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MEASUREMENT OF THE RANGE TO THE SOURCE OF ALIGNMENT SIGNAL IN THE NEAR ZONE OF ANTENNA ARRAY

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The authors suggest several methods for measurement of the range to the external source of alignment signal placed in the near zone of a digital antenna array.

The method proposed in [1] for correcting the receiving channel characteristics of a digital antenna array (DAA) with the aid of a standard source in the near zone implies that we have at our disposal some exact information about the distance of the alignment source from the phase center of the antenna system. Apart from traditional ways of obtaining this information, we can offer another promising method: based on measurement of interchannel time shift of the signals from a pulse generator placed at the point coincident with location of a tonal alignment signal (if the correction is performed by a continuous signal). Another way is to perform measurement of the alignment transmitter itself in the pulse mode of operation.

Consider the algorithms of range measurement for linear antenna arrays with an odd and even number of elements. In the case of a DAA with an odd number of channels, the antenna phase center, i.e., its center of symmetry, coincides with the central element. Since the range measurement must be performed in the near zone of the antenna array, the wave is assumed to have a spherical front. The instant of arrival of the wave at the antenna array is shown schematically in Fig. 1. Here D is the distance from the phase center of the alignment (pilot) signal to the phase center of the antenna array; A_r is the increment of the wave path due to wave front sphericity, which is calculated for the rth channel with respect to DAA phase center; R is the number of elements in the antenna array; and d is the distance between the elements.

Based on geometric ratios (Fig. 1) we may write that

$$(A_r + D)^2 = D^2 + (r - (R+1)/2)^2 d^2, \tag{1}$$

whence $D = (4r^2d^2 - 4rd^2(R+1) + (R+1)^2 d^2 - 4A_r^2)/8A_r$.

To determine the statistically optimal estimate of the range D the least squares method will be applied. The sum of squared residuals of all the system equations derived from (1) over the totality R of the DAA receiving channels takes the form

$$F = \sum_{r=1}^{R} \left\{ D^2 + (r - (R+1)/2)^2 d^2 - (A_r + D)^2 \right\}^2 = \min.$$

The F value is minimum at a fully defined estimate D, which can be found by differentiating F with respect to the above unknown variable and by setting the partial derivative obtained equal to zero:

$$\frac{\partial F}{\partial D} = -4\sum_{r=1}^{R} A_r \left[\left(r - \frac{R+1}{2} \right)^2 d^2 - A_r^2 - 2A_r D \right] = 0,$$

