Three-dimensional location of coherent sources using a borehole radar with a broadband conformal array

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1. Introduction

A borehole radar is one form of ground penetrating radars, which is used in deep boreholes. Most conventional borehole radars use dipole antennas, which are omnidirectional. However, in many engineering applications, the three-dimensional position of targets in the near range should be accurately determined.

We have designed and constructed a prototype broadband directional borehole radar system by using a network analyzer. A receiving antenna of this system is a conformal array antenna mounted on a relatively thick conducting cylinder[1]. This radar systems operates between 100MHz and 300MHz, and the corresponding wave length at the frequency range is much larger than the diameter of the boreholes, which is around 10cm. Because the space available for the array is limited, we need a super resolution technique for three-dimensional location of completely correlated sources.

This paper presents a method for three-dimensional location of correlated broadband sources impinging on a three-dimensional array with a known arbitrary geometry. This method is base on MUSIC algorithm[2]. Experimental result of estimation by using the borehole radar system is also shown.

2. Estimation method

Ogawa et al. formulated the problem of the two-dimensional simultaneous estimation of time delay and direction of arrival with a linear array[3]. Here we expand it for three-dimensional estimation for an arbitrary array geometry. Consider an array of N elements exposed to d far-field broadband sources F_k $(k=1,2,...d)$. The signals of sources are fully correlated. The data received at frequency f_i with the jth element is defined as $X_{i,j}$. We represent a delay time of the kth wave observed at the origin as t_k. We use a vector $\boldsymbol{\theta}_k=(\theta_k,\phi_k)$ to represent source arrival directions, where θ_k and ϕ_k is elevation and azimuth angles of the sources, respectively. We define a delay time between the origin and the jth element as $\tau_j(\boldsymbol{\theta}_k)$. The array output in the frequency domain is given by

$$\mathbf{X}(f_i) = \mathbf{A}(f_i)\mathbf{F} + \mathbf{W}(f_i) \qquad (i=1,2,...L) \tag{1}$$

where

$$\mathbf{X}(f_i) = [X_{i,1}, X_{i,2}, \ldots X_{i,N}, X_{i+1,1} \ldots X_{i+M-1,N}]^T \tag{2}$$

$$\mathbf{A}(f_i) = [\mathbf{a}(f_i,t_1,\boldsymbol{\theta}_1), \mathbf{a}(f_i,t_2,\boldsymbol{\theta}_2) \ldots \mathbf{a}(f_i,t_d,\boldsymbol{\theta}_d)] \tag{3}$$

$$\mathbf{a}(f_i, t_k, \theta_k) = [exp(-j\ 2\pi\ f_i(t_k+\tau_1(\theta_k))), exp(-j\ 2\pi f_i(t_k+\tau_2(\theta_k))), \cdots$$
$$exp(-j\ 2\pi f_i(t_k+\tau_N(\theta_k))), exp(-j\ 2\pi f_{i+1}(t_k+\tau_1(\theta_k))), \cdots$$
$$exp(-j\ 2\pi f_{i+M-1}(t_k+\tau_N(\theta_k)))]^{\mathrm{T}} \quad (4)$$

$$\mathbf{F} = [\, F_1, F_2 \,....\, F_d\,]^{\mathrm{T}} \quad (5)$$

and $\mathbf{W}(f_i)$ is a noise vector. $\mathbf{A}(f_i)$, $\mathbf{a}(f_i,t_k,\theta_k)$ and $\mathbf{F}$ 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. F is a constant vector, when all of the sources are completely correlated.

Ogawa et al. used the spatial smoothing technique with linear interpolation to deal with coherent sources[3]. However, this method is difficult to apply to the spatial smoothing in the case of an arbitrary array. Therefore, in this paper, we use the Coherent Signal-subspace Method(CSM)[4] as a preprocessing technique. In estimation using CSM, the factor $exp(-j2\pi f_i\, t_k)$ should be included in signal vectors to decorrelate. But, in Eq.(1), there is the factor not in the signal vector F, but in the mode vectors $\mathbf{a}(f_i,t_k,\theta_k)$. Therefore, in order to transfer the factor from the mode vector to a signal vector, we introduce a matrix $\mathbf{D}(f_i)$ as

$$\mathbf{D}(f_i) \equiv \mathrm{diag}\,[\ exp(-j\ 2\pi f_i t_1), exp(-j\ 2\pi f_i t_2), \cdots\ exp(-j\ 2\pi f_i t_d)] \quad (6)$$

And by using $\mathbf{D}(f_i)$, we define a new location matrix $\mathbf{B}(f_i)$ as

$$\mathbf{B}(f_i) \equiv \mathbf{A}(f_i)\ \mathbf{D}^*(f_i) \quad (7)$$

where * denotes complex conjugate. By using Eq.(7), Eq.(1) can be rewritten as

$$\mathbf{X}(f_i) = \mathbf{B}(f_i)\,\mathbf{G}(f_i) + \mathbf{W}(f_i) \qquad (i = 1,2,...L) \quad (8)$$

where

$$\mathbf{G}(f_i) \equiv \mathbf{D}(f_i)\,\mathbf{F} = [\ exp(-j\ 2\pi f_i t_1) F_1,\ exp(-j\ 2\pi f_i t_2) F_2\ ....\ exp(-j\ 2\pi f_i t_d) F_d\,]^{\mathrm{T}} \quad (9)$$

The vector $\mathbf{G}(f_i)$ is a new signal vector including the factor $exp(-j2\pi f_i\, t_k)$. After this process, we apply the CSM. The CSM is a procedure which transforms the signal subspace of the location metrics $\mathbf{B}(f_i)$ at each frequency $f_i (i=1,2,...L)$ and overlaps them in a predefined subspace with the *focusing matrix*[5], which is obtained with initial parameters(*focusing points*). And we can apply the MUSIC algorithm.

