specular/diffuse scatterers within an anisotropic scenario [6]. A perfectly conducting target was examined according to the target, transmitter and receiver geometry as shown in Figure 6.

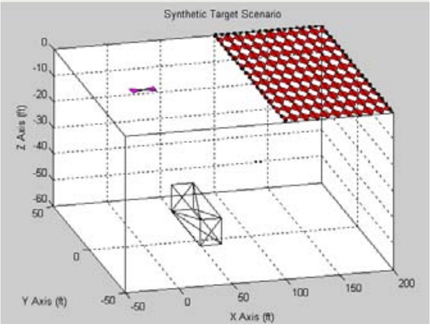


Figure 6. SAR Geometry

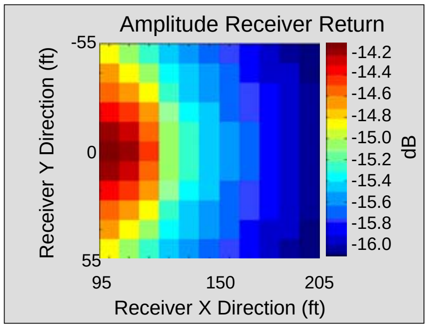


Figure 7. Received amplitudes (transmitter above ground).

The first experiment (see Figure 7) placed the transmitter 6” above the ground and measured the returns at each receiver position in the receiving grid. The second experiment (see Figure 8) placed the transmitter 6” below the ground and measured the returns at the same receiver positions.

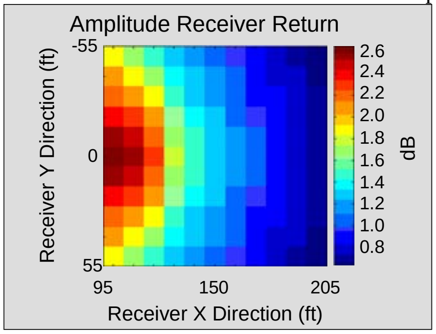


Figure 8. Received amplitudes (transmitter below ground).

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 indicate that by embedding the transmitter only 6” into the ground the received power is increased by more than 16 dB.

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 3 above. Furthermore, reference [3] presents below ground images using thinned arrays with data collected in patterns characteristic of loitering UAV platforms.

References

[13] GeoRadar Inc in Grass Valley CA manufactures a variety of spread spectrum shallow penetrating radars.

[14] Van Etten and Brown, US Patent 5,357,253, “System and Method for Earth Probing with Deep Subsurface Penetration Using Low Frequency Electromagnetic Signals” Issued Oct 18, 1994

[15] Brown, R, et al, “Thinned Arrays for Ground Penetrating Imaging Radar”, *Proceedings of Ground Penetrating Radar 2000 Conference*, page 164 – 169.

[16] Lynch, E.D., et.al., “Experimental HF radar for subsurface sensing” *Proceeding of the Seventh International Conference on Ground Penetrationg Radar*, University of Kanas, Lawrence, KS, May 1998.

[17] Brown, R.D., et.al, “Near field focusing algorithm for high frequency ground penetration imaging radar” *Proceedings of the 1999 IEEE Radar Conference*, Watham, MA, April 1999.

[18] Christophe Schlick, “A Customizable Reflectance Model for Everyday Rendering,” Fourth Eurographics Workshop on Rendering (Paris, France), June 1993, p73-83.

WAVEFORM DIVERSITY IN GROUND PENETRATING RADAR (GPR) APPLICATIONS

Michael Wicks*, John Norgard#, Randy Musselman#

*Air Force Research Laboratory, Rome Research Site, Sensors Directorate, Rome, NY USA
#US Air Force Academy, Colorado Springs, CO USA

Abstract— In this paper, trade-offs associated with critical issues involved with ground penetrating radar (GPR) techniques are addressed. The proliferation of subsurface 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 subsurface radiators, delivered as earth penetrating non-explosive, electronic "e-bombs", as the source of wave form diverse transmissions for GPR experiments using ground contact or airborne receivers. The goal is to achieve improved subsurface 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- waveform diversity, deep-penetrating radar, subsurface radiators, buried-objects, SAR, GPR, RCS

X. Introduction

In this paper, trade-offs associated with critical issues involved with GPR techniques are addressed. The proliferation of subsurface 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 subsurface 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 subsurface 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 subsurface features. Performance enhancement via waveform diversity os accomplished using ultra-wideband (UWB) signals, a variety of frequency modulations, and sidelobe modulation to separate surface clutter from buried object returns. In this paper, geometric diversity is as important as waveform diversity to achieve the desired detection results.

