Beam-Shape Correction in Deployable Phased Arrays

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***Abstract*—Deployable phased-array antennas—antennas that are recently receiving great attention—have a major problem in that they possess the possibility of an incomplete deployment and antenna shape distortion. These effects cause a displacement of the element antenna positions that results in deviation of the phase distribution on the antenna aperture, eventually causing antenna beam deflection. In this paper, we have investigated how to correct this beam deflection by observing the phased-array antenna from certain directions. There are cases when more than one observation point is necessary to carry out the proposed method depending on the extent of the antenna shape distortion and the number of the points is consulted. This correction method makes it possible to correct the deflection of the main beam and also to determine the displacement of relative element positions.**

***Index Terms*—Antenna arrays, phased arrays.**

I. Introduction

REQUIREMENTS for high-quality transmission with large-scale satellite antennas has been increasing year after year. Because of their large surface area after deployment, deployable phased-array antennas have been of recent concern as candidates for satellite antennas [1], [2]. However, there are high possibilities of incomplete deployment or distortion of the antenna surface due to many causes such as the change of satellite attitude and heat variation. These phenomena can lead to a change of the phase distribution on the antenna aperture from the initial design. In phased-array antennas, the beam is scanned by electronic control using phase shifters and the phase distribution on the antenna aperture is the most important factor for beam scanning. If this phase distribution changes, it can change the shape of the antenna beam. Our aim is to detect the change of phase distribution and the condition of deployment and eventually correct the shape of the antenna beam.

For the case when the observation point coincides with the point toward which the beam should be directed (such as in reference [1]) deflection of the main beam due to a change of the satellite attitude or distortion of the antenna surface can be corrected by determining the excitation phase by applying the rotating-element electric-field vector (REV) method [3] in the measurement of radiated power in the main beam direction. However, an antenna in which the shape of the main beam has to be maintained such as one for a solar power satellite (SPS) [4], the observation point should be outside the main beam region. Here, we investigate the necessary number of observation points and examine the case when distortion is negligibly small and the case when distortion should be considered. Also, a method using multiple observation points is presented, showing that not only can deflection of the main beam be corrected, but also displacement of the relative element positions can be measured. There are some restrictions concerning the relationship between the positions of the observation points, which is also discussed in the following sections.

In Section II, a brief explanation of the REV method is given first and then the theory of the abovementioned correction method is presented, followed by some restrictions. In Section III, the theory is confirmed by an experiment using a phased-array antenna.

Manuscript received June 13, 1997; revised June 2, 1998.

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Publisher Item Identifier S 0018-926X(99)04425-7.

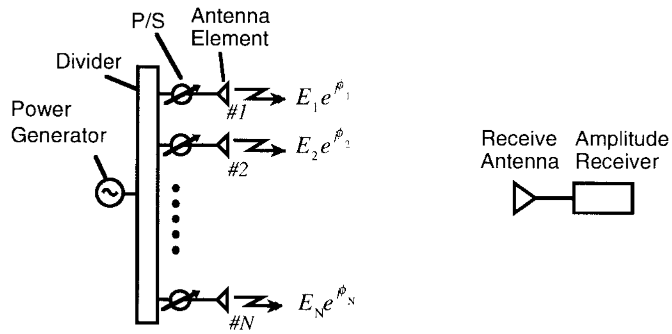

Fig. 1. Configuration example of a phased-array antenna.

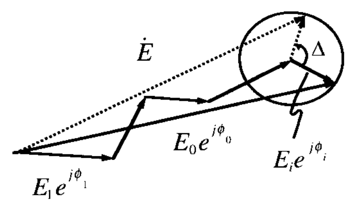

Fig. 2. Composite field vector and the field vector of each element antenna.

II. REV Method

The REV method is a method to determine amplitude and phase value of the electric field vector radiated from each element of a phased array in operation. Fig. 1 shows the configuration of a phased array used as a transmit antenna. As shown in Fig. 2, the composite field vector of the antenna of Fig. 1 in a specific direction is a superposition of the field vectors of the element anetnnas. When the phase of an element antenna is changed by its phase shifter, the composite vector varies as the element field vector rotates. Measuring the amplitude variation of the composite vector, the amplitude and phase of the element can be determined as follows.

