Super-Resolution of Coherent Targets by a Directional Borehole Radar

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Abstract—In this paper, an analytical method based on the multiple signal classification (MUSIC) algorithm is applied to three-dimensional (3-D) estimation of target positions using a directional borehole radar. A cylindrical conformal array on a conducting cylinder in a borehole was used for experimental measurements estimating the position of targets. It is also shown that the algorithm provides much better resolution than the Fourier-based algorithm in both a computer simulation and real tests. Soil at the experimental site is not necessarily uniform, and there can be many clutter sources such as small stones in the subsurface. For this situation, it is difficult for the super-resolution technique to work properly. Results of the experiments show that the super-resolution technique for locating targets, despite being seriously limited by both the space available for the array and the bandwidth, is promising for directional borehole radar. In the developed algorithm, it is assumed that the distribution of electromagnetic constants inside a borehole is known before estimation of target positions.

Index Terms—Coherent target, directional borehole radar, MUSIC algorithm.

I. INTRODUCTION

SUBSURFACE sensing techniques play an important role in subsurface space development. Seismic techniques have been used widely, but ground-penetrating radar (GPR) has emerged as another useful technique for subsurface sensing. Borehole radar is one of the GPR techniques. Its most significant feature is its ability to access targets [1].

Most conventional borehole radar systems use dipole antennas, which are omnidirectional. However, in many engineering applications, it is necessary to accurately determine target positions in three-dimensions (3-D). Such measurements can be achieved using one borehole if we can use a directional borehole radar.

Many efforts have been made to determine target positions in three dimensions using directional borehole radars. For example, control of the radiation pattern in a borehole was attempted using a dielectric medium [2]. Also, a cross-loop antenna, which consists of loops having a figure-eight pattern in air, was tried as a directional borehole radar [3], but there is no guarantee that the figure-eight pattern can be used in a borehole, because the borehole will influence the radiation pattern. An array antenna may be suitable for a directional antenna, and an adcock antenna, which is an array of dipole antennas, was also tried. However, the main lobe of the array in a plane, which is perpendicular to the borehole, is not narrow enough, because the space available for the antenna is limited by the diameter of the borehole. For example, the wavelength at 300 MHz in the medium (ε_r = 17) is 0.24 m, which is more than double the borehole diameter of 0.1 m.

If we can accurately obtain the phase information of a wave at a number of points in a borehole, we may be able to estimate the parameters with super-resolution spectral estimation techniques. In this paper, we describe the use of the multiple signal classification (MUSIC) algorithm [4], one of the popular super-resolution techniques. We designed and constructed a prototype directional borehole radar system in order to achieve the super-resolution. We chose a cylindrical conformal array on a conducting cylinder, as proposed by Sato and Tanimoto [5] for the receiving antenna of the radar. Also, a network analyzer was adopted in order to measure transmission of broadband signals between a transmitter and a receiver with high S/N, which is important in applying the super-resolution technique.

Both antenna characteristic and lossy medium around the radar limit the bandwidth. This is because the radiation efficiency of the antenna decreases for lower frequencies and wave attenuation is increased at medium to high frequencies. The limited narrow bandwidth will cause low resolution in estimating time delays, and the resolution of time delays can be improved with the super-resolution technique [6], [7]. Therefore, in order to estimate the locations of the targets, we need to simultaneously estimate three parameters: time delay of the waves and two directions: elevation and azimuth. This is done with the super-resolution technique.

The MUSIC algorithm can be easily extended to multidimensional estimation, such as two-dimensional (2-D) directions of incoherent signals. Also, in completely coherent signals such as radar signals, we can apply the MUSIC algorithm with decorrelation techniques. The 2-D imaging with the high-resolution technique using decorrelation has been carried out by several authors [8], [9], including an algorithm for 2-D estimation of both an angle and time delays using a linear array [10].

Boreholes are usually filled with fluid. The subsequent invasion of borehole fluid into the rock formation gives rise to an altered zone whose electromagnetic property varies radially as we move away from the borehole. Such a zone may be modeled by a cylindrically layered medium. This structure around the antenna always exists during the borehole radar measurement,
and the cylindrical structure can seriously influence the electromagnetic fields [11]. This cylindrical structure, which is non-homogenous around the borehole, must be considered in processing the borehole radar signals. Although many authors have proposed applying the super-resolution techniques to estimation of parameters, a problem involving a changing electromagnetic media, such as is encountered in a borehole, is a difficult one. Even in such a situation, the super-resolution technique can be applied within a theoretical model, including the influence of the borehole. The MUSIC algorithm can estimate parameters with an array, even in a cylindrical structure medium. Also, if the theoretical model included losses in medium, we could use the MUSIC algorithm in the lossy medium inside and around a borehole. In addition to the cylindrical structure around a borehole, there can be inhomogeneities such as clutters in the subsurface and the interface of horizontal layers, but we will ignore these in this paper.