XI. 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, operate 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.

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XIII. History

Typical e-bomb operations are shown Figures 1-2.

Figure 1: Incoming/penetrating/transmitting e-bomb missile

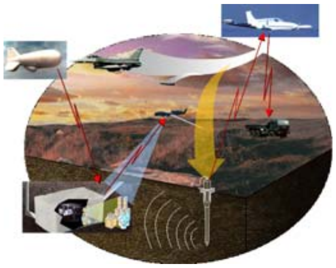

Figure 2: Ground embedded e-bomb operating in close proximity to potential threat target subsurface facility.

XIV. 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 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.

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Two critical issues are addressed with the application of the subsurface 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.

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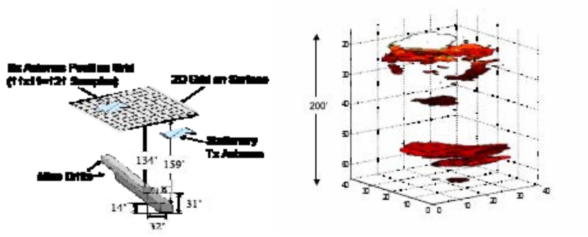

Figure 3: Early work on deep penetrating radar utilized surface contact antennas operating bistatically to detect natural and manmade objects to a depth of 200 feet.

A simple scenario has airborne sensors operating to detect likely hardened and deeply buried targets. Then, a subsurface radiator missile is launched, buries itself in the ground between 20 and 100 feet, and begins to radiate. This is illustrated in Figure 4. Here, we have a combination elevated/airborne transmitter/receiver pair operating in conjunction with a subsurface transmitter for precision engagement. In figure 5, a long term goal includes airborne UAV based transmitter and receiver pairs. This may be impractical given the difficult environments in which subsurface facilities may be built.

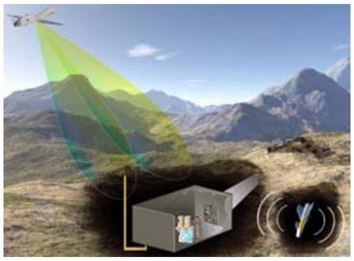

Figure 4: Realistic scene with an elevated (aerostat) airborne receiver, and a subsurface radiator to facilitate precision engagement.

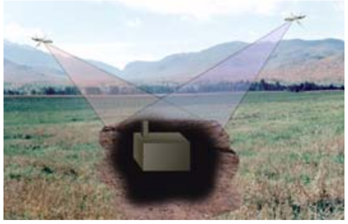

Figure 5: UAV based bistatic GPR for subsurface facility detection.

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. However, additional transmitters could be used in conjunction with multiple waveform diversity transmissions in order to separate below ground returns from surface clutter. In Figure 6, multiple transmitters are located at the end points of a regular polygon. Consider the polygon shaped distribution of transmitters to be at or near the surface. If sequential emissions are radiated by each source in order, then the phase center of the transmitter moves over the period of several (or more) sequential emissions. The effect is to induce a Doppler shift on surface clutter returns, while subsurface targets, being directly below the polygon array of transmitters, exhibit little or no doppler. As such, Doppler filtering is all that is required to filter out unwanted surface clutter returns that would otherwise mask weak underground backscatter signals. Clearly, as the number of transmitters is increased, then the number of pulses processed coherently is increased, and ones ability to separate below ground returns from surface clutter is enhanced. With a visual inspection of the terrain, dominant surface scattering centers such as buildings are easily identified. The geometry of the transmitting array may be selected accordingly. This deployment problem is easily addressed using knowledge based software tools commercially available today.