In Fig. 2, the amplitude and phase of the composite field vector in the initial state are denoted by E_0 and ϕ_0, and those of the ith element by E_i and ϕ_i. When the phase of the ith

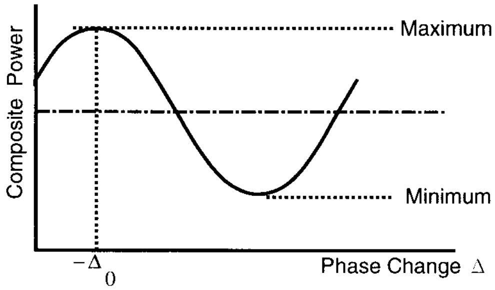

Fig. 3. Variation of the composite power of array field.

element is varied by Δ, the composite field can be expressed as

$$\dot{E} = (E_0 e^{j\phi_0} - E_i e^{j\phi_i}) + E_i e^{j(\phi_i + \Delta)}. \tag{1}$$

Here, the relative amplitude and relative phase of the ith element are defined as follows:

$$K = \frac{E_i}{E_0}, \quad X \doteq \phi_i - \phi_0. \tag{2}$$

Fig. 3 indicates that the composite power varies sinusoidally as the phase of one of the elements changes. The relative amplitude K and relative phase X of the element are determined by the following [3]:

$$K = \frac{\Gamma}{\sqrt{1 + 2\Gamma \cos\Delta_0 + \Gamma^2}} \tag{3}$$

$$X = \tan^{-1}\left(\frac{\sin\Delta_0}{\cos\Delta_0 + \Gamma}\right) \tag{4}$$

where Γ is $r - 1/r + 1$, r is the ratio of the maximum and minimum of the composite power, and $-\Delta_0$ is the phase that gives the maximum of the composite power. Then we can detect the relative amplitude and phase distribution of the phased array in operation by changing the phase of each element one by one and measuring the change of the composite power.

III. Theory of Proposed Measuring Scheme

A. Beam-Pointing Method

When the shape of the main beam has to be maintained in an antenna, such as one for an SPS [4], the observation point should be placed apart from the main beam region such as shown in Fig. 4. Here, an array antenna consisting of M elements on board the satellite is the antenna under test (AUT).

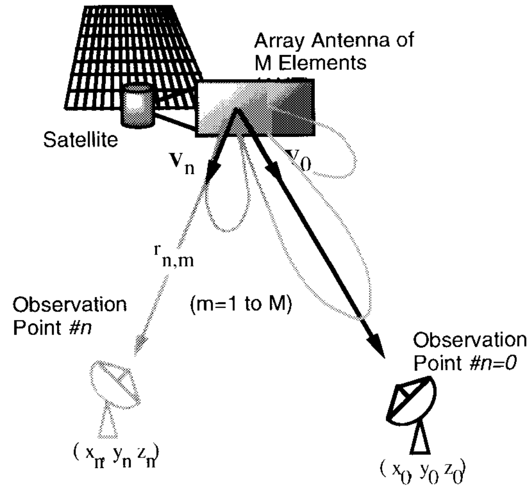

Fig. 4. Satellite antenna measuring scheme.

Fig. 5 shows details of this scheme. Here, the point of the standard element on the AUT is assumed as the origin of the coordinates in this scheme and z axis is in the direction to which the beam should be directed. Here, the relative position of the element of AUT is $\boldsymbol{r}_m$ and the unit vector of the observation point $\#n$ from the origin $\boldsymbol{v}_n$ is assumed to be known.

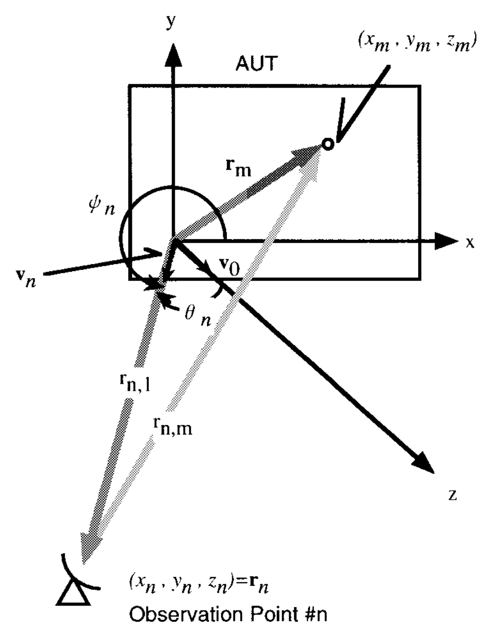

Fig. 5. Detail of the scheme.