In this paper, we present a three-dimensional (3-D) estimation method of a target position using directional borehole radar. In Section II, we review the conformal array. In Section III, we introduce a method of array signal processing based on the MUSIC algorithm. Examples of 3-D estimation of a target position by both computer simulations and experiments are given in Section IV.

II. THE CONFORMAL ARRAY

Calculation of electromagnetic fields produced by the scattering of a plane wave incident on a conducting cylinder is a basic problem, and an analytical solution for the problem can be derived [12]. Even if the cylinder is coated with multiple dielectric layers, an analytical formulation of the field can be derived [13]. The computation is carried out with transmission and reflection matrices [14]. There is usually fluid such as water or mud and air in the space between the antennas and the wall of boreholes, and the fluid may be a lossy media. If a conducting cylinder is in a borehole, the cylinder can be modeled as a dielectric coated cylinder. Most simple theoretical models for a conducting cylinder in a borehole can be represented as shown in Fig. 1. Fig. 2 shows the transient response of the $z$ component of magnetic field on a conducting cylinder, when a TE wave illuminates the dielectric layer coated conducting cylinder. TE wave is defined as a plane wave, an electric field of which is perpendicular to the $z$-axis. Since the current distribution on the conducting cylinder corresponds to directions of arrival of the incident waves, we can estimate the directions of arriving waves using the current distribution on the cylinder. A typical method for measuring the distribution of current, which can be related to the magnetic field on a highly conducting body is with small electric probes such as half-loops. Fig. 3(a) shows the cylindrical conformal array on a conducting cylinder [5] for a directional borehole radar. The antenna elements mounted on the relatively thick conducting cylinder are current probes in the form of small loop antennas [14]. Fig. 3(b) shows an antenna element used in Section IV.

In order to determine the direction of arrival waves from the received signals, we must estimate the dielectric constant distribution near the antenna. The simplest dielectric situation for the theoretical model is shown in Fig. 1. Some well-logging tools can be used to determine the dielectric constant in and around the borehole. In the case of conductive media, we can determine the direction of arrival waves if we can construct the correct theoretical model. Therefore, we can use the antenna in this lossy medium.

III. METHOD OF ESTIMATION

In this section, we introduce a signal processing method for estimating 3-D positions using the conformal array. After we define the array geometry and formulate the problem, we describe how the MUSIC algorithm can be used to estimate target positions.

A. Problem Formulation

In our experiment, a transmitter illuminates the field of view, and scattered waves from targets and a direct wave from the transmitter are recorded by the conformal array. The scattered signals from targets can be represented as a sum of complex scattered signals from each scattering center. We define the scattering centers, with positions $(x_k, y_k, z_k), (k = 1, 2, \ldots, d - 1)$ as coherent point sources, as shown in Fig. 4(a). Furthermore, we assume that the transmitter is also represented by a single point source at $(x_d, y_d, z_d)$. Therefore, the waves from $d$ point sources impinge on the conformal array.

We assume that the point sources are far from the receiver, and that the scattered waves and the direct wave can be approximated by a plane wave. If the wave incident on the conducting cylinder cannot be approximated as a plane wave, we need to describe the wave other than as a plane wave [15]. For example, if a scattered point is near the antenna, we should adopt a spherical wave incidence model. Generally, we need numerical integration to compute the scattered field, and the computation load of the integration is not light except for the plane wave mode. Furthermore, if an incident spherical wave mode is adopted, $\psi_{h, j}$ becomes a function of $t_k$ as well as $\theta_k, \phi_k$. This means that we
need to compute $\psi_{h,j}$ for each 3-D combination of $t_k$, $\theta_k$, and $\phi_k$, and this also is a heavy computational load.