Another benefit arising from waveform diversity is the selection of frequency span and pulse duration as a function of the local environment under evaluation. An ultra-wideband signal, covering the 1 MHz to 100 MHz band, could be used initially to assess both shallow buried target density and deeply buried objects. As the subsurface profile is formed, energy may then be concentrated in the frequency band that best facilitates the mission. For example, if little or no hard and deeply buried targets are detected, but shallow tunnels abound, then the ground penetrating radar could automatically tune to those higher frequencies essential to forming a quality image of shallow objects to depths of less than 50 feet. Energy at the low end of the band contributes little to resolution and may be dispensed with completely.

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.

XVII. CONCLUSIONS

These results indicate that by embedding the transmitter only 6” into the ground the received power is increased by more than 16 dB.

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 3 above. Furthermore, reference [3] presents below ground images using thinned arrays with data collected in patterns characteristic of loitering UAV platforms.

References

[19] GeoRadar Inc in Grass Valley CA manufactures a variety of spread spectrum shallow penetrating radars.

[20] Van Etten and Brown, US Patent 5,357,253, “System and Method for Earth Probing with Deep Subsurface Penetration Using Low Frequency Electromagnetic Signals” Issued Oct 18, 1994

[21] Brown, R, et al, “Thinned Arrays for Ground Penetrating Imaging Radar”, *Proceedings of Ground Penetrating Radar 2000 Conference*, page 164 – 169.

[22] Lynch, E.D., et.al., “Experimental HF radar for subsurface sensing” *Proceeding of the Seventh International Conference on Ground Penetrationg Radar*, University of Kanas, Lawrence, KS, May 1998.

[23] Brown, R.D., et.al, “Near field focusing algorithm for high frequency ground penetration imaging radar” *Proceedings of the 1999 IEEE Radar Conference*, Watham, MA, April 1999.

[24] Christophe Schlick, “A Customizable Reflectance Model for Everyday Rendering,” Fourth Eurographics Workshop on Rendering (Paris, France), June 1993, p73-83.

GROUND PENETRATING RADAR (GPR) SUB-SURFACE RADIATORS AND RECEIVERS

John Norgard*, Michael Wicks#, Randy Musselman*

*United States Air Force Academy, Colorado Springs, CO
#Air Force Research Laboratory, Rome Research Site, Sensors Directorate, Rome, NY

Abstract

In this paper, trade-offs associated with critical issues involved with ground penetrating radar (GPR) techniques are addressed. The proliferation of strategic subsurface 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 in this paper to use subsurface radiators, delivered as earth penetrating non-explosive, electronic “e-bombs”, as the source of strong radiated transmissions for GPR experiments using ground contact or airborne receivers. Alternately, by reciprocity, the receiver could be buried in close proximity to a suspected target using ground contact or airborne transmitters. The ultimate goal of this project is a stand-off capability using satellite communication links. The received signal could also be relayed to a surface repeater by deploying a fiber optics cable during earth penetration.

The goal of this study is to achieve improved subsurface surveillance characteristics of buried objects. Three-dimensional imaging techniques for deeply buried targets are being developed based on two-dimensional synthetic aperture radar (SAR) data collection techniques. Several GPR experiments using ground contact transmitters and receivers were performed at a zinc mine in New York State to validate the 2D SAR processing algorithms. Several tunnels buried several hundred feet below the ground were detected using this technique. Some surface clutter was present in the measured data. The buried sub-surface radiators or receivers proposed here should remove most of the surface clutter. Future tests are planned to confirm this assumption.

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Deep Ground Penetrating Radar (GPR)
WIPD-D Models a of Buried Sub-Surface Radiators

John D. Norgard*, Michael C. Wicks#, Randy L. Musselman
***US Air Force Academy**
Colorado Springs CO 80840, USA
 # Air Force Research Laboratory / Rome Research Site / Sensors Directorate
Rome, NY 13440, USA
john.norgard@usaf.af.mil

Abstract: — The proliferation of strategic subsurface sanctuaries has increased the need for enhanced remote sensing techniques providing for the accurate detection and identification of deeply buried objects. A new Ground Penetrating Radar (GPR) concept is proposed in this paper to use subsurface radiators, delivered as earth penetrating non-explosive, electronic "e-bombs", as the source of strong radiated transmissions for GPR experiments using ground contact or airborne receivers. Three-dimensional imaging techniques for deeply buried targets are being developed based on two-dimensional synthetic aperture radar (SAR) data collection techniques. Experiments over deep mine shafts have been performed to validate the 2D SAR processing algorithms. WIPL-D models have been used to verify the significant enhancement in the received signal-to-noise ratio obtained by burying the transmitter under the surface of the earth. Simple ray-tracing techniques have also been used to confirm the enhancements.