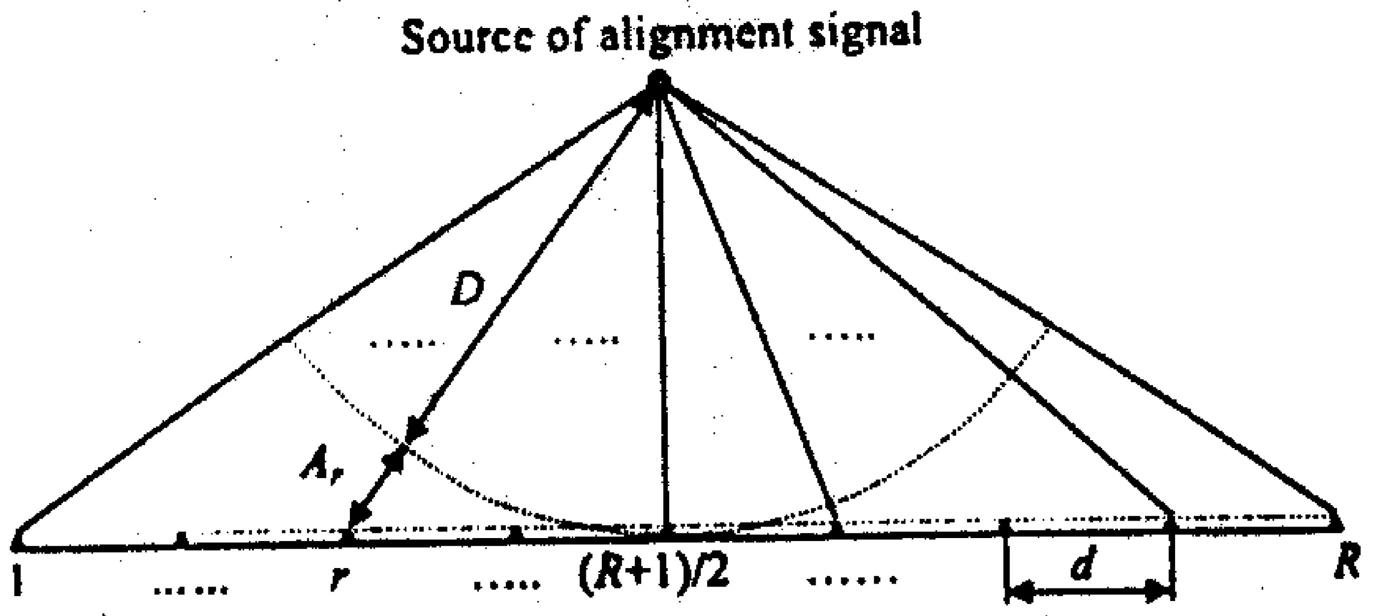


Fig. 1

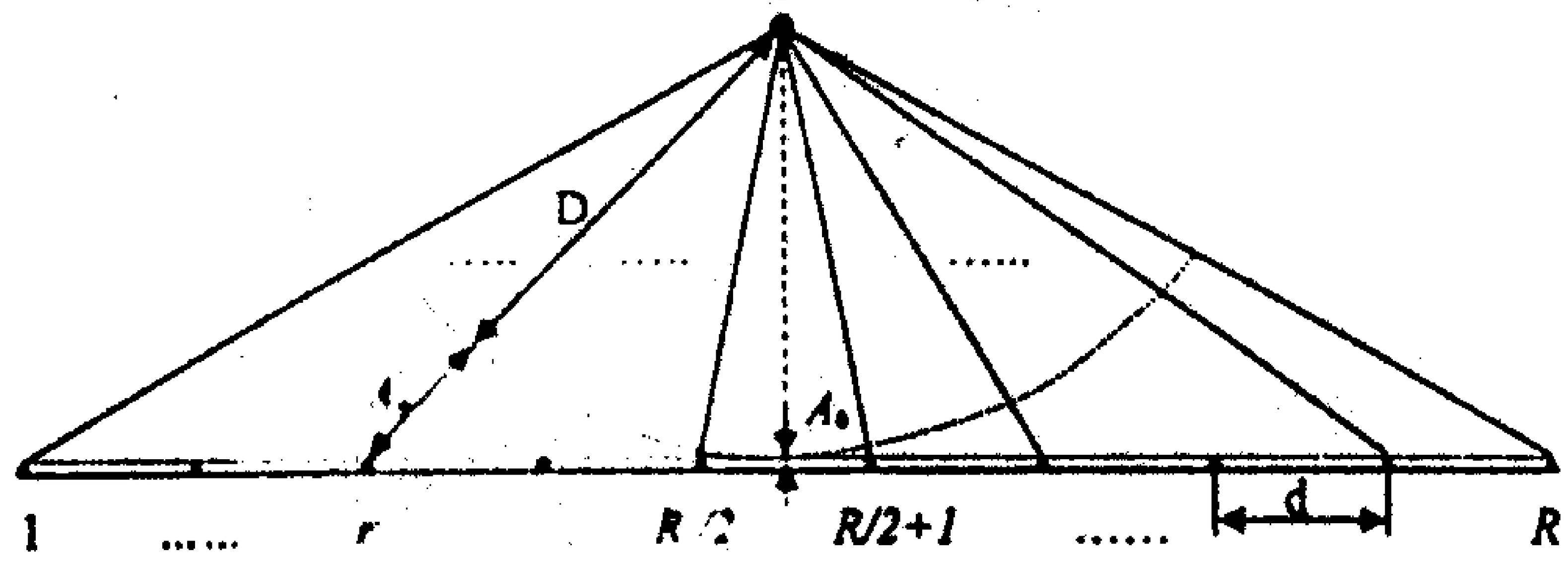


Fig. 2

whence

$$\tilde{D}=\left[\sum_{r=1}^{R}\left[A_r d^2\left(r-\frac{R+1}{2}\right)^2-A_r^3\right]\right]\cdot\left[2\sum_{r=1}^{R}A_r^2\right]^{-1}. \tag{2}$$