The scattering center locations $(x_k, y_k, z_k), (k = 1, 2, \cdots, d - 1)$ of the targets are associated with position $(r_k, \theta_k, \phi_k)$ of the arrival waves from the scattering centers as

$$
x_k = r_k \sin \theta_k \cos \phi_k \tag{1}
$$

$$
y_k = r_k \sin \theta_k \sin \phi_k \tag{2}
$$

$$
z_k = r_k \cos \theta_k \tag{3}
$$

Here, $r_k$ is the distance between the origin and the $k$th scattering center. A spherical coordinate system $(r_k, \theta_k, \phi_k)$ is used to represent the arrival directions of the incoming plane waves. The origin of the coordinate system is located at the center of the conformal array. Source elevation angles $\theta_k$ are measured down from the $z$-axis, and azimuth angles $\phi_k$ are measured counterclockwise from the $x$-axis.

The distance $r_k$ is given by

$$
r_k \approx t_k \nu - l_k \tag{4}
$$

where $t_k$ is the delay time of the $k$th wave observed at the origin, $l_k$ is the distance between the transmitter and the $k$th scattering center, and $\nu$ is the known propagation velocity in the material, which exists around the borehole.

Ogawa et al. formulated the problem of the 2-D simultaneous estimation of both the time delay and the direction of arrival with a linear array [10]. Here, we expand to 3-D estimation for the conformal array coated with a multilayered cylindrical dielectric. The array consists of uniform circular arrays uniformly distributed between $z = 0$ and $z = \zeta$ on a conducting cylinder, as shown in Fig. 4(b). We define that the number of sampled frequencies as $H$ and the number of the array elements as $N$. The data received at the sampled frequency points $f_h$, with the $j$th element, are defined as $x_{h,j} (h = 1, 2, \cdots, H; j = 1, 2, \cdots, N)$. Using a vector $\mathbf{\theta}_k = (\theta_k, \phi_k)$, the received signal $x_{h,j}$ is expressed as

$$
x_{h,j} = \sum_{k=1}^{d} s_k \eta_{h,j}(\mathbf{\theta}_k)e^{-i2\pi f_h t_k} + n_{h,j}. \tag{5}
$$

$s_k (k = 1, 2, \cdots, d)$ is the complex amplitude of each wave. We assume that white Gaussian noise samples $n_{h,j}$ having zero mean with variance $\sigma^2$ are superimposed on the signal. $\eta_{h,j}(\mathbf{\theta}_k)$ is a relative value of a complex amplitude of the field measured by the $j$th element at the frequency $f_h$ for the incident plane wave, which arrives with the vector $\mathbf{\theta}_k$. In order to obtain $\psi_{h,j}(\mathbf{\theta}_k)$, we use the model shown in Fig. 1 and described in Section II, where dielectric layer 1 corresponds to insulation between the borehole wall and the conducting cylinder, and layer 2 corresponds to soil or rock. Each layer may have different losses.

We must point out that $\psi_{h,j}(\mathbf{\theta}_k)$, calculated using the model in Fig. 1, diverges at $\theta = 0^\circ$ and $180^\circ$. Thus, we cannot use the model at these points. In this paper, we assume that all the waves impinge at $\theta = 0^\circ$ and $180^\circ$. This assumption is not valid when a transmitter and the conformal array are in a single borehole, because direct waves from the transmitter propagate along the borehole at $\theta = 0^\circ$ or $180^\circ$ [16], [17]. However, we can use the model without modification if we use two boreholes, as we shall see later in Section IV.
Here, we define the \( N \) vector \( \mathbf{x}_h \) as
\[
\mathbf{x}_h = \sum_{k=1}^{d} \mathbf{a}_h(t_k, \theta_k) s_k + \mathbf{n}_h
\] (6)
with the column-ordered vectors
\[
\mathbf{x}_k = \begin{bmatrix} x_{k1} & x_{k2} & \cdots & x_{kN} \end{bmatrix}^T
\] (7)
\[
\mathbf{a}_h(t_k, \theta_k) = \begin{bmatrix} a_{h1}(\theta_k) e^{-j2\pi f_h t_k} & a_{h2}(\theta_k) e^{-j2\pi f_h t_k} & \cdots & a_{hN}(\theta_k) e^{-j2\pi f_h t_k} \end{bmatrix}^T
\] (8)
\[
\mathbf{n}_h = \begin{bmatrix} n_{h1} & n_{h2} & \cdots & n_{hN} \end{bmatrix}^T
\] (9)

