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CORRECTION OF CHARACTERISTICS OF RECEIVING CHANNELS IN A DIGITAL ANTENNA ARRAY BY A TEST SOURCE IN THE NEAR ZONE

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The author suggests some procedures for correction of receiving channel characteristics of a digital antenna array with the aid of an alignment source in the near zone.

The correction of voltages of primary channels of a digital antenna array (DAA) is known to equalize the complex-valued transfer factors of receiving channels. In the simplest case, for narrow-band tasks, the correction procedure may be implemented by a monochromatic signal, whose source is either external or internal (built-in) with respect to DAA equipment.

In the paper below we consider some methods for correction of characteristics of receiving channels based on using an external source of a special alignment signal placed in the near zone of the antenna array.

Any correction procedure includes two steps. First, by the adjustment signal (AS) we form the correction coefficients, and second, the instantaneous values of the complex-valued amplitudes (orthogonal components) of output voltages undergo a weighting with the use of the correction coefficients just calculated.

Assuming that AS has a planar wave front, the algorithm for calculation of correction coefficients based on a series of N digital samples of AS voltages for all outputs of the planar antenna array consisting of $R\times Q$ elements can be represented in the form [1]

$$\alpha^c_{rq} = \frac{\sum\limits_{i=1}^{N}\left\{V^c_{rq_i}\cdot\hat{a}^c_i + V^s_{rq_i}\cdot\hat{a}^s_i\right\}}{RQ\sum\limits_{i=1}^{N}\left\{V^{c^2}_{rq_i} + V^{s^2}_{rq_i}\right\}}, \quad \alpha^s_{rq} = \frac{\sum\limits_{i=1}^{N}\left\{V^c_{rq_i}\cdot\hat{a}^s_i - V^s_{rq_i}\cdot\hat{a}^c_i\right\}}{RQ\sum\limits_{i=1}^{N}\left\{V^{c^2}_{rq_i} + V^{s^2}_{rq_i}\right\}}, \tag{1}$$

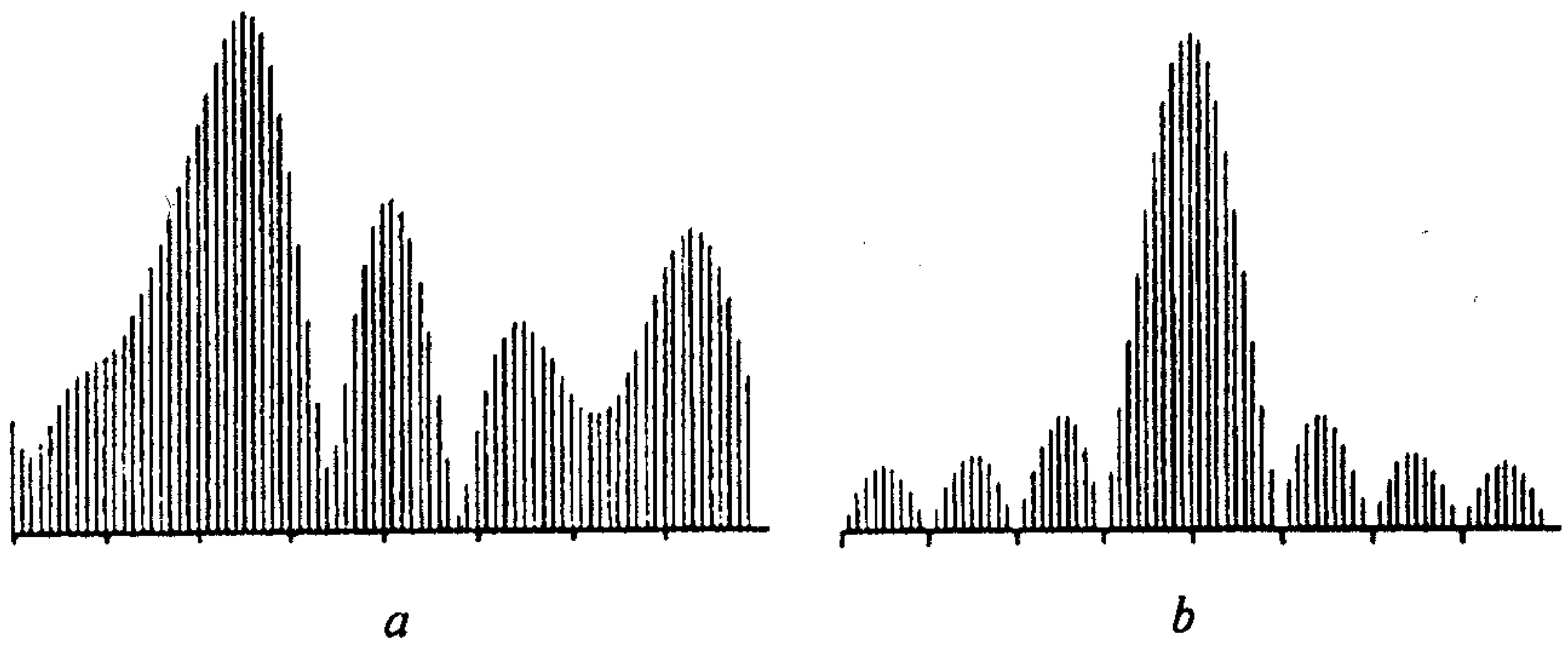
where α^c_{rq}, α^s_{rq} are cosine and sine components of the correction coefficient of the response of the DAA rqth primary channel located in the rth row of the qth column; R, Q denote the number of array elements in the row and column, respectively;