4. Experimental results

In order to certify the performance of the proposed method, first we locate a source by using direct waves from a transmitting antenna. The measurement was carried out in soil.

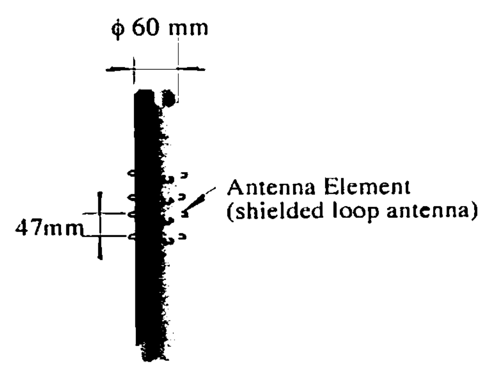

Fig. 1. Configuration of the conformal array on a conducting cylinder.

The conformal array antenna which we used as a receiving antenna is shown in Figure 1. A slot antenna on a conducting cylinder[6] is used as a transmitting antenna. Figure 2 illustrates the experimental arrangement. We theoretically calculated the scattered field at oblique incidence of a plane wave to the conducting cylinder coated with dielectric materials[7] and obtained the $\tau_j(\theta_k)$. Figure 3 shows the result obtained by the proposed MUSIC algorithm. The density is high around the actual position of the transmitting antenna. This result shows that the MUSIC algorithm can successfully estimate the source position in the measurement.

Next we applied the proposed method to location of reflector. We carried out the experiment in the air. Figure 4 shows the experiment arrangement. In order to obtain a strong reflected waves,

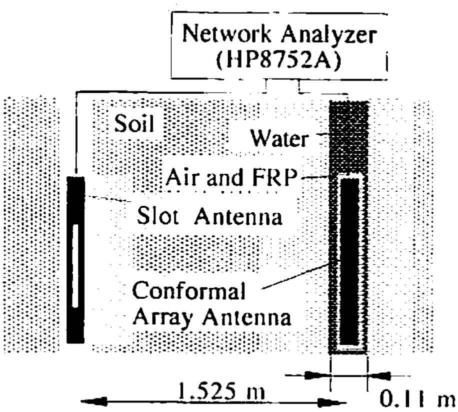

Fig. 2. Borehole radar measurement for estimation of a source position.

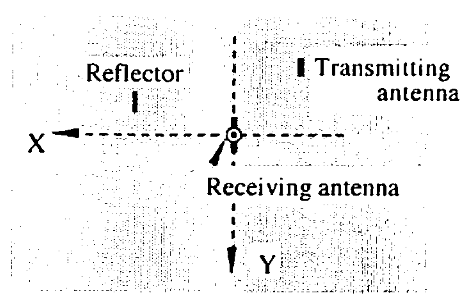

Fig. 4. Experiment in the air.
Top view. The antennas lie at a distance 0.4m apart from the earth surface.

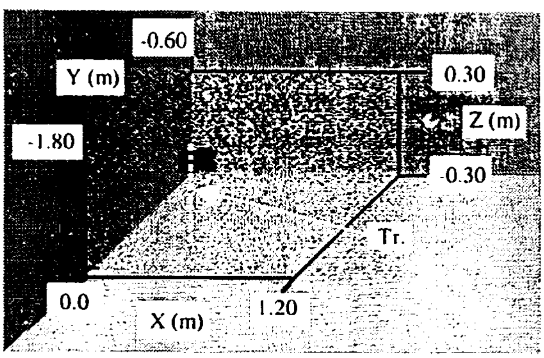

Fig. 3. Three-dimensional location of the source in the borehole radar measurement.
The density indicates the position where the estimator value is high. Actual position of the source is indicated by the arrow.
Used frequency: 100-300MHz, L = 38, M = 4, N = 12, d = 1.

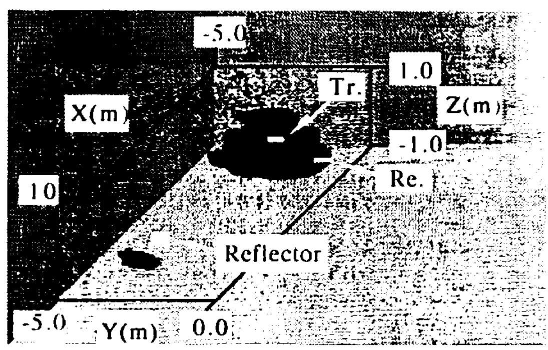

Fig. 5. Three-dimensional location of the reflector and the source in the air.
The density indicates the position where the estimator value is high. The each arrows indicates the actual position of the antennas and the reflector
Used frequency: 200-400MHz, L = 39, M = 3, N = 12, d = 2.

we placed a metallic reflector near the receiving antenna. Figure 5 shows a result. In the figure, we find that the estimator value is high around the actual place of the transmitting antenna and the reflector. We think that it indicates good estimation.

5. Conclusion

The MUSIC algorithm was demonstrated to be suited for three-dimensional location with the broadband directional borehole radar.

We expanded the MUSIC algorithm to the three-dimensional location of completely correlated sources with an arbitrary array. The CSM was used for decorrelation. We applied the MUSIC algorithm to the data, which is obtained in the borehole radar measurement and the experiment in the air. As a result of the data analysis, we could locate the transmitting antenna in the soil, and the reflector in the experiment in the air, respectively. We think that this result indicates possibility to detect reflectors and estimate the three-dimensional position by the broadband directional borehole radar with the MUSIC algorithm.

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