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Evaluation of a Prototype Continuous-wave, Borehole, Ground-Penetrating Radar

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Evaluation of a Prototype Continuous-wave, Borehole, Ground-Penetrating Radar

Final Report for Laboratory Directed Research & Development Project #32810

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Abstract

Borehole radar systems can provide essential subsurface structural information for environmental evaluation, geotechnical analysis, or energy exploration. Sandia developed a prototype continuous-wave Borehole Radar (BHR) in 1996, and development of a practical tool has been continuing at a Russian institute under a Sandia contract. The BHR field experiments, which were planned for the summer of 2001 in Russia, provided a unique opportunity to evaluate the latest Sandia algorithms with actual field data. A new three-dimensional code was developed to enable the analysis of BHR data on modest-sized desktop workstations. The code is based on the staggered grid, finite difference technique, and eliminates 55% of the massive storage associated with solving the system of finite-difference linear equations. The code was used to forward-model the Russian site geometry and placement of artificial targets to anticipate any problems that might arise when the data was received.

Technical software and equipment problems in the Russian field tests, conducted in August 2001, invalidated all but one of the data sets. However, more field tests with improved equipment and software are planned for 2002, and analysis of that data will be presented in a future report.

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Introduction

Borehole radar systems can provide essential subsurface structural information for environmental evaluation, geotechnical analysis, or energy exploration. Existing borehole radars (BHR), operating in a pulsed mode at 100MHz and above, are used for applications where the surrounding media has a favorable, or small, conductivity. They are not useful for oil and gas exploration because the electrical parameters of the host media are unknown at depth and the conductivity may be large. Very high peak power would be required in the transmitter to provide a useful radial range, and, because temperature increases with depth, substantial work in high temperature dielectric materials would be required for a practical tool. Sandia developed a prototype continuous-wave BHR in 1995-96 that included a very high efficiency, heat-tolerant amplifier. The development of a practical tool is continuing at the Measurement Systems Research Institute (NIIS), a MinAtom institute, in Nizhny Novgorod, Russia, under a Sandia contract. Field experiments were planned for the summer of 2001 in Russia

Sandia is a world leader in subsurface imaging algorithms for electromagnetic data, and has state-of-the-art algorithms available for BHR data analysis and modeling. The BHR field experiments were to provide a unique opportunity to evaluate the latest Sandia algorithms with actual field data.

Accordingly, a new three-dimensional code was developed to enable the analysis of BHR data on modest-sized desktop workstations. Based on the staggered grid finite difference technique, the code (FDM3D) eliminates 55% of the massive storage associated with solving the FD system of linear equations. This was achieved by employing a matrix-free paradigm where, at each step of the iterative linear solver, the matrix action is computed "on the fly" without the need of storing a matrix. This new approach makes it possible to model problems on a relatively inexpensive personal computer that would otherwise require at least 2GB of core memory on a high-end workstation. The modified code was used to forward-model the Russian site geometry and placement of artificial targets to anticipate any problems that might arise when the data was received.

All but one of the data sets collected in the Russian field tests, conducted in August, were invalidated by a variety of software and equipment problems. However, more field tests with improved equipment and software are planned for mid November, and analysis of that data will be presented in a future report. This report describes the BHR, and presents the forward-modeling results of the field experiment together with a comparative description of two additional transmitter-receiver combinations that may have application to continuous-wave borehole radars.

Borehole Radar

The Borehole Radar is designed specifically to detect discontinuities in the electrical properties of geophysical media that are more or less parallel to the borehole, *i.e.*: *vertical fissures*, that, in some oil & gas fields, dominate the permeability of the media. The Austin chalk formation in the US, and the Tangize field near the Caspian Sea are examples. Caffey (1997) described experiments with a proof-of-concept prototype in a Sandia report, and explained why a horizontal magnetic dipole (HMD), with its moment directed along the positive X-axis of a Cartesian coordinate system, was the practical choice for a source.