When the REV method is carried out at the observation point $\#n$, the relative amplitude $E_{n,m}$ and phase $\phi_{n,m}$ of the $\#m$th element are measured. $E_{n,m}$ and $\phi_{n,m}$ are expressed as

$$E_{n,m} e^{j\phi_{n,m}} = \frac{E_m}{E_{0n}} e^{j\Phi_m} \frac{d^{-jkr_{n,m}}}{r_{n,m}} e^{-jP_{0,n}} \quad (m = 1 \text{ to } M). \tag{5}$$

E_m and Φ_m are the amplitude and phase of the $\#m$th element, $E_{0,n}$ and $P_{0,n}$ are those of the initial composite field at observation point, $\#n, k$ is the wave number, and $r_{n,m}$ is the distance between the $\#m$th element of the AUT and observation point $\#n$. From this equation, the phase $\phi_{n,m}$ can be expressed as

$$\phi_{n,m} = \Phi_m - k \cdot r_{n,m} - P_{0,n}. \tag{6}$$

Next, the phase $\phi_{n,m}$ is normalized by that of the standard element #1 because the relative phase is the value needed for beam scanning. The normalized phase $\phi'_{n,m}$ is expressed as

$$\phi'_{n,m} = \Phi'_m - k \cdot (r_{n,m} - r_{n,1}). \tag{7}$$

Here, $\phi'_{n,m} = \phi_{n,1}$ and $\Phi'_m = \Phi_m - \Phi_1$. Now, when the vector pointing from the standard element toward the element $\#m$ is $\boldsymbol{r}_m$, (7) can be transformed as follows in the case of far-field approximation ($r_{n,m} \gg |\boldsymbol{r}_m|$):

$$\phi'_{n,m} = \Phi'_m + k \cdot (\boldsymbol{r}_m \cdot \boldsymbol{v}_n). \tag{8}$$

When observing in the main beam direction (such as in [1]) the optimum excitation phase is determined by applying the REV method at the observation point $n = 0$ in Fig. 4, which is the position to which the beam should be directed.

When the observation point is placed apart from the main beam direction such as in SPS, the REV method is applied at the observation point $\#n$ $(n \neq 0)$. From (8), $-\phi'_{0,m}$ is the excitation phase for the beam direction. The relation is expressed by the following equation:

$$\phi'_{n,m} - \phi'_{0,m} = k\boldsymbol{r}_m \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0) \tag{9}$$

where $\boldsymbol{v}_0$ is the unit vector pointing in $+z$ direction.

When the antenna structure is distorted, causing a difference in the element position, the position vector is expressed as

$$\begin{aligned}\boldsymbol{r}_m &= \boldsymbol{r}_{m0} + \Delta\boldsymbol{r}_m \\ &= (x_{m0} + x_m, y_{m0} + y_m, z_{m0} + z_m)\end{aligned} \tag{10}$$

where $\Delta\boldsymbol{r}_m$ is the displacement of element $\#m$ and $\boldsymbol{r}_{m0}$ is its initial relative position. Accordingly, (9) becomes

$$\phi'_{0,m} = \phi'_{n,m} - k(\boldsymbol{r}_{m0} + \Delta\boldsymbol{r}_m) \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0). \tag{11}$$

Now, we consider two cases: 1) when $k \cdot \Delta\boldsymbol{r}_m \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0)$ is negligible and 2) when $k \cdot \Delta\boldsymbol{r}_m \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0)$ needs to be considered.

1) If $k \cdot \Delta\boldsymbol{r}_m \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0)$ is small, (11) becomes as follows:

$$\phi'_{0,m} = \phi'_{n,m} - k\boldsymbol{r}_{m0} \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0). \tag{12}$$

Terms on the right-hand side are known and $\phi'_{0,m}$ can be determined from this equation and only one observation point is sufficient.