\( T \) denotes a transpose. Let \( LN \) vector \( \mathbf{y}_i \), \( d \) vector \( \mathbf{s} \), and \( LN \) vector \( \mathbf{m}_i \) be column vectors containing the received signals, signal complex amplitude and noise, respectively, i.e.,
\[
\mathbf{y}_i = \begin{bmatrix} \mathbf{x}_i \\ \mathbf{x}_{i+M} \\ \vdots \\ \mathbf{x}_{i+(L-1)M} \end{bmatrix}, \quad \mathbf{s} = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_d \end{bmatrix}, \quad \mathbf{m}_i = \begin{bmatrix} \mathbf{n}_i \\ \mathbf{n}_{i+M} \\ \vdots \\ \mathbf{n}_{i+(L-1)M} \end{bmatrix}.
\] (10)

The received signal vector has the form
\[
\mathbf{y}_i = \mathbf{B}_i \mathbf{s} + \mathbf{m}_i \quad (i = 1, 2 \cdots I)
\] (11)

where \( \mathbf{B}_i \) is a \( LN \times d \) matrix
\[
\mathbf{B}_i = [\mathbf{b}_1(t_1, \theta_k), \mathbf{b}_2(t_2, \theta_k), \cdots, \mathbf{b}_d(t_d, \theta_k)]
\] (12)
and
\[
\mathbf{b}_i(t_k, \theta_k) = \begin{bmatrix} a_{i1}(t_k, \theta_k) \\ a_{i2}(t_k, \theta_k) \\ \vdots \\ a_{iL}(t_k, \theta_k) \end{bmatrix}.
\] (13)

\( L \) is the number of the frequency points contained in \( \mathbf{y}_i \), and \( M \) is an integer holding \( I + M(L - 1) \leq H \). The \( LN \times d \) matrix \( \mathbf{B}_i \), \( LN \) vector \( \mathbf{b}_i(t_k, \theta_k) \), and \( d \) vector \( \mathbf{s} \) are called the location matrix, the mode vector, and the signal vector, respectively. And the signal subspace is defined as the column span of the location matrix. The problem here is to determine the azimuth \( \phi_k \), elevation \( \theta_k \), and time delay \( t_k \) from the measurements \( \mathbf{y}_i(i = 1, 2, \cdots, I) \).

**B. Application of MUSIC Algorithm**

The correlation matrix is defined as
\[
\mathbf{R}_i = \mathbf{E} [\mathbf{y}_i \mathbf{y}_i^H] = \mathbf{B}_i \mathbf{S} \mathbf{B}_i^H + \sigma^2 \mathbf{I}
\] (14)

Here, \( \mathbf{E}[\cdot] \) denotes an ensemble average, \( \mathbf{H} \) denotes a complex conjugate transpose, and \( \mathbf{S} = \mathbf{E} [\mathbf{s} \mathbf{s}^H] \) is the \( LN \times LN \) identity matrix. We assume that \( \mathbf{E} [\mathbf{m} \mathbf{m}^H] = \sigma^2 \mathbf{I} \). Since in our case all arrival waves are fully correlated, the signal vector \( \mathbf{s} \) is not a random vector but a deterministic one, and the signal matrix \( \mathbf{S} \) is singular. The MUSIC algorithm does not work properly under such a condition [18], so we need to adopt a decorrelation technique. If the array elements receive broadband signals, we can decorrelate the signals with a decorrelation technique such as the coherent signal-subspace method (CSM) proposed by Wang and Kaveh [19]. Several studies have been made on the CSM [20]–[22], but Valae and Kabal showed that an unbiased estimation is not possible using the CSM, and they proposed the two-sided correlation transformation (TCT) algorithm.
which reduces the bias error. They also showed the simulation results of one-dimensional (1-D) bearing estimation with a linear array, and that the TCT algorithm can estimate parameters for four sources, including two coherent ones. Now we will describe the decorrelation method, based on the TCT algorithm, in order to estimate time delay as well as angles with the conformal array.

In the TCT algorithm shown in [23], the time factor $e^{j\omega t}$ is not contained in a location matrix, but in a signal vector. This leads to decorrelation, since the time factor $e^{j\omega t}$ of each signal incoherently changes among different frequencies. However, in our case, the signal vector $\mathbf{s}$ does not contain the time factor in (11). Therefore, we must reformulate (11) for a new signal vector to include the delay time $t$ as

$$\mathbf{y}_i = \mathbf{G}_i \mathbf{f}_i + \mathbf{m}_i \quad (i = 1, 2 \cdots I)$$