The HMD_X generates only two field components that are parallel to the borehole axis, namely:

$$E_Z = j\mu_r\mu_o\omega M \sin\theta \sin\phi(1 - jkR)\exp(jkR) / R^2, \quad (1)$$

and

$$H_Z = M\left\{\sin^2\theta \cos\theta \cos\phi\left[3 - j3kR - k^2R^2\right]\right\}\exp(jkR) / R^3. \quad (2)$$

$$M = \frac{IdA}{4\pi}, \text{ where}$$

I = dipole current, peak Amperes;

dA = area of the infinitesimal loop through which 'I' circulates in a counter-clockwise sense as viewed from the positive X-axis, meters²;

$$j = \sqrt{-1};$$

$k = \alpha + j\beta$, is the propagation factor, meters⁻¹, in which

$$\alpha = \omega\sqrt{\frac{\mu_o\mu_r\epsilon_o\epsilon_r}{2}\left(+1 + \sqrt{1 + g^2}\right)}, \text{ is the real part, and}$$

$$\beta = \omega\sqrt{\frac{\mu_o\mu_r\epsilon_o\epsilon_r}{2}\left(-1 + \sqrt{1 + g^2}\right)} \text{ is the imaginary part,}$$

where

σ = Conductivity of the media, Siemens/meter; $1\text{E-}4 \leq \sigma \leq 4$ S/m;

ϵ_o = Dielectric constant of free-space, about $8.854\text{E-}12$ Farads/meter;

ϵ_r = Relative dielectric constant of the media; $1 \leq \epsilon_r \leq 81$;

μ_o = Permeability of free space, $4\pi \cdot 10^{-7}$ Henries/meter;

μ_r = Relative magnetic permeability of the media;

f = Frequency, Hz; $\omega = 2\pi f$;

$$g = \frac{\sigma}{\omega \epsilon_0 \epsilon_r}, \text{ a dimensionless ratio called the loss tangent;}$$

and R , θ , and ϕ are the spherical coordinates of distance, polar angle, and azimuth angle. Time-dependence as $\exp(-j\omega t)$ is suppressed.

The relative magnitude of each component is independent of both R and kR , and depends only on the trigonometric terms.

The relative distribution of the E_Z -field is a maximum along the Y-axis, and is zero throughout the entire XZ-plane as shown in Figure 1. The half-power beamwidth of each lobe is 90 degrees in both θ and ϕ . The two lobes are out-of-phase with each other. The addition of an HMD_Y-source, properly combined with the HMD_X, allows a composite two-lobed beam to be steered in the azimuth plane. Because of the bi-lobed structure, it is only necessary to steer the beam through 180 degrees. A vertical electric dipole (VED), carefully centered on, and parallel to, the Z-axis is null-coupled to both sources and can be used to detect any backscattered E_Z -field.

The relative distribution of the H_Z -field has four lobes in the XZ-plane as shown in Figure 2. Each lobe is out of phase with the lobe adjacent to itself, and is in-phase with the lobe in the opposite quadrant. This more complicated lobe structure, and the fact that the H_Z -field decreases more rapidly than the E_Z -field for moderate values of the spherical radius, favored the use of the E_Z -field in the BHR.

The BHR is designed to operate at depths of up to 2440m at temperatures up to 60C at any of ten selectable frequencies from 12.5kHz to 4.04MHz. The instrument is 914cm long by 10.6cm in diameter. The two HMD sources are located 338cm below the top of the tool. This places the center of the 100cm-VED antenna 403cm beneath the midpoint of the separation of the two sources. The receiver operates from an independent battery supply at the lower end of the tool, and all communication between the receiver and the rest of the BHR takes place via fiber optic links to ensure isolation between the two sets of antennas.

Russian Field Tests

NIIS, the Russian institute, under a provision of the Sandia contract, was required to make certain measurements with the BHR suspended at least 30m below the surface of the ground. The object was to simply demonstrate proper functioning of the tool using artificial targets rather than to detect geological structure as such. NIIS examined three sites outside of Nizhny Novgorod, but finally settled on developing a site at their antenna range about an hour's drive away from the institute.