$$V^c_{rq_i} = U^c_{rq_i}\cdot\cos\left(x_r + x_q\right) + U^s_{rq_i}\cdot\sin\left(x_r + x_q\right),$$

$$V^s_{rq_i} = U^s_{rq_i}\cdot\cos\left(x_r + x_q\right) - U^c_{rq_i}\cdot\sin\left(x_r + x_q\right),$$

$$x_r = \frac{2\pi}{\lambda}\cdot d_r\cdot\sin\beta\cdot\cos\varepsilon\left(r - \frac{R+1}{2}\right) \quad x_q = \frac{2\pi}{\lambda}\cdot d_q\cdot\sin\beta\cdot\sin\varepsilon\left(q - \frac{Q+1}{2}\right),$$

$U^c_{rq_i}, U^s_{rq_i}$ are the quadrature components of the response of the DAA rqth primary channel in the ith time sample; x_r, x_q are the generalized coordinates of the calibrating source with respect to the DAA normal; λ is the wavelength of the calibrating



a b

Fig. 1

source radiation; d_r, d_q is the distance between the array elements in a row and column, respectively; β, ε are angular coordinates of the calibrating source about the array normal;

$$\hat{a}_i^c = \frac{1}{RQ}\sum_{r=1}^{R}\sum_{q=1}^{Q}\left[U_{rq_i}^c \cdot \cos(x_r + x_q) + U_{rq_i}^s \cdot \sin(x_r + x_q)\right],$$

$$\hat{a}_i^s = \frac{1}{RQ}\sum_{r=1}^{R}\sum_{q=1}^{Q}\left[U_{rq_i}^s \cdot \cos(x_r + x_q) - U_{rq_i}^c \cdot \sin(x_r + x_q)\right].$$

This procedure for CC calculation has been synthesized by the least square method by means of minimization, in terms of unknown variables α_{rq}^c, α_{rq}^s, of the functional [1]

$$F = \sum_{i=1}^{N}\left(\left[\tilde{U}_{rq_i}^c - a_{rq_i}^c\right]^2 + \left[\tilde{U}_{rq_i}^s - a_{rq_i}^s\right]^2\right) = \min \tag{2}$$

where $\tilde{U}_{rq_i}^c = U_{rq_i}^c \cdot \alpha_{rq}^c - U_{rq_i}^s \cdot \alpha_{rq}^s$, $\tilde{U}_{rq_i}^s = U_{rq_i}^s \cdot \alpha_{rq}^c + U_{rq_i}^c \cdot \alpha_{rq}^s$ are corrected quadrature components of the voltage with reference to the output of primary channels, $\alpha_{rq_i}^{c(s)}$ are the required quadrature components of the voltage with reference to the output of the rqth primary channel in the ith time sampling, corresponding to a given position of the calibrating source with respect to the DAA plane.