Consider now the algorithm for range measurement in the case of a linear antenna array with an even number of elements. Now the DAA phase center does not coincide with its central element, and to apply the above algorithm it is necessary to arrange an additional receiving channel in the antenna phase center. Because of this, preference has to be given to another measurement algorithm that deals with the differences of the wave front paths not about its phase center but about two array elements adjacent to it — as shown in Fig. 2.

Based on the geometric relationships of Fig. 2,

$$(r-(R+1)/2)^2d^2+(D-A_0)^2=(A_r+D)^2 \tag{3}$$

where A_0 can be determined from the expression $(D-A_0)^2+(d/2)^2=D^2$.

After calculating the feasible root A_0 of this quadratic equation and substituting it into (3) followed by some rearrangements, we may write that

$$(r-(R+1)/2)^2d^2-(d/2)^2=A_r^2+2A_rD, \tag{4}$$

whence the deterministic estimate of the distance to the pilot source takes the form

$$D=\left((r-(R+1)/2)^2d^2-(d/2)^2-A_r^2\right)/2A_r.$$

Having applied the method of statistical synthesis of the range-measuring procedure for the case of an antenna array with an odd number of elements, let us define the range estimate over an even number of the receiving channels. Based on (4), the normal equation of the least squares method for the case under consideration has the form

$$F=\sum_{r=1}^{R}\left\{\left(r-\frac{R+1}{2}\right)^2d^2-(d/2)^2-A_r^2-2A_rD\right\}^2=\min.$$

To find the minimum of this function, differentiate it with respect to the unknown D:

$$\frac{\partial F}{\partial D}=-4\sum_{r=1}^{R}A_r\left[\left(r-\frac{R+1}{2}\right)^2d^2-\left(\frac{d}{2}\right)^2-A_r^2-2A_rD\right].$$

Setting the partial derivative obtained equal to zero and expressing D in the explicit form gives

$$\tilde{D}=\sum_{r=1}^{R}\left[A_r\left(r-\frac{R+1}{2}\right)^2d^2-A_r\left(\frac{d}{2}\right)^2-A_r^3\right]\cdot\left[2\sum_{r=1}^{R}A_r^2\right]^{-1}. \tag{5}$$

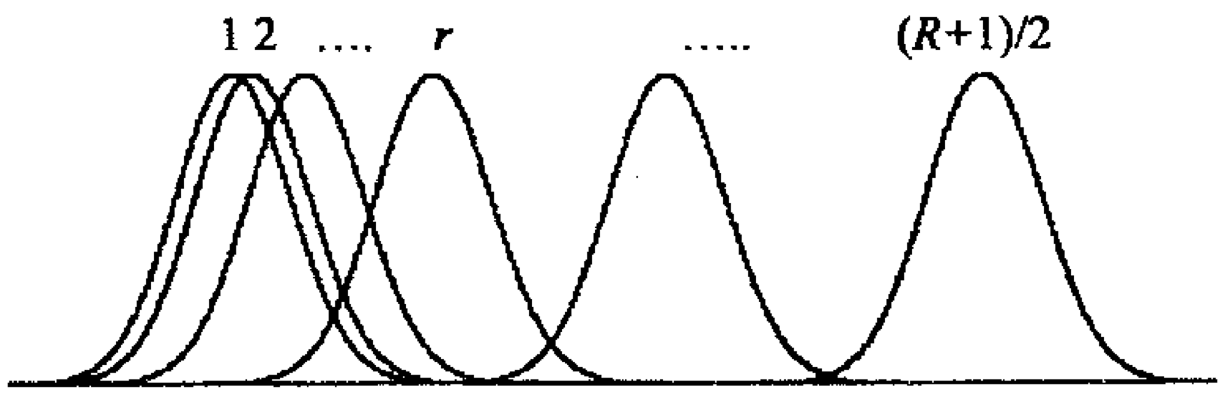


Fig. 3

In (2) and (5) we can find the unknown difference A_r of the wave path about the phase center. In the quantization period units

$$A_r = cN_r\Delta t, \tag{6}$$

where c is the light speed; N_r is the delay of the pulse received by the rth channel from the pulse received by the $(R + 1)/2$-th channel in the event of antenna array with an odd number of channels, and by the $R/2$-th or $(R/2 + 1)$-th channels in the event of an even number of elements — in the quantization period units; and Δt is the quantization period.

