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Resolution Improvement of the MUSIC Algorithm Utilizing Two Differently Polarized Antennas

Toshiharu YAMAKURA†, *Student Member*, Hiroyoshi YAMADA†, *and* Yoshio YAMAGUCHI†, *Members*

SUMMARY Recently, a short range millimeter wave or a microwave sensing system has been extensively studied to estimate a target position or a source location. It can be applied to indoor propagation analysis, carborne applications, etc. The application of the superresolution technique has been proposed to obtain a high resolution performance in the time domain or the spatial domain. However, the availability of the polarization synthesis in the receiving antennas has not been considered. In this paper, we use a pair of polarized swept frequency data and propose two modifications of the MUSIC algorithm to enhance the resolution of time delay. One modification is the correlation matrix formulation which relates to the total signal power, and the other is a polarization filtering applied to the correlation matrix. These modifications have advantages such that: 1) Reduction of the estimation problem to the delay time estimation only; 2) Easy implementation. Experimental results are illustrated to show the availability of the methods, and to confirm the high resolution performance compared with the conventional method.

key words: *superresolution technique, MUSIC algorithm, polarization, indoor propagation*

1. Introduction

Recently, the sensing techniques for estimating the targets or the source locations in a short distance have been extensively studied. The superresolution techniques such as the MUSIC algorithm [1] among many others have been introduced to the fields. The application of the techniques can be found in the indoor radio propagation estimation, carborne radar system, and so forth. In the analysis of the indoor radio propagation phenomenon, there exist a direction finding technique with an spatial array, a delay time estimation technique using the swept frequency data, and a simultaneous estimation technique of the direction and the delay time of the incident signals [2]-[4].

In addition to the delay time and the direction of arrival, the polarization state of the incoming signals is an important parameter to identify the propagation path of each multipath signal in the indoor environment. In the direction finding problem which is the main application area of the superresolution technique, it has been reported that the resolution performance could be improved when the antennas having diverse polarizations or the cross dipole antennas were employed [5], [6]. The polarization parameter of the signals can be also obtained simultaneously. These techniques are applicable to the indoor propagation estimation or the carborne radar. However, the algorithms become complicated and demand high the computational burden. Besides, the requirements of the array are difficult to be satisfied due to the hardware restriction or the measurement environment.

In this paper, we propose the MUSIC algorithms that utilize a pair of swept frequency data received with different polarized antennas. The methods use two receiving antennas to obtain the swept frequency data. The parameters to be estimated are the delay time and the polarization state of the incoming signals. The MUSIC algorithm for the frequency data [7] is applicable to each antenna's data separately, but the polarization data have not been utilized in such an algorithm yet.

We focus our attention to the structure of the data correlation matrix that includes two received polarization data. Two modified correlation matrices are proposed. One is for maximizing the received signal power, and the other relates to the polarization nulling filter [8]. The modifications are restricted in the correlation matrix only, and they change the target detection problem into a delay time search problem. No further modification is required in the remaining procedure in the MUSIC algorithm. The computational requirement, therefore, is almost the same as the conventional technique [7]. Furthermore, the technique relating to the MUSIC algorithm [9], [10] can be easily applied. In the following section, we formulate the problem. A brief introduction of the MUSIC algorithm and the two proposed modifications are given in Sects. 3 and 4. We show the experimental results to examine the validity of the modifications in Sect. 5. Section 6 contains conclusions.

2. Formulation

Assume that a pair of swept frequency domain data is obtained by using a network analyzer and two different polarized antennas. For simplicity, the polarization states of the antennas are linear horizontal (H) and vertical (V), respectively, and the phase center of them is coincident with each other. It is assumed that the polarization state of an incoming wave is constant in the measurement frequency band. The data is expressed in a complex form and composed of a phase factor corresponding to the propagation time delay and the complex amplitude depending on a target. When the number of targets is d, the received data at the frequency f_l ($l = 1, 2, \cdots, L$) with

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† The authors are with the Faculty of Engineering, Niigata University, Niigata-shi, 950-21 Japan.