where

$$\mathbf{G}_i = \mathbf{B}_i \mathbf{D}_i^H$$

$$\mathbf{f}_i = \mathbf{D}_i \mathbf{s}$$

and $\mathbf{D}_i$ is a diagonal matrix with diagonal elements $\phi_j (j = 1, 2 \cdots d)$ is a diagonal matrix with diagonal elements

$$\mathbf{F}_0 = \frac{1}{I} \sum_{i=1}^{I} \mathbf{F}_i.$$  

This processing removes the coherence [23]. The focusing noise-free correlation matrix is calculated as

$$\hat{\mathbf{R}}_0 = \hat{\mathbf{G}}_0 \mathbf{F}_0 \hat{\mathbf{G}}_0^H.$$  

We define the matrix $\mathbf{E}$ to be the $LN \times (LN - d)$ matrix, whose columns are the $(LN - d)$ noise eigenvectors of the matrix $\hat{\mathbf{R}}_0$. We give the MUSIC estimator as

$$P_{\text{music}}(t, \theta) = \frac{\mathbf{g}_0^H(t, \theta) \mathbf{g}_0(t, \theta)}{\mathbf{g}_0^H(t, \theta) \mathbf{E} \mathbf{E}^H \mathbf{g}_0^H(t, \theta)}.$$  

The decorrelation technique described above is for broadband signals, and works properly when any two time delays of $t_k (k = 1, 2 \cdots d)$ are not identical. This situation may be rare when a direct wave from a transmitter and multiple scattered signals from flatly extended fractures or interfaces among layers in subsurface arrive at the receiver. But the limitation of separating signals having the same time delays may be a problem when we get multidimensional images of some targets having shapes, as shown in [8], [9]. In borehole radar measurements, estimation of the 3-D shape of voids, gas pipes, electrical lines, and so on may correspond to the 3-D imaging. Even in such cases, some modification of the algorithm is possible. For example, we may achieve multi-dimensional imaging if we apply both the decorrelation for broadband signals and the spatial smoothing method [18] utilizing difference of elevation angles $\theta_k$. In this paper, we concentrated on a decorrelation technique for broadband signals, because we think that we can expect relatively wide and stationary bandwidth in the frequency domain in our borehole radar measurements. Inhomogeneity of the medium might cause signals to be not spatially stationary.

IV. SAMPLE RESULTS

In this section, we present examples of target positioning with both computer simulations and experiments in order to show the performance of the algorithm. We consider one transmitter and one target. They may be described by two coherent sources $(x_k, y_k, z_k)$, $(k = 1, 2)$ in the examples. This is a typical and basic problem of separation of coherent signals in borehole radar measurements. Although there is only one target, we can confirm the resolution of coherent signals with this example. Also, we compare the resolution with the Fourier based method, whose estimator is given by

$$P_{\text{ordinary}}(t, \theta) = c(t, \theta)^H \mathbf{R} c(t, \theta)$$

where

$$c(t, \theta) = \begin{bmatrix} a_0(t, \theta) \\
 a_{1+M}(t, \theta) \\
 \vdots \\
 a_{I+M}(t, \theta) \\
 x_1 \\
 x_{I+M} \\
 \vdots \\
 x_{I+M}(I+M-1) \end{bmatrix}, \quad \mathbf{R} = E[zz^H].$$

In order to obtain $\mathbf{v}_{k,j(\theta)}$, which is needed in our estimation, we use the theoretical model as shown in Fig. 1. Here, the parameters are $a_0 = 0.06$ m, $a_2 = 0.11$ m, $c_{r1} = 1$, and $c_{r2} = 17$. In the estimation, we assume that only TE waves illuminate the array. In our estimation, we assume that all the waves arrive
at the conformal array at $30^\circ \leq \theta \leq 150^\circ$, since the range of $\theta$ in the theoretical model should be limited, as we pointed out in the previous section. In all the estimations, a single snapshot of data was used. The frequency band for estimation was between 230 MHz and 270 MHz.

Estimator values for both the MUSIC estimator and the Fourier-based method are normalized with the maximum value in each estimation. The maximum value is always 0 dB after the normalization. We will show the normalized values in 3-D space. The MUSIC estimator value is the Euclidean distance between the mode vector and the signal subspace [4]. Resolution is associated with relative values rather than absolute values in the MUSIC estimator [24].