Let us find the N_r estimate through evaluating the interchannel time shift between signals coming from the pilot source. A variant of signal mixture produced by multiple addition of time samples of the signals received by R channels of a hypothetical antenna array with an odd number of elements is shown schematically in Fig. 3.

To define the estimate N_r we need only information on the envelope shape. If the envelope can be described in the analytical form, the required estimates can be defined by solution of the system of algebraic equations or a single M-th order equation (M is the number of the signal readings produced within the limits of the signal mixture's existence) — as in the method considered in [2]. When the solutions to these equations are difficult or even impossible to obtain in the analytical form, the iterative estimation methods must be used.

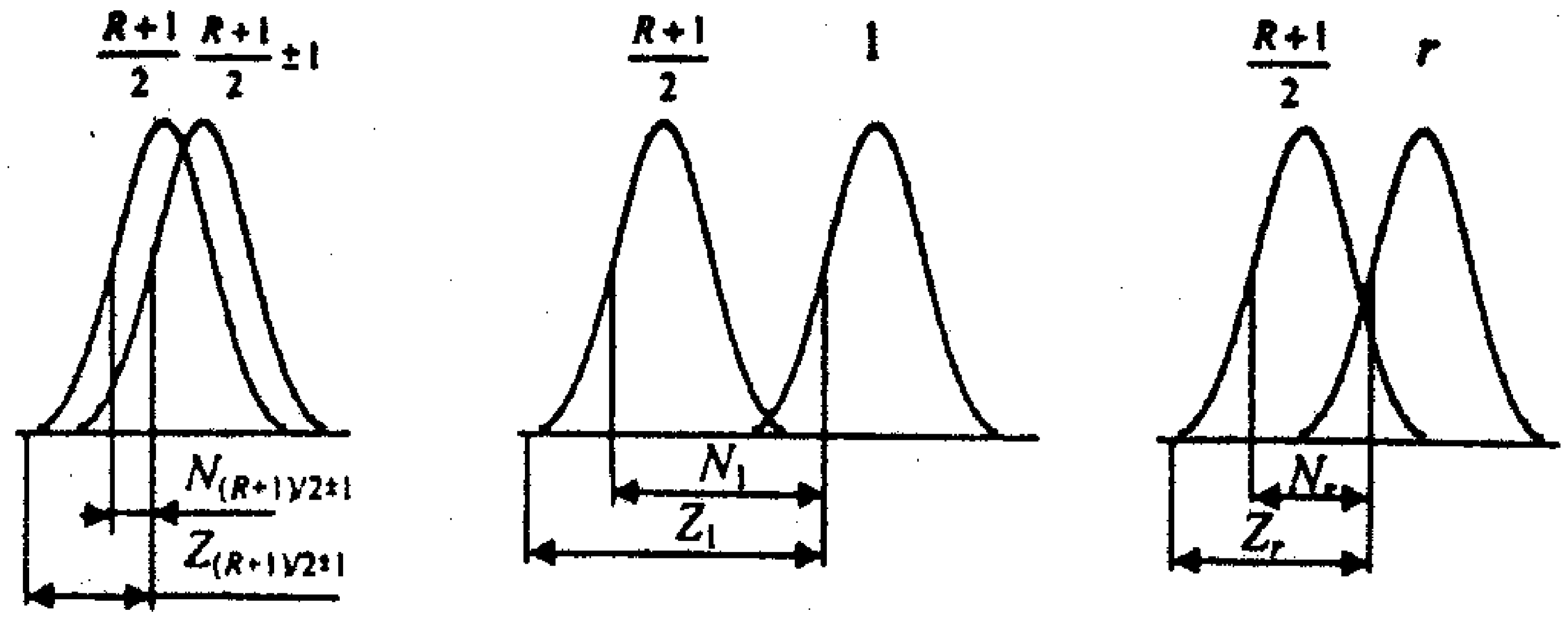
In accordance with the approach suggested for estimating N_r, we shall use the pairwise sums of the envelopes of the reference signal and that picked up at the output of the DAA rth channel. For the reference one we take a pulse having zero difference of its path. The variants of the signal mixture obtained after the interchannel summation operation for an array with an odd number of elements are shown in Fig. 4. Here the a position corresponds to the sum of the reference pulse and of signals of the $((R + 1)/2\pm1)$-th channels, b — to the sum of the reference and the 1st or Rth channel, and c — to the rest of the combinations.