The algorithm of the correction itself, under radar working conditions, reduces to weighting the signal mixture voltages in accordance to the rule [1], i.e.,

$$\tilde{U}_{rq_i}^c = U_{rq_i}^c \cdot \alpha_{rq}^c - U_{rq_i}^s \cdot \alpha_{rq}^s, \quad \tilde{U}_{rq_i}^s = U_{rq_i}^s \cdot \alpha_{rq}^c + U_{rq_i}^c \cdot \alpha_{rq}^s \tag{3}$$

where $\tilde{U}_{rq_i}^c$, $\tilde{U}_{rq_i}^s$ are corrected values of the respective orthogonal components at the ith time instant.

When passing from a planar to linear DAA, the calculation by formulas (1) and (2) becomes simpler, since in the values α_{rq}^c, α_{rq}^s, $U_{rq_i}^c$, $U_{rq_i}^s$ we have to omit the index q and to set x_q equal to zero:

$$V_{r_i}^c = U_{r_i}^c \cdot \cos x_r + U_{r_i}^s \cdot \sin x_r, \; V_{r_i}^s = U_{r_i}^s \cdot \cos x_r - U_{r_i}^c \cdot \sin x_r,$$

$$\hat{a}_i^c = \frac{1}{R}\sum_{r=1}^{R}\left[U_{r_i}^c \cdot \cos x_r + U_{r_i}^s \cdot \sin x_r\right],$$

$$\hat{a}_i^s = \frac{1}{R}\sum_{r=1}^{R}\left[U_{r_i}^s \cdot \cos x_r - U_{r_i}^c \cdot \sin x_r\right],$$

$$x_r = \frac{2\pi}{\lambda} \cdot d \cdot \left(r - \frac{R+1}{2}\right) \cdot \sin\beta.$$

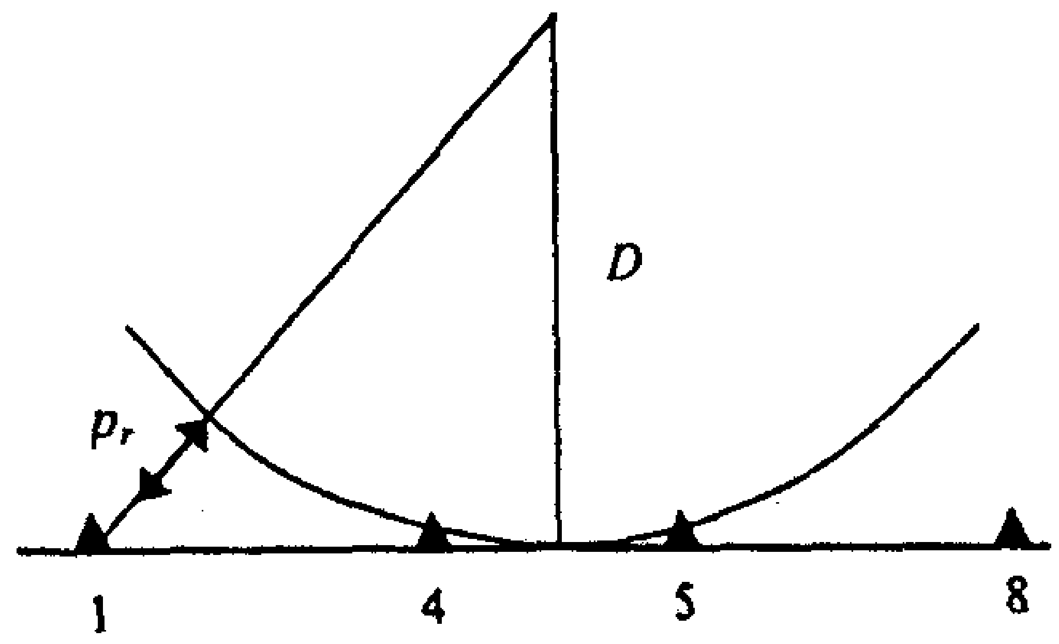


Fig. 2

Relations (3) will be modified in a similar manner:

$$\tilde{U}^c_{r_i} = U^c_{r_i}\cdot\alpha^c_r - U^s_{r_i}\cdot\alpha^s_r,\quad \tilde{U}^s_{r_i} = U^s_{r_i}\cdot\alpha^c_r + U^c_{r_i}\cdot\alpha^s_r. \tag{4}$$

The above approach to synthesis of the correction procedures was checked experimentally at a radar brassboard with a linear eight-channel DAA [2]. An example confirming the consistency of this approach represents the result of digital diagram shaping based on the discrete Fourier transform prior to correction of primary channels' characteristics (Fig. 1*a*) and after it (Fig. 1*b*).

A peculiar feature of the adjustment signal when its source is located in the near zone is the fact that, because of proximity of the source to the antenna array, the wave front is not absolutely planar. If we do not take special measures then the front curvature will penetrate into the correction coefficients and cause the signal distortion. To avoid it, before forming the correction coefficients we have to compensate the phase increments arising from the wave front curvature.

In the typical mode of operation, when the direction finding of sources acting in the remote zone is performed, the correction coefficients must correspond to the planar wave front. Thus, there arises a problem: to develop such a correction method in which the calculation of flat-wave correcting coefficients would be performed based on AS of the curved wave but the correction of channel voltages itself based by (3). Then we can use one and the same correction algorithm both for the planar wave in normal working conditions (by signals from the remote zone) and during the antenna alignment.

The basis for the approach suggested is deliberate rectification of the phase front of the alignment signal prior to forming the correction coefficients. This is made by compensation of the respective phase increment arising from deformation of the wave front. In order to simplify the mathematics explaining the essence of the method, assume that the above phase increment obeys the quadratic law of variation, which corresponds to a spherical model of isophasal surfaces of the adjustment field wave.

The algorithm for calculating the phase accumulation in the channels of a linear antenna array because of wave front curvature (under assumption of its sphericity) can be developed based on geometric relations presented in Fig. 2. Here D is the distance from the phase center of the alignment signal source to the phase center of the antenna array, the latter being placed into its center of symmetry; and p_r is the difference between the wave paths arising from the wave front sphericity and calculated with reference to the phase center of DAA.

Variation of wave path increments referenced to the phase center as a function of the array channel number for 8-element DAA is shown in Table 1.

The behavior of the above difference of paths p_r, when the carrier frequency is 170 MHz and the distance to the AS source is 100 m, is shown graphically in Fig. 3. The figures under the horizontal axis denote the channel number, and at the vertical one — the path difference p_r in meters.

Taking all this into account, the phase increment at the rth element of the antenna array due to curvature of the electromagnetic wave front can be expressed as

$$\Delta\varphi_r = \omega_r\cdot\Delta t = 2\pi f_r\cdot\frac{p_r}{c} = \frac{2\pi}{\lambda}\cdot p_r$$

where p_r is the wave path difference listed in Table 1, $r = 1,\ldots, R$; and R is the number of receiving channels in DAA.

In the general case, the expression for the phase shift in the DAA rth channel arising from sphericity of the wave front, and at an even number of elements, can be written as

Table 1

Channel number	p_r	Channel number	p_r
1	$\sqrt{D^2+3.5^2\cdot d^2}-D$	5	$\sqrt{D^2+0.5^2\cdot d^2}-D$
2	$\sqrt{D^2+2.5^2\cdot d^2}-D$	6	$\sqrt{D^2+1.5^2\cdot d^2}-D$
3	$\sqrt{D^2+1.5^2\cdot d^2}-D$	7	$\sqrt{D^2+2.5^2\cdot d^2}-D$
4	$\sqrt{D^2+0.5^2\cdot d^2}-D$	8	$\sqrt{D^2+3.5^2\cdot d^2}-D$

$$\Delta\varphi_r=\frac{2\pi}{\lambda}\cdot\left\{\sqrt{D^2+\left(r-\frac{R+1}{2}\right)^2\cdot d^2}-D\right\}. \tag{5}$$