The site geology consisted of a vertical stack of horizontal layers with a top layer of loam, 2m thick, followed by 13m of sand, 15m of soft clay, 11m of clay with particulate matter, 9m of very dense clay, and ending in a limestone basement rock at 50m. The water level in the borehole was at the top of the first clay layer at 15m. The conductivity of

the loam and sand was about 10mS/m, and the conductivity of the water-saturated clay layers was about 100mS/m.

The site had four boreholes, 50m deep, located on the corners of a 30m square. Each borehole was lined with 180/225mm polyethylene pipe, washed clear of clay, and open at the bottom. Metallic casing was not emplaced at the top of the boreholes. The borehole was placed 4m away from the center of a dry well that was 1.5m x 1.5m square (inside) by 10m deep and shored with horizontal aspen logs about 20-23cm in diameter. The diagonal of the target subtended an angle of about 38 degrees in the XY-plane. NIIIS chose this unusual geometry to allow for the placement of different objects and media material within the dry well. The very close spacing was chosen in order to examine embedded targets at the highest operating frequency of 4.04MHz.

The interior of the well contained only air for the initial tests that were conducted from 14-16 August 2001 with Sandia observers present. The first test was an azimuth sweep at 252.5kHz with the top of the tool located at a depth of 4m. This placed the HMD-sources at a depth of 7.4m, and placed the receiver at 11.4m so that the receiver VED was beneath the bottom of the dry well but above the water level in the borehole. The results were not useful because the back-scattered signal level exceeded the linear, calibrated range of the receiver that was set at 10mV_{rms} referred to the input. Useful noise measurements (with the transmitter turned-off) were made at a depth of 25m, and the rms noise at 252.5kHz was measured as 0.6 μ V and 0.4 μ V for the in-phase and quadrature channels of the receiver respectively.

Additional azimuth sweeps at 1.0, 2.0, and 4.04MHz at a depth of 12.5m were made, but none of the tests were credible. The Sandia observers departed on 17 August after receiving assurances that the problems would be identified and that necessary modifications would be made. Field tests were resumed the week of 12 November, but results are not yet available for evaluation.

NUMERICAL MODELING

Numerical modeling for the predicted response of the BHR instrument was conducted using a staggered grid finite difference (FD) algorithm for fully 3D heterogeneous conductivity distributions. Briefly stated, the algorithm solves for electric fields in the low-frequency limit where displacement currents can justifiably be ignored-an assumption which is reasonable for BHR frequencies lower than 1MHz. Furthermore, the algorithm discretizes the model domain in terms of structured Cartesian grid that defines a rectilinear array of cells that can be assigned arbitrary material properties. Further details of the algorithm can be found in Newman and Alumbaugh (1995) and Weiss (2001).

The objective of the modeling exercise was to compute the effect of a 1.5 x 1.5 x 10m air-filled cavity on the predicted response for the BHR instrument. The reference frame for the numerical simulations that follow is illustrated in Figure 3 and the geometry of the BHR instrument is illustrated in Figure 4.

In all of the simulations, the Earth conductivity was taken to be 10mS/m. The 20 x 20 x 30m FD mesh is composed of 81 x 81 x 81 nodes with a 5% geometric increase in node spacing from the origin. In computing the instrument response, FD calculations were performed first for X and Y -directed source dipoles. The responses for intermediate dipole orientations were later computed via superposition of the 2 FD solutions at each source depth. Voltages for the BHR receiver antenna were computed by a Riemann sum integration of 1000 electric field values along the antenna's length, and are shown in Figure 4. The calculations in Figure 5 indicate that the azimuth of the target cavity is resolved (with a 180deg ambiguity) for the BHR instrument.

Summary

Numerical modeling of the azimuthal sweep method for a continuous-wave borehole radar has been conducted in support of field data collected at the Russian test site in 2001. While the data was unusable due to instrumentation problems, the numerical results can be applied to future work at the test site where the integrity of the collected data is not compromised. These results indicate that the present configuration of the BHR instrument should be sufficient to resolve the 1.5mx1.5m air-filled cavity at the test site.