Keywords: Deep Ground Penetrating Radar, Subsurface radiators, buried objects, SAR, GPR, RCS

1. Introduction

In this paper, trade-offs associated with critical issues involved with GPR techniques are addressed. The proliferation of subsurface 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 subsurface 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 subsurface 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 subsurface features**.**

2. Ground Penetration Radar (GPR)

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, operate 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 GPR, 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 new configuration is modeled with WIPL-D to determine the benefits of burying the transmitting antenna.

3. 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 subsurface 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 radiator, 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 is being developed.

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, the intrinsic wavelength of the radiated waves in the lossy earth is smaller than that in the air. Therefore, the subsurface antenna can be smaller than one in the air.

The advantages of a subsurface 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.

4. Embedded Scenerio

Typical e-bomb operations are shown Figures 1-2.

Figure 1: Incoming/penetrating/transmitting e-bomb missile

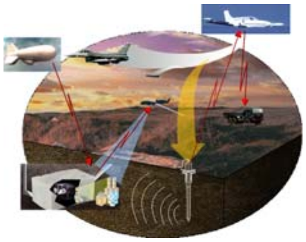

Figure 2: Ground embedded e-bomb operating in close proximity to potential threat target subsurface facility.

a) 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 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.

b) 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.

c) 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.

d) 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.

e) Performance Summary

Surface	Subsurface	Radiator	Improvement
Radiation Efficiency	20%	80%	6 dB
Ground Losses	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

5. Critical Issues: Clutter/Mismatch

Two critical issues are addressed with the application of the subsurface 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.

6. 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 with 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 subsurface 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 3 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 setup described by Lynch [4] and Brown [5], as shown in Figure 3. 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.

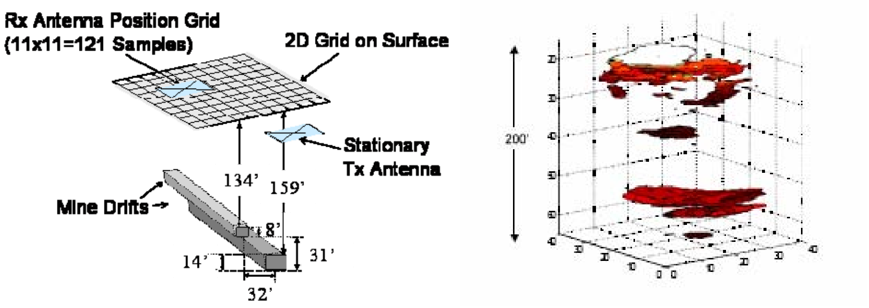

Figure 3: Early work on deep penetrating radar utilized surface contact antennas operating bistatically to detect natural and manmade objects to a depth of 200 feet.

A simple scenario has airborne sensors operating to detect likely hardened and deeply buried targets. Then, a subsurface radiator missile is launched, buries itself in the ground between 20 and 100 feet, and begins to radiate. This is illustrated in Figure 4. Here, we have a combination elevated/airborne transmitter/receiver pair operating in conjunction with a subsurface transmitter for precision engagement. In figure 5, a long term goal includes airborne UAV based transmitter and receiver pairs. This may be impractical given the difficult environments in which subsurface facilities may be built.

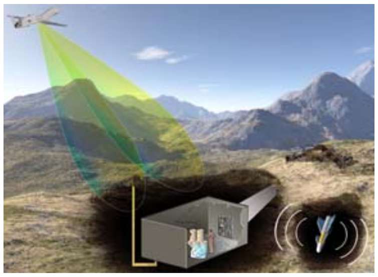

Figure 4: Realistic scene with an elevated (aerostat) airborne receiver, and a subsurface radiator to facilitate precision engagement.