The values of $\Delta\varphi_r$ in degree units, recalculated from Fig. 3, are shown in Fig. 4. Before the correction procedure intended for a planar wave, we have to shift the phase of the complex-valued voltages by a magnitude that compensates the phase shift generated because of wave front sphericity, in accordance with the following expressions:

$$\tilde{U}^c_{r_i}=U^c_{r_i}\cdot\cos(\Delta\varphi_r)-U^s_{r_i}\cdot\sin(\Delta\varphi_r),\ \tilde{U}^s_{r_i}=U^s_{r_i}\cdot\cos(\Delta\varphi_r)+U^c_{r_i}\cdot\sin(\Delta\varphi_r). \tag{6}$$

A similar procedure can be applied to calculation of compensating phase increments for a planar DAA.

In the process of alignment the pilot signal source is always located in the vertical plane passing through the optical axis of the antenna array (in its normal direction), then the number of operations in the suggested correction technique can be reduced substantially. The point is that with such source position its generalized coordinates $x_r=x_q=0$. In this event, for example, for a planar DAA the calculation of correction coefficients must be performed, in conformity with (1), with the following relations taking into account:

$$\hat{a}^c_i=\frac{1}{RQ}\sum_{r=1}^{R}\sum_{q=1}^{Q}U^c_{rq_i},\ \hat{a}^s_i=\frac{1}{RQ}\sum_{r=1}^{R}\sum_{q=1}^{Q}U^s_{rq_i},\ V^c_{rq_i}=U^c_{rq_i},V^s_{rq_i}=U^s_{rq_i}.$$

In the case of a linear DAA,

$$\hat{a}^c_i=\frac{1}{R}\sum_{r=1}^{R}U^c_{r_i},\ \hat{a}^s_i=\frac{1}{R}\sum_{r=1}^{R}U^s_{r_i},\ V^c_{r_i}=U^c_{r},V^s_{r_i}=U^s_{r_i}.$$

The operation of summing the quadrature components of the primary channels' responses, which is available in the expressions for calculation of the correction coefficients, is pertinent in the event of insignificant nonidentities of their phase-amplitude characteristics. At a wide spread these sums do not answer to the true values of the signal-to-noise ratio at the antenna input and may vanish. Moreover, such a summation, at any case, complicates the process of correction of primary channels' characteristics. Taking all this into account, in a number of problems, particularly, at the stage of preproduction model manufacture, a more appropriate decision is adjustment of phase-amplitude responses not to the mean (hypothetical) channel but to some actual receiver among those present in the array. This receiver may be taken as a standard, for example, with account of minimum noise factor, lack of failures in the digital circuitry, etc. In this event the calculation formulas for correction coefficients have to be modified by substituting $\hat{a}^c_r=U^c_{\mathrm{st}_i}$, $\hat{a}^s_r=U^s_{\mathrm{st}_i}$, where $U^c_{\mathrm{st}_i},U^s_{\mathrm{st}_i}$ are quadrature components of output voltages in the standard channel at the *i*th time instant.