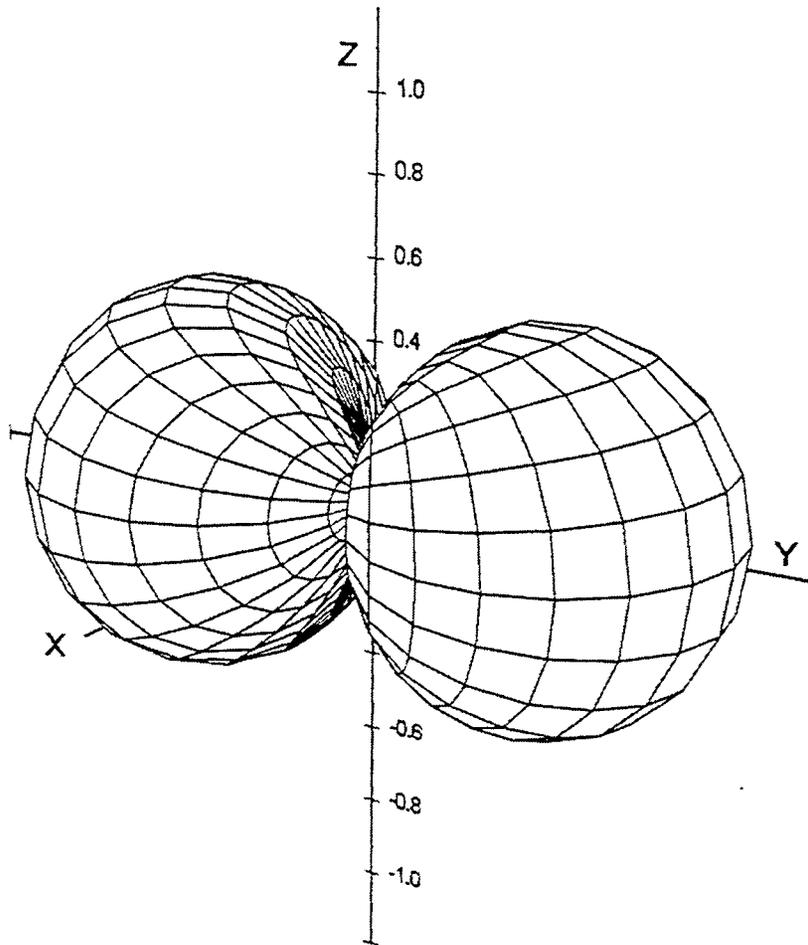


Figure 1. Relative E_z -field from an HMD_x -source

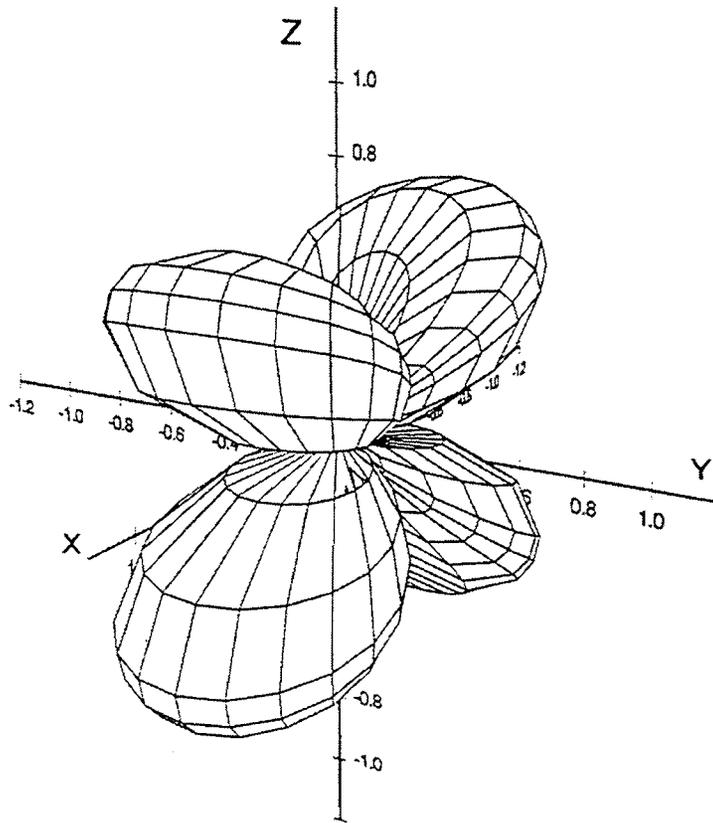


Figure 2. Relative H_z -field from an HMD_x -source

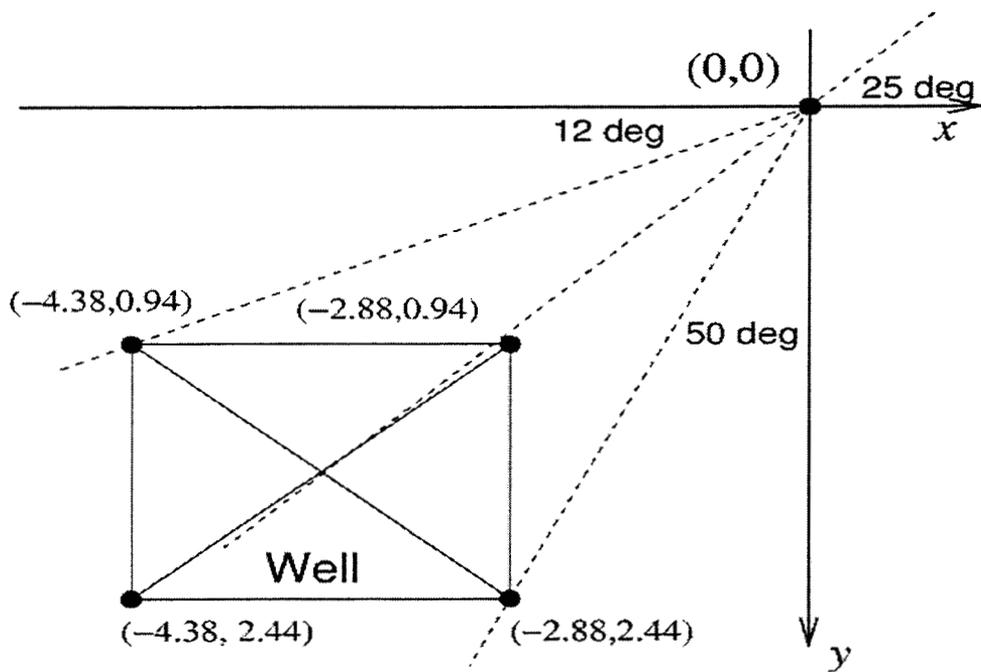


Figure 3. Diagram indicating the lateral coordinates (in meters) of the resistive 10m deep well whose effect on BHR response was computed using the 3D finite difference algorithm. The borehole axis is located at the origin $(0,0)$.