We take SPS as an example [4]. Fig. 6 is a general view of the SPS system. Here, we assume the SPS to be 36 000 km above the equator. The beam is directed toward a rectenna on the earth. If the unit vectors are expressed by direction angles as shown in Fig. 5, $(\boldsymbol{v}_n - \boldsymbol{v}_0)$ could be written as

$$\boldsymbol{v}_n - \boldsymbol{v}_0 = (\sin\theta_n \cos\varphi_n, \sin\theta_n \sin\varphi_n, \cos\theta_n - 1) \tag{13}$$

where θ_n and φ_n are components of polar coordinates in which the polar axis is the Z axis. Let us define $\Delta\phi_m$ as the allowable error of excitation phase of the antenna

$$|\Delta\phi_m| \geq |k \cdot \Delta\boldsymbol{r}_m \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0)|. \tag{14}$$

From the above equation, when we assume as $\varphi_n = 0$ and $0 \leq \theta_n \leq (\pi/2)$, the displacement of the element position along the x axis x_m is expressed as follows:

$$x_m \leq \left|\frac{\Delta\phi k_m}{k \cdot \sin\theta_n}\right|. \tag{15}$$

Let a receiving antenna be located 10 km from the center of the rectenna $(\theta = 0.016°)$ and $\Delta\phi_m$ be $\pi/16$, then x_m is less than 13.7 m.

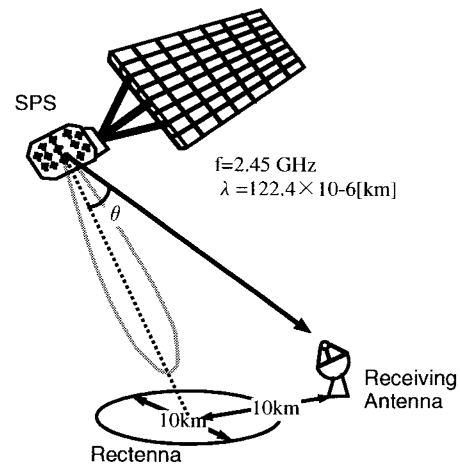

Fig. 6. SPS system configuration.

2) When the distance between the AUT and the observation point is not large enough like in SPS case, (11) is transformed as follows:

$$\phi'_{n,m} - \phi'_{0,m} = A_{n,m} + B_{n1}x_m + B_{n2}y_m + B_{n3}z_m \tag{16}$$

where

$$\begin{aligned} A_{n,m} &= k\boldsymbol{r}_{m0} \cdot (\boldsymbol{v}_n - \boldsymbol{v}_0), \quad B_{n2} = k\sin\theta_n \sin\varphi_n \\ B_{n1} &= k\sin\theta_n \cos\varphi_n, \quad B_{n3} = k(\cos\theta_n - 1)\end{aligned}.$$

This is an equation composed of four unknowns, which are $\phi'_{n,m}, x_m, y_m$, and z_m (other terms are known values). By using four observation points, simultaneous equations can be set up from the above relations and the excitation phase $-\phi'_{0,m}$ and the displacement of element antennas could be derived.

B. Restrictions on the Positions of the Observation Points

Here, we investigate possible restrictions on the positions of the observation points when more than one is necessary. We simply consider (16) in a matrix form and examine the value of the determinant of this matrix. The following are restrictions on the relation between the multiple observation points.

1) The angles either θ_n or φ_n of the four observation points must not coincide.
2) When angles φ_n of the two observation points coincide, angles θ_n of the other two observation points must not coincide.

Furthermore, we have investigated the relation between calculation errors of the above equations and the angle θ_n when angles φ_n of the four observation points differ. Fig. 7 shows the relation when the angles φ_n are in different quadrants and Fig. 8 shows the relation when the angles φ_n are in the same quadrant. Only the z-axis data, which showed the largest error value are shown here. These figures show that when θ_n is larger than $0.05°$, the calculation error of the position displacement is less than 0.05λ in either case. Here, when an antenna of a satellite in geostationary orbit is observed from the earth, $\theta = 0.05°$ is equivalent to 32 km on the ground. Also, the relation between observation distance and calculation error is investigated as shown in Fig. 9. Here, the angles of