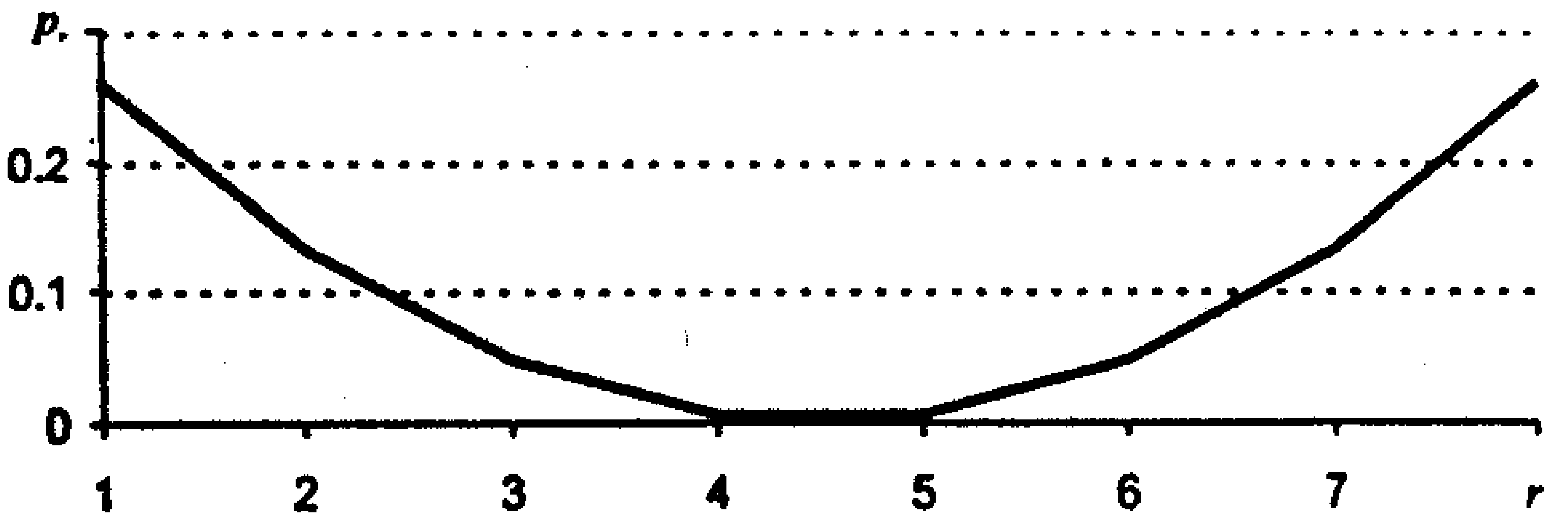


Fig. 3

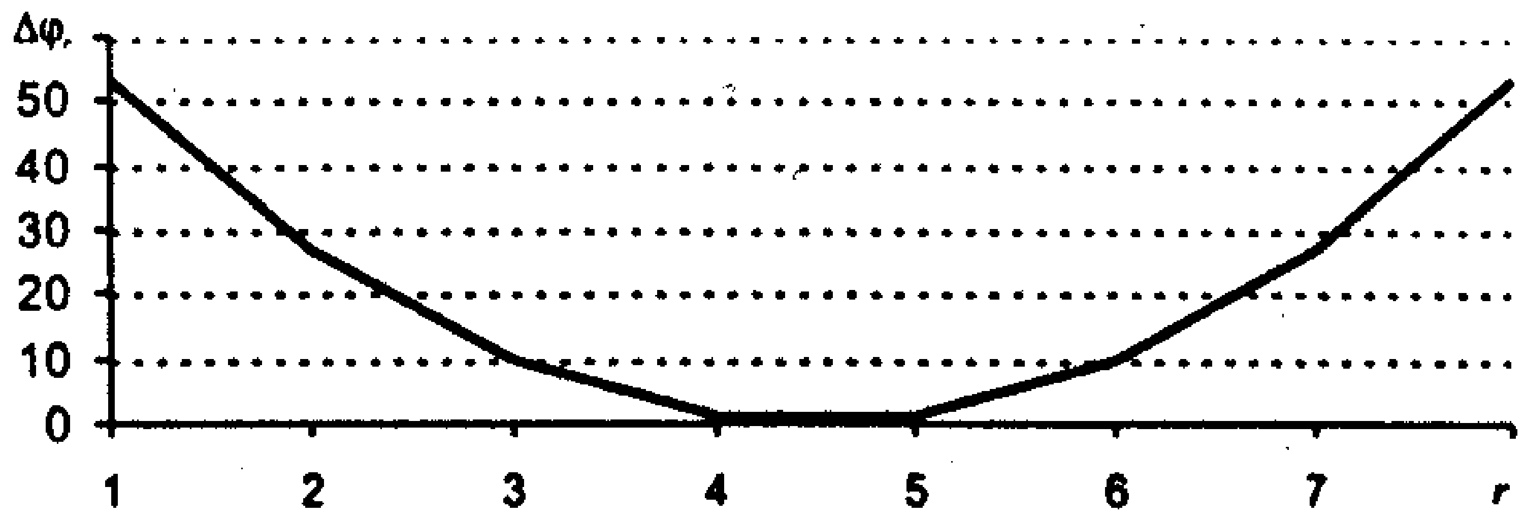


Fig. 4

As a result, the correction coefficient values α_r^c and α_r^s are calculated, like in (1), by N samples of the pilot signal voltages in the frame channel $U^{c(s)}_{s,\,\mathrm{st}}$:

$$\alpha_r^c=\frac{\sum\limits_{i=1}^{N}\left\{U^c_{\mathrm{st}_i}\cdot U^c_{r_i}+U^s_{\mathrm{st}_i}\cdot U^s_{r_i}\right\}}{\sum\limits_{i=1}^{N}\left\{U^{c^2}_{r_i}+U^{s^2}_{r_i}\right\}},\quad \alpha_r^s=\frac{\sum\limits_{i=1}^{N}\left\{U^s_{\mathrm{st}_i}\cdot U^c_{r_i}-U^c_{\mathrm{st}_i}\cdot U^s_{r_i}\right\}}{\sum\limits_{i=1}^{N}\left\{U^{c^2}_{r_i}+U^{s^2}_{r_i}\right\}}. \tag{7}$$

Now, the algorithm for correction of the receiving channels by the alignment signal in the near zone can be formulated.

At the stage of establishment of the correction coefficients we do the following:

1) measure the distance D to AS source in the near zone situated on the normal to the array;

2) calculate the phase increments $\Delta\varphi_r$ due to curvature of the alignment signal front, with the use of formula (5);

3) at every time instant the DAA response to the alignment signal is shifted, in terms of phase, in conformity with the algorithm

$$\tilde{U}^c_{r_i}=U^c_{r_i}\cdot\cos(\Delta\varphi_r)-U^s_{r_i}\cdot\sin(\Delta\varphi_r),\ \tilde{U}^s_{r_i}=U^s_{r_i}\cdot\cos(\Delta\varphi_r)+U^c_{r_i}\cdot\sin(\Delta\varphi_r);$$

4) calculate the correction coefficient by formulas (7), with voltages (6) taken into account.

The correction of signals of the sources located in the remote zone is performed by algorithm (4) for every time sampling. In the case of mobile radar systems the use of an external alignment signal is not always feasible, so we face a new problem: to retain the characteristics, once corrected, of DAA receiving channels for a long time with the use of a built-in AS source, whose part is played by the standard heterodyne of the receiving system [2]. It should be noted that the process of CC calculation and DAA alignment with the aid of a built-in generator of the pilot signal has much in common with the correction using a source in the near zone. The method is based on the assumption that the time constant of the receiving channel instability exceeds the time interval required for cut-off of the signal source in the near zone, application (to the array input) of the pilot action from the built-in driver, and accumulation of the array of its digital reading with a given sampling volume. This assumption makes it possible to expect that, immediately after CC calculation and DAA alignment by the signal from the near zone, the channel characteristics remain unchanged for some time. So, within the framework of our correction procedure, we propose to take as a standard the array of voltage readings from the built-in source of pilot signal. This array is generated immediately after calculation of "planar-wave" correction coefficients by the alignment source in the near zone.