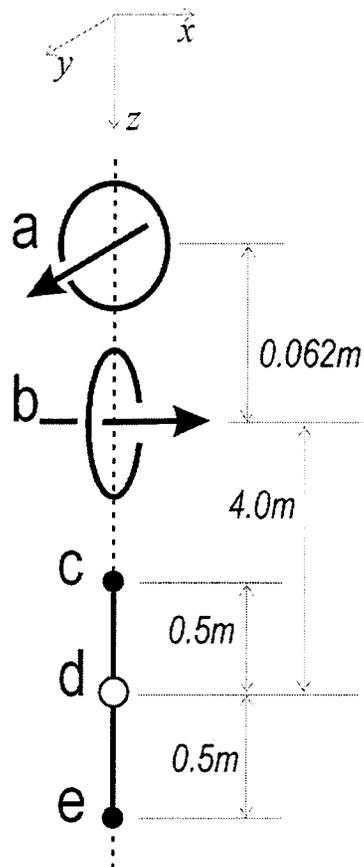


Figure 4. Dimensions of the BHR instrument relevant to the generation of synthetic data. Two magnetic dipole transmitters (a and b) are oriented in the x and y directions and located approximately 4m above the midpoint (d) of a 1m vertical electric field dipole receiver. Endpoints of the receiver antenna are denoted by (c) and (e).