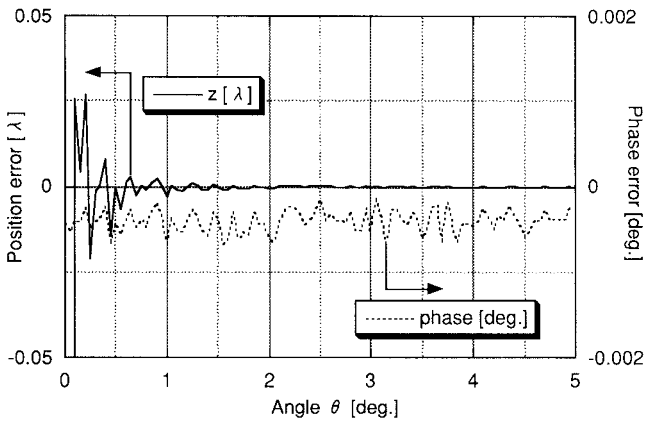

Fig. 7. Calculation error of position displacement and phase when all φn are in different quadrants.

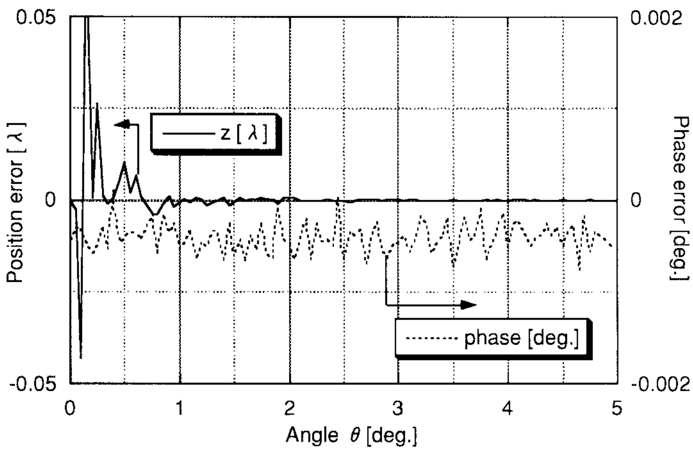

Fig. 8. Calculation error of position displacement and phase when all φn are in the same quadrant.

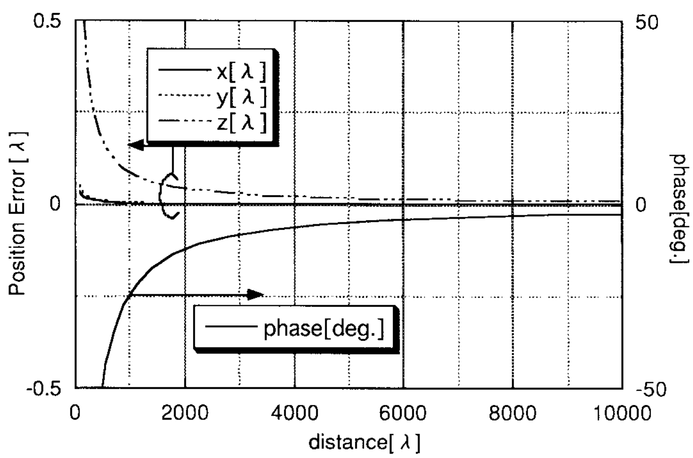

Fig. 9. Relation between observation distance and calculation error of position displacement and phase.

the four observation points vary between 1–5° for θ_n when φ_n are in the different quadrants. As seen from Fig. 9, when the observation distance is larger than 2000λ, the calculation error is less than 0.1λ in position and 25° in phase.

C. Receiving Phase of Less Than 360°

In an actual situation, the value of the relative receiving phase $\phi'_{n,m}$ can only be measured within 0–360°, although the relative length of the element antenna in question and the observation point from that of the standard element may be larger than one wavelength. These situations occur when the AUT is large and the element in question is far apart from the standard element. In this case, one must revise the phase data by adding a multiple of 360° to an optimum value.