horizontal or vertical antennas is given by

$$r^{(*)}(f_l)=\sum_{i=1}^{d} s_i^{(*)}\exp(-j2\pi f_l t_i)+n^{(*)}(f_l),\ (*=H \text{ or } V), \quad (1)$$

where $s_i^{(*)}(*=H$ or $V)$ denotes the scattering coefficient of the i-th signal observed with the holizontally (H) or vertically (V) polarized receiving antenna, and t_i denotes the delay time of the i-th signal. The term $n^{(*)}(f_l)$ denotes a noise component measured by the horizontally or vertically polarized antenna. It is assumed that the $n^{(*)}(f_l)$ are zero mean with variance σ^2 in the frequency domain. The relationship between each polarization component ($s_i^{(H)}$ or $s_i^{(V)}$) and the essential scattering coefficient (s_i) can be expressed as (see Fig. 1(a))

$$s_i^{(H)}=\cos\gamma_i\, s_i, \quad (2a)$$

$$s_i^{(V)}=\sin\gamma_i\, e^{j\phi_i} s_i. \quad (2b)$$

where ϕ_i is the difference of the phase angle between $s_i^{(H)}$ and $s_i^{(V)}$. γ_i can be defined by amplitude ratio :

$$\tan\gamma_i=|s_i^{(V)}/s_i^{(H)}|.$$

Instead of γ_i and ϕ_i, we can represent the wave polarization with the parameters of ε_i and τ_i as shown in Fig. 1(b), where ε_i and τ_i are the ellipticity angle and the tilt angle, respectively. The relationship between (γ_i , ϕ_i) and (ε_i , τ_i) can be given by

$$\tan 2\tau_i=\tan 2\gamma_i \cos\phi_i, \quad (3a)$$

$$\sin 2\varepsilon_i=\sin 2\gamma_i \sin\phi_i, \quad (3b)$$

or

$$\cos 2\gamma_i=\cos 2\varepsilon_i \cos 2\tau_i, \quad (4a)$$

$$\tan\phi_i=\tan 2\varepsilon_i \csc 2\tau_i. \quad (4b)$$

Let $\boldsymbol{r}^{(*)}$, $\boldsymbol{s}^{(*)}$, and $\boldsymbol{n}^{(*)}$ be column vectors representing the received signals, the signal parameters, and the noise, respectively, i.e.,

$$\boldsymbol{r}^{(*)}=[r^{(*)}(f_1),\ldots,r^{(*)}(f_L)]^T, \quad (5a)$$

$$\boldsymbol{s}^{(*)}=[s_1^{(*)},\ldots,s_d^{(*)}]^T, \quad (5b)$$

$$\boldsymbol{n}^{(*)}=[n^{(*)}(f_1),\ldots,n^{(*)}(f_L)]^T. \quad (5c)$$

The received signal (1) is expressed in a matrix form

$$\boldsymbol{r}^{(*)}=\boldsymbol{A}\boldsymbol{s}^{(*)}+\boldsymbol{n}^{(*)}, \quad (6)$$

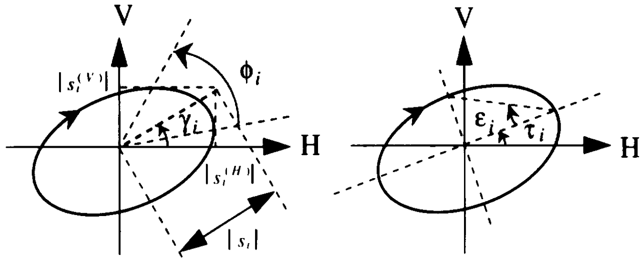
where $\boldsymbol{A}$ is a $L\times d$ matrix

$$\boldsymbol{A}=[\boldsymbol{a}(t_1),\ldots,\boldsymbol{a}(t_d)], \quad (7)$$

with $\boldsymbol{a}(t_i)$ being a $L\times 1$ matrix

$$\boldsymbol{a}(t_i)=[\exp(-j2\pi f_1 t_i),\exp(-j2\pi f_2 t_i),\ldots,\exp(-j2\pi f_L t_i)]^T, \quad (8)$$

where T denotes transpose.