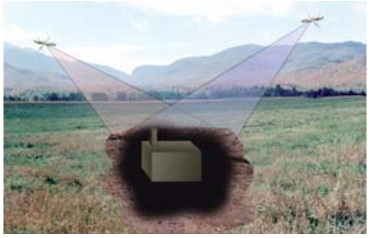

Figure 5: UAV based bistatic GPR for subsurface facility detection.

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.

7. Modeling & 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 incorporates specular/diffuse scatterers within an anisotropic scenario

[6]. A perfectly conducting target was examined according to the target, transmitter and receiver geometry as shown in Figure 6.

A simple WIPL-D model was constructed of dielectric blocks to model the tunnel below a homogeneous erath, as shown in Figure 7 (solid) and 8 (grid). The transmitting antenna was located 6” above or 2 ft below the ground. The receiving antenna was located 3” below the ceiling of the tunnel. The received energy when the transmitter was located below the ground was compared to the received energy when the transmitter was located above the ground. The enhancement predicted by WIPL-D was 15.1 dB; the enhancement predicted by the ray-tracing algorithm was 15.8 dB. This is a significant increase in received power, which translates into stronger signals at greater depths.

The first experiment (see Figure 7) placed the transmitter 6” above the ground and measured the returns at each receiver position in the receiving grid. The second experiment (see Figure 8) placed the transmitter 6” below the ground and measured the returns at the same receiver positions.

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.

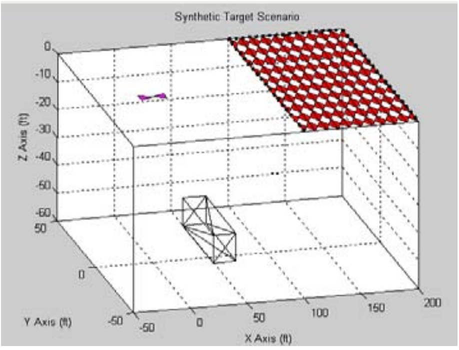

Figure 6. SAR Geometry

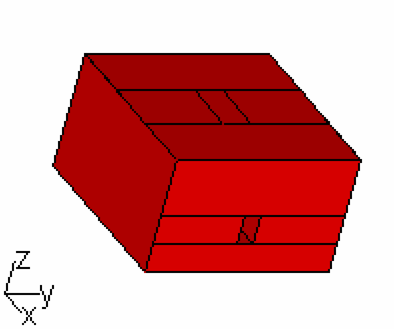

Figure 7. WILP-D Solid Model

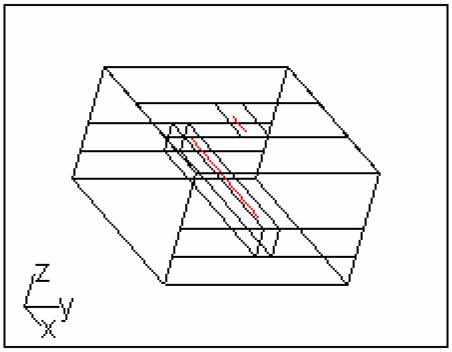

Figure 8. WIPL-D Grid Model (Transmitting Antenna Above or Below Ground).

8. Conclusions

These results indicate that by embedding the transmitter only 6” into the ground the received power is increased by more than 16 dB.

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 3 above. Furthermore, reference [3] presents below ground images using thinned arrays with data collected in patterns characteristic of loitering UAV platforms.

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[27] Brown, R, et al, “Thinned Arrays for Ground Penetrating Imaging Radar”, *Proceedings of Ground Penetrating Radar 2000 Conference,* page 164 – 169.

[28] Lynch, E.D., et.al., “Experimental HF radar for subsurface sensing” *Proceeding of the Seventh International Conference on Ground Penetrationg Radar*, University of Kanas, Lawrence, KS, May 1998.

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[30] Christophe Schlick, “A Customizable Reflectance Model for Everyday Rendering,” Fourth Eurographics Workshop on Rendering (Paris, France), June 1993, p73-83.