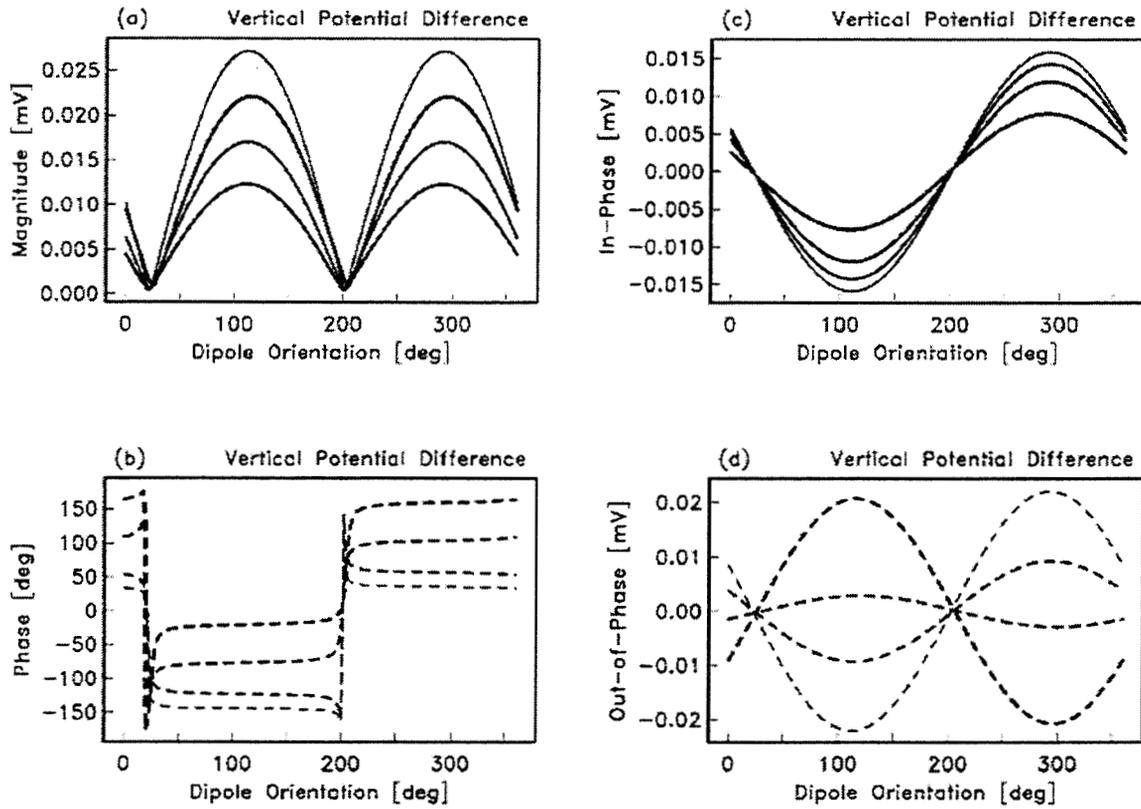


Figure 5. Computed 252.5kHz response of the BHR at four transmitter depths (6.5m - light line, 5.5m, 4.5m and 3.5m-heavy line) as a function of a transmitter dipole orientation. Dipole moment is taken as unity and the receiver electrodes are located at 3.5m and 4.5m below the transmitter dipole. Magnitude and phase are shown in (a) and (b), respectively. The corresponding in-phase and quadrature components are shown in (c) and (d).

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