(a) The polarization parameters of (γ_i , ϕ_i) (b) The polarization parameters of (ε_i , τ_i)

Fig. 1 The polarization state with the parameters of (γ_i , ϕ_i) and (ε_i , τ_i).

3. MUSIC Algorithm

In this section, we introduce the MUSIC algorithm [1] briefly. Since the frequency domain data obtained by a network analyzer are coherent, we must employ the spatial smoothing technique [11] before applying the algorithm [7]. Thus, we make M overlapped sub-vectors of N frequency samples, $\boldsymbol{r}_m^{(*)}$ ($m=1,2,\cdots,M$), from the L-dimensional data vector $\boldsymbol{r}^{(*)}$ in (5a),

$$\boldsymbol{r}_m^{(*)}=[r^{(*)}(f_m),r^{(*)}(f_{m+1}),\ldots,r^{(*)}(f_{m+N-1})]^T. \quad (9)$$

The spatial smoothed data correlation matrix is defined by

$$\boldsymbol{R}_{ssp}^{(*)}=\frac{1}{M}\sum_{m=1}^{M}\boldsymbol{R}_m^{(*)}, \quad (10a)$$

$$\boldsymbol{R}_m^{(*)}=E[\boldsymbol{r}_m^{(*)}\boldsymbol{r}_m^{(*)\dagger}], \quad (10b)$$

where $\dagger$ and $E[\bullet]$ denote the complex conjugate transpose and the ensemble average, respectively. The data correlation matrix $\boldsymbol{R}_{ssp}^{(*)}$ has the following two properties when the condition $M\geq d$ is satisfied. First property is that the eigenvalues λ_i ($i=1,2,\cdots,d$) of the matrix can be divided into two groups according to their magnitude. The magnitude of ($N-d$) eigenvalues belonging to the small eigenvalue group is equal to the noise power σ^2. The magnitude of the remaining eigenvalues is greater than the noise power σ^2. Then, the relationship among the magnitude of the eigenvalues can be expressed by

$$\lambda_1\geq\lambda_2\geq\cdots\lambda_d>\lambda_{d+1}=\cdots=\lambda_N=\sigma^2. \quad (11a)$$

Second property is that the eigenvectors ($\boldsymbol{e}_{d+1},\cdots,\boldsymbol{e}_N$) corresponding to the small eigenvalues ($\lambda_{d+1},\cdots,\lambda_N$) span the noise subspace which are orthogonal to the signal mode vector in (8), i.e.,

$$\{\boldsymbol{e}_{d+1},\cdots,\boldsymbol{e}_N\}\perp\{\boldsymbol{a}(t_1),\cdots,\boldsymbol{a}(t_d)\}. \quad (11b)$$

We can estimate the number and the delay time of the incoming waves from the first and second property, respectively. The following function is often used in the delay time estimation.

$$P_{MUSIC}(t) = \frac{a(t)^{\dagger} a(t)}{a(t)^{\dagger} E_N E_N^{\dagger} a(t)}, \tag{12}$$

where E_N denotes an $N \times (N-d)$ matrix whose columns are the noise eigenvectors corresponding to the small eigenvalues of $R_{ssp}^{(*)}$. The resolution of the method is independent of the frequency bandwidth when the exact correlation matrix in (10b) are obtained. However, we must estimate the signal delay time from the finite number of snapshots in the actual applications. Therefore the resolution of the algorithm depends on the number of snapshots, SNR (signal-to-noise ratio), and the frequency bandwidth of the data. It is possible to apply the MUSIC algorithm separately to the data received by the horizontally or vertically polarized antenna. However, detection performance for each data is different in general, because the incident SNR is different. Thus the estimated delay time of the signals in each polarized antenna do not often coincide with each other. Therefore, an improved algorithm which evaluates a pair of the data simultaneously with a reasonable computing burden is desired. So, we propose some modifications of the MUSIC algorithm using the polarization information to improve the resolution.