To define the estimates N_r let us use the least squares method. The sum of squared residuals of the system equations for the quadrature components of the normalized complex-valued envelope with respect to the output of the rth channel $k(s - z_r)$ and of the reference one, with its ordinal number $(R + 1)/2$, taking value $k(s - z_r - N_r)$, for the case of an antenna array with an odd number of elements, can be expressed as

$$F_r = \sum_{s=0}^{S}\left\{U_c - \tilde{a}_r^c V_c - \tilde{a}^c_{\frac{R+1}{2}} W_c\right\}^2 + \sum_{s=0}^{S}\left\{U_s - \tilde{a}_r^s V_s - \tilde{a}^s_{\frac{R+1}{2}} W_s\right\}^2 \to \min, \tag{7}$$

where $U_p = U^p_{sr} + U^p_{s(R+1)/2}$, $V_p = k^p(s-\tilde{z}_r)$, $W_p = k^p(s-\tilde{z}_r-\tilde{N}_r)$, s is the ordinal number of the reading produced by ADC; S is the sampling length in the quantization periods; $U^c_{sr}, U^s_{sr}, U^c_{s(R+1)/2}, U^s_{s(R+1)/2}$ are quadrature components of the measured pulse voltages of the rth and the $(R + 1)/2$-th channels of DAA in the sth reading of ADC; $a^c_r, a^s_r, a^c_{(R+1)/2}$, $a^s_{(R+1)/2}$ are quadrature components of amplitude of the signal in the rth and $(R + 1)/2$-th channels of DAA; and $\tilde{z}_r$ is the estimate of the offset of the first reading of the measurement sample from the beginning of the pulse signal in the rth channel in the quantization period units.

In order to find the estimate $\tilde{N}_r$, it would be reasonable to pass to the residual function modified in conformity with [3]. To do this, the summands contained in (7) shall be squared followed by removing the brackets. Then



a *b* *c*

Fig. 4

$$F_r=\sum_{s=0}^{S}U_c^2-2\tilde{a}_r^c\sum_{s=0}^{S}U_cV_c-2\tilde{a}^c_{\frac{R+1}{2}}\sum_{s=0}^{S}U_cW_c+\left(\tilde{a}_r^c\right)^2\sum_{s=0}^{S}V_c^2+$$
$$+\left(a^c_{\frac{R+1}{2}}\right)^2\sum_{s=0}^{S}W_c^2+2\tilde{a}_r^c\tilde{a}^c_{\frac{R+1}{2}}\sum_{s=0}^{S}V_cW_c+\sum_{s=0}^{S}U_s^2-2\tilde{a}_r^s\sum_{s=0}^{S}U_sV_s-$$
$$-2\tilde{a}^s_{\frac{R+1}{2}}\sum_{s=0}^{S}U_sW_s+\left(\tilde{a}_r^s\right)^2\sum_{s=0}^{S}V_s^2+\left(a^s_{\frac{R+1}{2}}\right)^2\sum_{s=0}^{S}W_s^2+2\tilde{a}_r^s\tilde{a}^s_{\frac{R+1}{2}}\sum_{s=0}^{S}V_sW_s.$$

The minimum of F_r is attained at the maximum value of the summands with "minus" sign and at certain estimates of the amplitude components $a_r^c, a_r^s, a^c_{(R+1)/2}, a^s_{(R+1)/2}$. We can obtain these estimates by differentiating (7) with respect to the above unknowns and setting their partial derivatives equal to zero.