RCS of Aircraft
Using HPC/CEM Hybrid Codes

John Norgard and Randall Musellman

US Air Force Academy
Colorado Springs, CO USA
john.norgard@usafa.af.mil

Abstract—

In this paper, hybridized Computational Electromagnetic (CEM) codes are developed to predict radiation from antennas mounted on aircraft and the Radar Cross Section (RCS) of the aircraft. Modeling and simulation (M&S) is performed with a combination of Moment Method (MM), Finite Difference Method (FDM), and Uniform Theory of Diffraction (UTD) to analyze large, complex structures including surface-mounted radiators and external sources.

The overall goal of this study is to develop and demonstrate techniques for predicting radiation, scattering, and coupling on aircraft platforms. An F16 aircraft was chosen as an example because measured probe data was available from experiments performed on an actual aircraft at the "Upside-Down" Experimental Tests Facility at AFRL/RRS (Rome, NY)

Simple RCS experiments were also conducted with a scale model F16 aircraft to validate the code. The experiments were performed in the anechoic chambers at the AFRL/RRS (Sensors Directorate) and at the AFRL/PRS (Directed Energy Directorate). The experiments were performed using a thermal imaging technique. This technique uses a minimally perturbing, thin, planar IR detection screen to produce a thermal image (e.g., an IR thermogram) of the intensity of the EM energy over the two-dimensional region of the screen.

Several examples are presented using this thermal technique to measured EM fields using electric field detector screens (carbon loaded foams). These examples illustrate the use of this thermal technique to correlate numerically predicted data with experimental observations. This technique can be used to experimentally validate hybrid codes which predict electric field distributions in areas where conventional hard-wired probes would significantly perturb the fields being measured, for example inside the cavities of the aircraft and near apertures in the fuselage. Surface current distributions (magnetic fields) on metallic surfaces also can be measured with this technique using magnetic field detector screens (ferrite loaded foams).

The overall goal of this work is to achieve improved aircraft models and simulation capabilities to predict radiation, scattering, and coupling of aircraft fields. This hybrid code will improve the CEM M&S process.

Surveillance of Sub-Surface Sanctuaries Using Earth-Penetrating Radiators

John Norgard and Randall Musellman

US Air Force Academy
Colorado Springs, CO USA
john.norgard@usafa.af.mil

Abstract—

Electromagnetic (EM) imaging techniques are being developed to survey strategic sub-surface sanctuaries. The overall goal of this study is to develop and demonstrate techniques for sub-surface profiling from ground based and/or airborne (or even space) platforms.

This surveillance scheme combines and utilizes bistatic RCS measurement techniques, broadband GPR antenna technologies, and far-field SAR remote sensing techniques. The combined RCS/GPR/SAR surveillance technique is used to extract target signatures concealed in measured RCS data and to remove thermal nose and ground clutter at the earth/air interface from the SAR data.

The combined RCS/GPR/SAR surveillance process utilizes ground contact and airborne transmitting (TX) and receiving (RX) antennas. Small, but efficient, ultra-wideband (100:1 bandwidth) conformable GPR antennas are being designed and developed to operate over the HF/VHF bands.

Planar wire-grid bowtie antennas are being developed as broadband GPR radar antennas. These antennas are 2D approximations to frequency independent, i.e., ultra-wideband, 3D solid biconical antennas. The antennas are truncated to finite lengths, which reduce the bandwidth to a finite range that is adjusted to cover the HF/VHF bands. 2D cross-sectional versions of the bowtie antennas were built and tested at the AFRL/RRS sub-surface antenna range and were compared to an adjustable standard-gain half-wave dipole antenna.

Experiments were conducted at an abandoned Zinc mine in New York. Two bowtie antennas were 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 setup developed at AFRL/RRS – Sensors Directorate.

Remote sensing using an elevated GPR system, as used in the mine experiment, provides a safe stand-off distance, but 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 subsurface radiator, delivered as an earth penetrating non-explosive, electronic bomb (e-bomb), for the source of the transmission and ground contact or airborne receivers.

Most notable in the Zinc mine data were 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. Modeling and simulation of this scenario showed a 15 dB improvement in received signal.

The overall goal of this work is to achieve improved subsurface 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.