4. The MUSIC Algorithm Using the Polarization Information

4.1 The MUSIC Algorithm for Maximizing the Received Signal Power

The data correlation matrix of each polarization data vector can be also expressed by

$$R_{ssp}^{(*)} = A\,\overline{S}_{ssp}^{(*)} A^{\dagger} + \sigma^2 I, \tag{13}$$

where I is an $N \times N$ identity matrix. $\overline{S}_{ssp}^{(*)}$ is a signal correlation matrix whose i-th diagonal element can be written as

$$\overline{S}_{ssp}^{(H)}(i,i) = \cos^2\gamma_i\,|s_i|^2, \tag{14a}$$

$$\overline{S}_{ssp}^{(V)}(i,i) = \sin^2\gamma_i\,|s_i|^2. \tag{14b}$$

Defining a new correlation matrix as

$$R_{ssp}^{(P)} = R_{ssp}^{(H)} + R_{ssp}^{(V)}$$
$$= A(\overline{S}_{ssp}^{(H)} + \overline{S}_{ssp}^{(V)})A^{\dagger} + 2\sigma^2 I, \tag{15}$$

we obtain a data correlation matrix based on the total power of the incident signal regardless of their polarization state. Apparently, the i-th diagonal element of the signal correlation matrix, $\overline{S}_{ssp}^{(H)} + \overline{S}_{ssp}^{(V)}$, can be expressed by

$$\overline{S}_{ssp}^{(H)}(i,i) + \overline{S}_{ssp}^{(V)}(i,i) = |s_i|^2. \tag{16}$$

Since the signal mode vectors in the matrix A contain no polarization parameter, the conventional procedure is applicable to the correlation matrix in (15). This means only one dimensional search for the delay time is required.

As seen in (15), when all of the incident signals only have vertical or horizontal polarization state, no change appears in this processing scheme except for the doubled noise term. In such a case, the conventional MUSIC algorithm has enough performance, when we can match the polarization state of the receiving antenna with the incoming signals. However, we cannot match the polarization state of the antenna with the signals having diverse polarizations. The method proposed here focuses on the latter signal environment. In the method, the optimum reception in the signal power for all incoming signals can be realized by the correlation matrix in (15). Therefore, the total signal to the noise power ratio can be improved in general, though the SNR of some signals would be deteriorated. In addition, the number of the snapshots is doubled equivalently since the two spatial smoothed correlation matrix is added in (15). Thus, the resolution improvement due to the doubled number of snapshots is also expected. As can be seen in (15), the matrix A whose columns express signal mode vectors is independent of the polarization parameters. Moreover, size of the correlation matrix is the same as that in conventional MUSIC algorithm though the two receiving antennas are employed. Hence, the computational burden in the following procedures is also the same as those in the conventional method.

4.2 The MUSIC Algorithm with the Polarization Filtering

The resolution performance of the MUSIC algorithm can be also improved if the number of incident signals is reduced. Several filtering schemes have been proposed in this viewpoint [4],[12]. In this section, we introduce a polarization filtering scheme to reduce the number of the dominant signals [8]. This polarization filter is realized by the transformation of the polarization basis.

The electric vector E can be expressed by an arbitrary orthogonal polarization basis. Now, we express the electric vector E as shown in Fig. 2(a) with AB polarization basis as shown in Fig. 2(b). In this case, the electric vector E in the XY and the AB polarization basis are expressed by

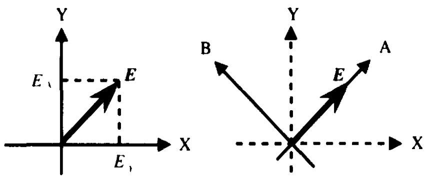
$$E = E_X\,x + E_Y\,y = E_A\,a + E_B\,b, \tag{17}$$

where (x, y) and (a, b) denote the unit vectors for the XY and the AB polarization basis, respectively. This transformation of the basis is realized by the basis transformation matrix T:

$$E(AB) = T^{-1} E(XY), \tag{18}$$

where

$$T = \frac{1}{\sqrt{1+\rho_{XY}\rho_{XY}^*}} \begin{bmatrix} 1 & \rho_{XY}^* \\ \rho_{XY} & -1 \end{bmatrix},$$