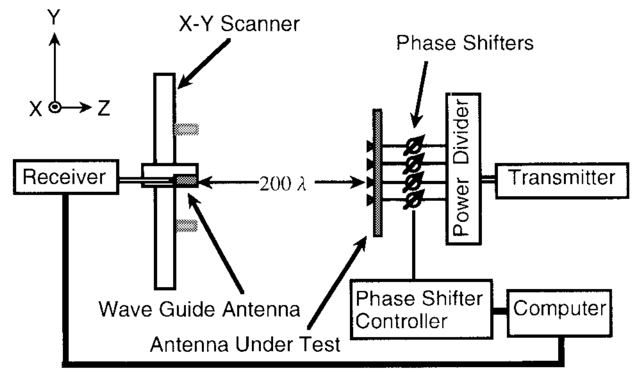

Fig. 10. Measurement structure.

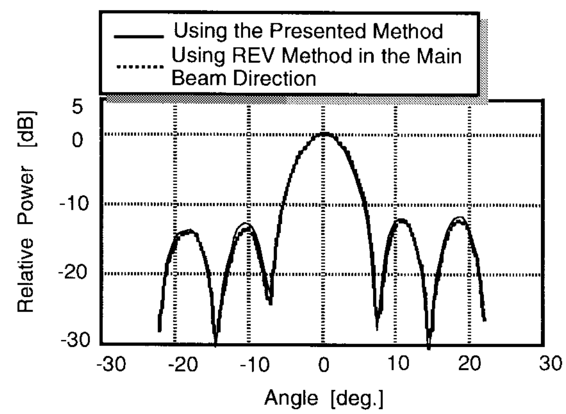

Fig. 11. Antenna pattern after phase control.

IV. Experiment

In this section, we confirm the previous theory by an experiment using a phased-array antenna. Fig. 10 shows the measuring system of this experiment. The measurement frequency is 11.85 GHz and an eight-element array antenna is used as the AUT. The type of the antenna elements is a patch antenna that are located on a ground plane in fixed positions. However, the element positions have a slight displacement caused during manufacturing and system setup. This displacement leads to the degredation of the antenna pattern, which we now try to correct by using the conventional REV method and the proposed method.

First, the antenna pattern is corrected by using the conventional REV method explained in Section II. The measurement is done from only one observaton point, which is in the main beam direction. In this case, the displacement of the element position cannot be determined, but the antenna pattern can be corrected.

Next, the antenna is observed from four observation points. The position of the observation points were set by a three axis

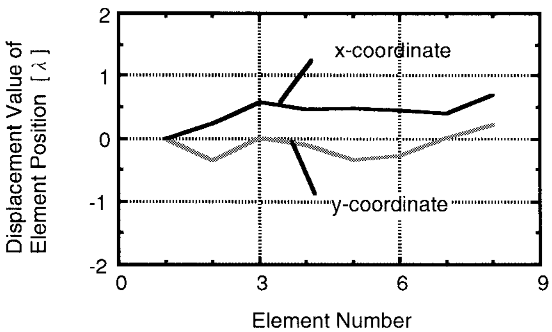

Fig. 12. Displacement value of element position in x and y coordinates.

scanner, and the receiving phase was measured at each point for all the elements using the REV method. In this case, not only can the antenna pattern be corrected, but also the element displacement values are determined.

Fig. 11 shows the radiation pattern comparing the two cases mentioned above. A good agreement between the two methods can be seen from these results. Fig. 12 shows the calculated results of the displacement of element positions using the proposed method. These values are used in calculation for the correct excitation phase for beam pointing in (16), and are reflected in the radiation pattern of Fig. 11. In this case, one can scan the beam by taking into account the displacement values of the element positions.

V. Conclusion

We have investigated the necessary number of observation points in cases when the observation point is placed apart from the main beam region such as in an SPS and have examined the case when the distortion is negligibly small and the case when the distortion should be considered. As a result, it was confirmed that when the distortion is small, one observation point is sufficient to correct main beam deflection. When the distortion is large, by using four observation points not only can deflection of the main beam be corrected, but also displacement of relative element positions can be determined.

The element positions are determined by measuring the phase of each element antenna from multiple receiving points using REV method. The effectiveness of this method was experimentally confirmed.

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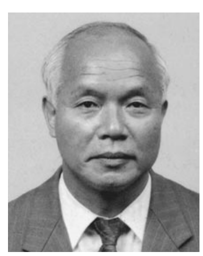

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