In this event, the procedure of CC generation and of linear DAA alignment by the pilot signal must be preceded by calculation of the planar-wave CC α_r^c and α_r^s, for the operating condition needs (by the source in the near zone), loading them into digital receiving units, switch-off of the AS source and switch-on of the built-in generator of the pilot signal or readjustment of the heterodyne [2], and creation of the corrected (by coefficients α_r^c and α_r^s) array of the readings of the pilot action $U^{c(s)}_{r,\,\mathrm{st}_i}$. Since it is hardly possible to distribute a pilot signal with fixed phase delays over the receiving channels, we now have to calculate the correction coefficients, which "map" the distribution of thus corrected pilot action voltages $U^{c(s)}_{r,\,\mathrm{st}_i}$ into a sequence corresponding to an ideal "planar-wave" reception situation. These coefficients will be called "mapping" and denote as $\dot{\beta}_{r_0} = \beta^c_{r_0} + j\beta^s_{r_0}$. The calculation of the mapping coefficients $\beta^c_{r_0}$, $\beta^s_{r_0}$ is identical with the procedure of generation of planar-wave CC α^c_r and α^s_r for the alignment source in the near zone, and can be represented in the form

$$\beta^c_{r_0} = \frac{\sum\limits_{i=1}^{N}\left\{U^c_{r,\mathrm{st}_i} \cdot U^c_{r_i} + U^s_{r,\mathrm{st}_i} \cdot U^s_{r_i}\right\}}{\sum\limits_{i=1}^{N}\left\{U^{c^2}_{r_i} + U^{s^2}_{r_i}\right\}}, \quad \beta^s_{r_0} = \frac{\sum\limits_{i=1}^{N}\left\{U^s_{r,\mathrm{st}_i} \cdot U^c_{r_i} - U^c_{r,\mathrm{st}_i} \cdot U^s_{r_i}\right\}}{\sum\limits_{i=1}^{N}\left\{U^{c^2}_{r_i} + U^{s^2}_{r_i}\right\}},$$

where $U^{s(c)}_{r_i}$ are the voltage readings of the *r*th receiving channel at the *i*th time instant in the event of action of the built-in pilot signal.

Based on the initially calculated ("primary") mapping coefficients, the further process of DAA alignment with the use of the internal pilot signal may be organized in several ways. Particularly, one of the versions implies the storage of the products of initial mapping coefficients $\dot{\beta}_{r_0}$ by the planar-wave CC $\dot{\alpha}_r$ calculated by the near zone signal, followed by loading the produced values $\xi_{r_0} = (\beta^c_{r_0} + j\beta^s_{r_0})(\alpha^c_r + j\alpha^s_r)$ as correction coefficients into the digital receiving units every time before applying the pilot signal to the inputs of the receiving channels. Because of use of the coefficients $\dot{\xi}_{r_0}$ at the receiver output we obtain the voltages $\tilde{U}^c_{r_i} = U^c_{r_i} \cdot \xi^c_{r_0} - U^s_{r_i} \cdot \xi^s_{r_0}$, $\tilde{U}^s_{r_i} = U^s_{r_i} \cdot \xi^c_{r_0} + U^c_{r_i} \cdot \xi^s_{r_0}$ corrected with account of the mapping coefficients $\dot{\beta}_{r_0}$.

Afterwards, at every successive alignment by the pilot signal, we come to define the set of new mapping coefficients $\Delta\dot{\beta}_r$, which take into account the true deviation of output voltages in the receiving channels, transformed into a planar-wave array with the aid of coefficients ξ_{r_0}, from their standard distribution corresponding to the ideally flat front of the electromagnetic wave. It remains to calculate the products $\tilde{\alpha}_r = (\Delta\beta^c_r + j\Delta\beta^s_r)(\alpha^c_r + j\alpha^s_r)$, and load them into the digital receiving units as correction coefficients used in working conditions.

The procedure of channel voltage correction in the normal mode of operation now takes the form

$$\tilde{U}^c_{r_i} = U^c_{r_i} \cdot \tilde{\alpha}^c_r - U^s_{r_i} \cdot \tilde{\alpha}^s_r, \quad \tilde{U}^s_{r_i} = U^s_{r_i} \cdot \tilde{\alpha}^c_r + U^c_{r_i} \cdot \tilde{\alpha}^s_r.$$

The approach presented above makes it possible only occasionally (at periodic maintenance, for instance) to use the external near-zone AS source for correcting the characteristics of DAA receiving channels, and thus to facilitate and improve the quality of maintenance and operation of radar systems.

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