(a) XY polarization basis (b) AB polarization basis

Fig. 2 The transformation of the basis.

$$E(AB)=\begin{bmatrix}E_A\\E_B\end{bmatrix},\ E(XY)=\begin{bmatrix}E_X\\E_Y\end{bmatrix},$$

$$\rho_{XY}=\frac{E_Y}{E_X}=\tan\gamma_{XY}e^{j\phi_{XY}}.$$

In this AB polarization basis, we can receive the incoming electric vector maximally in the polarization state A, but we cannot receive the electric vector completely in the polarization state B. Thus, the transformed data vector in the polarization B can be employed as the polarization nulling filter. When we know the polarization parameters of the k-th signal (γ_k , ϕ_k), the filtered data vector can be obtained by

$$r^{(F)}=\frac{1}{\sqrt{1+\rho_k\rho_k^*}}(\rho_k r^{(H)}-r^{(V)}), \qquad (19)$$

where

$$\rho_k=\tan\gamma_k e^{j\phi_k}. \qquad (20)$$

Dividing the vector into subarrays $r_m^{(F)}$ as shown in (9), the data correlation matrix with the filter can be defined by

$$R_{ssp}^{(F)}=\frac{1}{M}\sum_{m=1}^{M}R_m^{(F)}$$

$$=\frac{1}{M}\sum_{m=1}^{M}E[r_m^{(F)}r_m^{(F)\dagger}]. \qquad (21)$$

The conventional MUSIC algorithm can also be applied to $R_{ssp}^{(F)}$ in this modification. Note that the signals having almost the same polarization can be suppressed. The polarization basis A is another choice. In the basis, though the SNR of the k-th signal can be maximized, the total number of the signal is unchanged in general. Then, The polarization basis B is usually appropriate in the filtering basis for the resolution enhancement of the MUSIC algorithm.

5. Experimental Results

We arranged three linear targets as shown in Fig. 3. The angles of the target#1, #2, and #3 are 60, –45, and –45 degrees, respectively. Two standard horn antennas are used as the transmitting and the receiving antenna. The polarization state of the transmitting antenna was fixed in the vertical polarization. We obtained two swept frequency data sets by using the horizontally and vertically polarized receiving antenna.

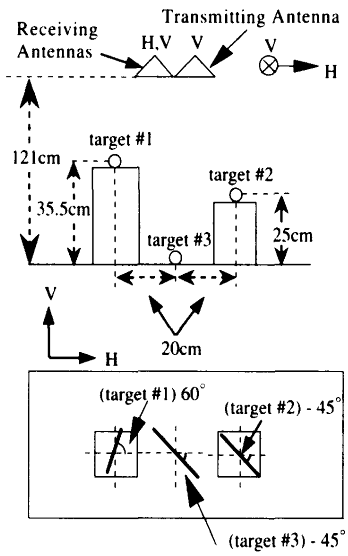


Fig. 3 Arrangement of the targets.

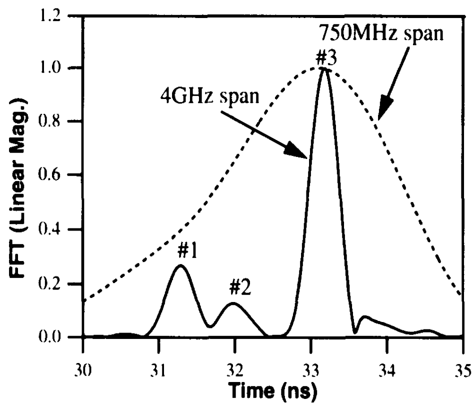


Fig. 4 Time-domain responses estimated by the inverse FFT (V-pol data). 4 GHz span (13 GHz - 17 GHz), 750 MHz span (14.5 GHz - 15.25 GHz).