The equation systems for the quadrature amplitude components of signals will have the form

$$\begin{cases}\dfrac{\partial F_r}{\partial\tilde{a}_r^c}=-2\sum\limits_{s=0}^{S}U_cV_c+2\tilde{a}_r^c\sum\limits_{s=0}^{S}V_c^2+2\tilde{a}^c_{\frac{R+1}{2}}\sum\limits_{s=0}^{S}V_cW_c=0;\\ \dfrac{\partial F_r}{\partial\tilde{a}^c_{\frac{R+1}{2}}}=-2\sum\limits_{s=0}^{S}U_cW_c+2\tilde{a}^c_{\frac{R+1}{2}}\sum\limits_{s=0}^{S}W_c^2+2\tilde{a}_r^c\sum\limits_{s=0}^{S}V_cW_c=0,\end{cases}$$

$$\begin{cases}\dfrac{\partial F_r}{\partial a_r^s}=-2\sum\limits_{s=0}^{S}U_sV_s+2a_r^s\sum\limits_{s=0}^{S}V_s^2++2a^s_{\frac{R+1}{2}}\sum\limits_{s=0}^{S}V_sW_s=0;\\ \dfrac{\partial F_r}{\partial a^s_{\frac{R+1}{2}}}=-2\sum\limits_{s=0}^{S}U_sW_s+2a^s_{\frac{R+1}{2}}\sum\limits_{s=0}^{S}W_s^2+2a_r^s\sum\limits_{s=0}^{S}V_sW_s=0.\end{cases}$$

The solution of these equation systems in terms of $a_r^c, a_r^s, a^c_{(R+1)/2}, a^s_{(R+1)/2}$, using, for example, the Cramer rule, gives

$$\tilde{a}_r^c=\frac{l_1p_2-f_1l_2}{p_1p_2-f_1^2};\quad \tilde{a}^c_{(R+1)/2}=\frac{l_2p_1-f_1l_1}{p_1p_2-f_1^2};$$
$$\tilde{a}_r^s=\frac{l_3p_4-f_2l_4}{p_3p_4-f_2^2};\quad \tilde{a}^s_{(R+1)/2}=\frac{l_4p_3-f_2l_3}{p_3p_4-f_2^2},$$

where $l_1 = \sum_{s=0}^{S} U_c V_c$; $l_2 = \sum_{s=0}^{S} U_c W_c$; $l_3 = \sum_{s=0}^{S} U_s V_s$; $l_4 = \sum_{s=0}^{S} U_s W_s$; $p_1 = \sum_{s=0}^{S} V_c^2$; $p_2 = \sum_{s=0}^{S} W_c^2$; $p_3 = \sum_{s=0}^{S} V_s^2$; $p_4 = \sum_{s=0}^{S} W_s^2$; $f_1 = \sum_{s=0}^{S} V_c W_c$; $f_2 = \sum_{s=0}^{S} V_s W_s$.

With the above estimates taken into account, the modified function of residuals takes the form

$$F_{m_r} = \frac{l_1^2 p_2 + l_2^2 p_1 - 2 f_1 l_1 l_2}{p_1 p_2 - f_1^2} + \frac{l_3^2 p_4 + l_4^2 p_3 - 2 f_2 l_3 l_4}{p_3 p_4 - f_2^2}.$$

The estimate $\tilde{N}_r$ sought can be found by searching (with a given increment) through its possible values until the function F_{m_r} reaches its maximum maximorum. Having defined the $\tilde{N}_r$ values and substituting them in (6), we calculate the differences between wave paths $\tilde{A}_r$ for each channel of the array. Then, with the use of (2), we find the exact range to the alignment signal source located in the near zone of the antenna system. Acting in the same manner, we can calculate the estimates $\tilde{N}_r$ for the pairwise combinations of the channels of an antenna array with an even number of elements.

In conclusion we have to note that the approach suggested can be extended to the case of measurement of velocity and angular coordinates of point sources of pulse echo-signals in radar systems with DAA, where this method can be regarded as an alternative to traditional methods of measurement.

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