A. Computer Simulation

We consider a model having the transmitter and the conformal array located at $(x, y, z) = (0.13 \text{ m}, 1.49 \text{ m}, 0.08 \text{ m})$ and $(0, 0, 0)$, respectively, and the scattering center of the target at $(-0.94 \text{ m}, -0.67 \text{ m}, 0.09 \text{ m})$. Therefore two completely correlated TE waves impinge on the conformal array at $(t, \theta, \phi) = (20.6 \text{ ns}, 87^\circ, 265^\circ)$ and $(31.7 \text{ ns}, 86^\circ, 216^\circ)$, which correspond to the direct wave from the transmitter and the scattered wave from the target, respectively. Here, the $(t, \theta, \phi)$ can be calculated with (1)–(4) and $v = v_0/\sqrt{17}$. The standard deviation $\sigma$ of the white Gaussian noise is 0.001, and the signal complex amplitude $s_1$ and $s_2$ are 1 and $-1$, respectively.

Results of the 3-D estimation are shown in Figs. 5 and 6. Fig. 5 shows the result generated with the algorithm. Only places where the estimator values are above $-10$ dB are shown. Frequency: 230 MHz to 270 MHz, $I = 5$, $L = 3$, $\lambda f = 18$, $N = 12$, $d = 2$.

B. Experimental Results

The following experiment was conducted at the field test site at Tohoku University, Sendai, Japan. There are boreholes $BR-1$ and $BR-2$, as shown in Fig. 7. In order to obtain a strong scattered wave, a cave $A$ is placed at a distance 0.8–1 m away from the boreholes. A metal plate reflector is placed on a wall of the cave $A$. The relative dielectric constant of the soil at the field site is around 17, which was estimated from measured propagation delay between two boreholes. We use shielded loop antennas for measuring the $z$ component of the magnetic field on the conducting cylinder. Transmission between feeding points of the transmitter and the receiver was measured by a network analyzer (HP8752A). We use an axial slot antenna on a conducting cylinder [25], radiating the TE wave as the transmitting antenna. In our experiment, we set the transmitting antenna at a depth of 1.4 m in $BR-1$. In $BR-2$, and the cylindrical conformal array, acting as a receiver, is placed at the same depth as the transmitter. We gated the data in the time window of $0 \text{ ns} \leq t \leq 60 \text{ ns}$ before estimation in order to reduce noise power [26].

Fig. 8 shows the MUSIC estimator distribution in 3-D space. In Fig. 8, we find two areas of the space where the estimator shows a high value. One area is located near the cave $A$ wall, which corresponds to the true position of the reflector, as shown in Fig. 8(b). The other area is on the segment between the transmitter and receiver. This corresponds to the direct wave from the transmitter. Fig. 9 shows the result generated with the Fourier-based method. Using the Fourier-based method, it is impossible to distinguish the transmitter from the target. Our algorithm yields an accurate estimation of the target position, though there is little difference between the estimated and the true positions. An important point about this result is that we resolved...
and separated the two coherent sources using the super-resolution technique, although the Fourier-based method could not. It is possible that the error is caused by inhomogeneity of the soil. Another possible cause for the error is that we used a plane wave incidence model in the estimation, as discussed in Section III. Since the scattering center is near the receiver, the incident wave should be a point source model rather than a plane wave. Use of a point source model may improve the estimation. The difficulty with this approach is the increased computational load.

Between the antenna and the wall of cave $A$, the soil composition changes slightly with depth. There are a number of small stones in the soil, since the soil at the field test site is not an artificially uniform medium. These may cause clutter and can distort the scattered waves. But in our algorithm, we did not consider clutter caused by the inhomogeneity of the soil.

V. CONCLUSION

The MUSIC algorithm was demonstrated to be suited to 3-D estimation of target position in a directional borehole radar measurement using the cylindrical conformal array. The estimation results were generated from simulated and measured targets, and we confirmed that the algorithm works properly in both cases.

In this paper, we showed that under practical conditions, using borehole radar measurement with the conformal array, our MUSIC algorithm did separate the scattered wave from the direct wave, while the Fourier-based method did not. Furthermore, this method estimated the scattering center position of the target in the 3-D space. In borehole radar using the conformal array, a super-resolution technique is very important to achieve significant measurement, because frequency bandwidth is seriously limited by the medium and the space available for the conformal array.

We believe that resolution improvement in the MUSIC, which was shown in this paper, will lead to 3-D imaging, which we have not shown in this paper. Future work should demonstrate 3-D imaging, as well as estimation of 3-D target distance using directional borehole radar. As we discussed in Section III, some modification of the algorithm is needed to achieve these results.

REFERENCES


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