Figure 4 shows the time domain responses of V-pol data obtained by applying the inverse FFT to the measured data with the 4 GHz (13 GHz - 17 GHz) and 750 MHz (14.5 GHz - 15.25 GHz) bandwidth data, respectively. The responses of the three targets can be detected with 4 GHz bandwidth data, however they cannot be resolved with 750 MHz bandwidth data. Figure 5 shows the time domain responses when applying the MUSIC algorithm to the 750 MHz bandwidth data. The responses of target#1, and target#3 can be discriminated, however, it is difficult to resolve the response of the target#2.

In Fig. 6, we show the results of the time estimation by using the MUSIC algorithm for maximizing the received signal power as described in Sect.4.1 with the data. It is possible to resolve the three targets. Moreover, the reflection from the floor beneath the target#3 cab be detected. Figure 7 shows the time domain responses of the same data by using the MUSIC algorithm with the polarization filtering scheme. In Fig. 7, the "X-pol1" and the "X-pol3" mean the estimated results with the filtering scheme suppressing the target#1 and #3, respectively. We can resolve the target#2 clearly by

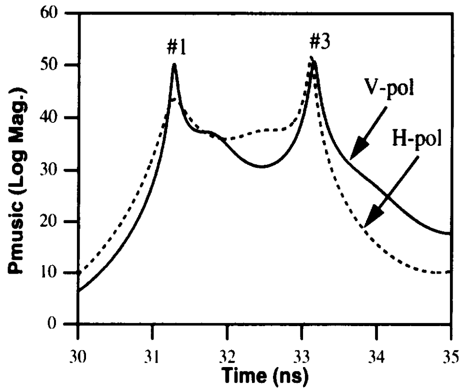


Fig. 5 Time-domain responses estimated by the conventional MUSIC algorithm. f_l=14.5 GHz, Δf =30 MHz, N =20, M=7. The total used frequency bandwidth is 750 MHz.

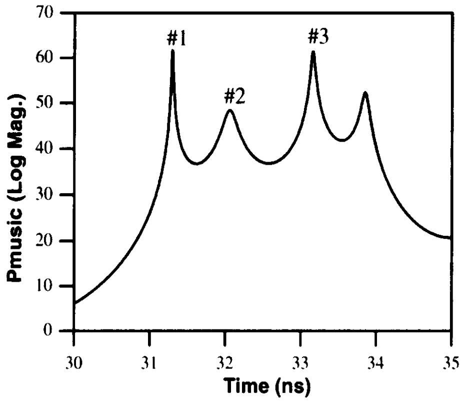


Fig. 6 Time-domain responses estimated by the MUSIC algorithm for maximizing the received signal power. f_l=14.5 GHz, Δf =30 MHz, N =20, M=7. The total used frequency bandwidth is 750 MHz.

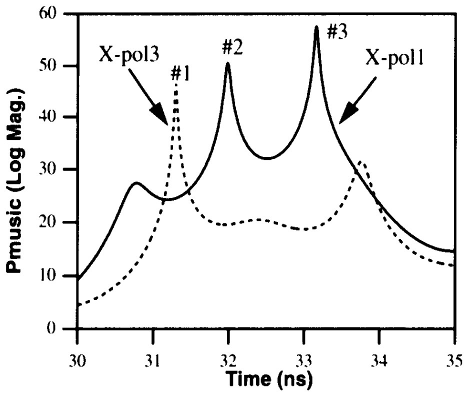


Fig. 7 Time-domain responses estimated by the MUSIC algorithm with polarization filtering. f_l=14.5 GHz, Δf =30 MHz, N =20, M=7. The total used frequency bandwidth is 750 MHz.

suppressing the target#1, and detect the reflection from the floor located around 33.8 ns by suppressing the target#3.

The estimated delay time and the polarization parameters of the three targets in each methods are listed in Tables 1, 2, and 3. Since the linear targets were used in this experiment, the tilt angle of each target is expected to coincide with the corresponding target angle shown in Fig. 3. In addition, the ellipticity angle of the targets is expected

Table 1 The estimated delay time and the polarization parameters of the target#1, target#2 and target#3 using the inverse FFT. The total used frequency bandwidth is 4 GHz (13 GHz - 17 GHz).

	delay time (ns)	tilt angle (degree)	ellipticity angle (degree)
target#1	31.30	60.5	8.5
target#2	31.99	-44.5	-6.5
target#3	33.18	-46.5	-6.7

Table 2 The estimated delay time and the polarization parameters of the target#1, target#2 and target#3 using the MUSIC algorithm for maximizing the received signal power. The total used frequency bandwidth is 750 MHz (14.5 GHz - 15.25 GHz).

	delay time (ns)	tilt angle (degree)	ellipticity angle (degree)
target#1	31.30	61.3	10.5
target#2	32.06	-39.4	-9.7
target#3	33.16	-46.7	-4.7

Table 3 The estimated delay time and the polarization parameters of the target#1, target#2 and target#3 using the MUSIC algorithm with the polarization filtering. The total used frequency bandwidth is 750 MHz (14.5 GHz - 15.25 GHz).

	delay time (ns)	tilt angle (degree)	ellipticity angle (degree)
target#1	31.30	61.1	7.2
target#2	31.98	-39.8	-10.8
target#3	33.16	-47.1	-4.9

to be zero. As can be seen in Table 1, the estimated angles using the inverse FFT with 4 GHz bandwidth data agree with the experimental situation. The estimated values by the proposed MUSIC algorithms, shown in Table 2 and 3, respectively, almost coincide with those by the inverse FFT. Since the SNR of the target#2 was lower than that of the other targets, the estimated tilt and ellipticity angles for the target are slightly biased in the MUSIC analyses. However the total frequency bandwidth used in each estimation was 750 MHz. This bandwidth is almost 1/5 of that required in the inverse FFT.

6. Conclusions

In this paper, we proposed a new method to improve the resolution performance of MUSIC algorithm using a polarization filtering scheme. The strategy for increasing performance is either the maximization of received power or the elimination of a specific wave (i.e., filtering out). This modification is made to only correlation matrix of the conventional MUSIC algorithm. No further modification is needed. Experimental results revealed a superior performance to the present method. The quantitative performance evaluation of the proposed two methods in comparison with the methods in [5] and [6] remains to be solved in future.

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Toshiharu Yamakura was born in Niigata, Japan, on February 5, 1974. He received the B.S. degree from Niigata University, Niigata, Japan in 1996 in information engineering. He is currently pursuing the M.S. degree in information engineering. His current research involves superresolution techniques for the polarization estimation.

Hiroyoshi Yamada was born in Hokkaido, Japan, on November 2, 1965. He received the B.S., M.S., and Ph.D. degrees from Hokkaido University, Sapporo, Japan, in 1988, 1990 and 1993, respectively, all in electronic engineering. Since 1993, he has been with Niigata University, where he is currently a lecturer. His current research involves superresolution techniques, time-frequency analysis, electromagnetic wave measurements, and radar signal processings. Dr. Yamada is a member of the IEEE.

Yoshio Yamaguchi was born in Niigata, Japan, on March 12, 1954. He received the B.E. degree in electronics engineering from Niigata University in 1976, and the M.E. and Dr.Eng. degrees from Tokyo Institute Technology, Tokyo, Japan, in 1978 and 1983, respectively. In 1978, he joined the Faculty of Engineering, Niigata University, where he is a Professor. From 1988 to 1989, he was a Research Associate at the University of Illinois at Chicago. His interests are in the field of propagation characteristics of electromagnetic wave in lossy medium, radar polarimetry, microwave remote sensing and imaging. Dr. Yamaguchi is a senior member of IEEE and a member the Japan Society for Snow Engineering.