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An adaptive algorithm for interference suppression in phased antenna arrays*

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Abstract. This paper describes an algorithm designed for adapting a phased antenna array to an interference environment. Based on this algorithm, the authors have proposed a design of an adaptive beamformer.

1. Introduction

Phased antenna arrays are becoming an essential part of many modern electronic devices. Despite their complicated design and relatively bulky appearance, phased antenna arrays have one major advantage over simple antennas – it is possible to control the shape of their radiation pattern.

Typically, radiation patterns are controlled in two situations: the forming of minimums in direction to the source of interference and maximums in direction of the source or sources of the desired signal; this includes shifting signals. If a phased antenna array is used in the design of command and measurement systems of ground control facilities for spacecraft, both of these situations are considered.

Phased antenna arrays significantly improve such technical and economical performance factors of command and measurement systems of ground control facilities for spacecraft as:

- increasing the number of spacecraft which are tracked simultaneously from the ground;
- providing protection from all types of electronic interference using adaptive spatial filtering algorithms;
- improving the operation efficiency of data exchange from the satellite and the performance of the technological operations; reducing the time interval for performing a technological control cycle;
- improving the reliability of the measurement systems of ground control facilities by excluding mechanical elements from the actuator of the antenna system.

It is considered that among the more perspective methods for suppressing interference are

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adaptive spatial filtering algorithms [1]; such algorithms are used in phased antenna arrays. Theoretical issues behind the design and application of phased antenna arrays have been widely discussed in both Russian and international publications. However the application of phased antenna arrays in measurement systems of ground control facilities for spacecraft has a number of features, which require further investigation. These features include a low level of the desired signal, a requirement for receiving desires signals from different directions, and the high speed of the satellite.

In [2] it had been demonstrated that when the weighted vector of the phased antenna array is calculated, the choice of the criterion for determining the efficiency does not matter. It is more important to select an appropriate control algorithm for adjusting the radiation pattern of the phased antenna array; this algorithm directly influences the speed of the transition process and the complexity of the whole system. In [3, 4] an adaptive phased antenna array with initial uniform amplitude distribution has been described; the efficiency of its adaptive algorithm has been determined using a basis in the form of a partial exponential Fourier row in comparison to an optimal algorithm. In this paper we shall perform a synthesis of an adaptive algorithm for an 8-element circular phased antenna array.

2. A synthesis of an adaptive algorithm for an 8-element circular phased antenna array

The received signal generally follows the vector function, which considers its specification in time and space. If a signal is extracted during interference, the differences between them are used. From a mathematical point of view, it is convenient to consider these differences by means of the dependence of signals from interference and other spatial or time-frequency factors. Thus, the input oscillation shall be

$$y(t) = x(t, \alpha, \beta) + n(t, \nu), \tag{1}$$

where $x(t, \alpha, \beta)$ is the vector of the input desired signal, having parameters α and β; α is the vector of the informative signal parameters (phase, delay, Doppler shift, etc.); β is the vector of noninformative parameters, produced by signal fluctuations; $n(t, \nu)$ is the vector of interference-induced oscillation; ν is the vector of the interference parameters.

In terms of the interference, let us suppose that it is a vectorial accidental stationary process. The normal law of distributing interference-induced oscillation is physically justified in the majority of cases since the interference signal becomes normal in the relatively narrowband frequency paths of the receivers.

The phase of the input signal in each antenna element of the array is determined by the coordinates of this element, the direction of the source of the signals and interference, and the angle of the beam.

In order to determine the vector of the amplitude and phase distribution of the signal, it is necessary to know the direction, from which the signal arrives, the coordinates of the antenna elements and their radiation pattern.

The direction from which the signal arrives can be described by a single vector from a selected antenna element or phased center of the array to the signal source [5]

$$L(\psi,\gamma)= (\cos(\psi)\cos(\psi); \sin(\psi)\cos(\gamma); \sin(\psi))^{\mathrm{T}}, \tag{2}$$

where ψ is the azimuth to the signal source (navigation satellite); γ is the angular altitude to the signal source.

The structure of the phased antenna array is dictated by matrix A in which the k-th column contains orthogonal coordinates, y, z i-th antenna element with respect to the phase center of the array, which matches the circumference center of radius R; the antenna elements are situated on this circumference.

$$\mathbf{A} = R \cdot \begin{vmatrix} 0 & \frac{\sqrt{2}}{2} & 1 & \frac{\sqrt{2}}{2} & 0 & -\frac{\sqrt{2}}{2} & -1 & -\frac{\sqrt{2}}{2} \\ 1 & \frac{\sqrt{2}}{2} & 0 & -\frac{\sqrt{2}}{2} & -1 & -\frac{\sqrt{2}}{2} & 0 & \frac{\sqrt{2}}{2} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}, \quad (3)$$

Let us suppose that the elements of the phased antenna array are omnidirectional and their positioning is shown in Fig. 1.

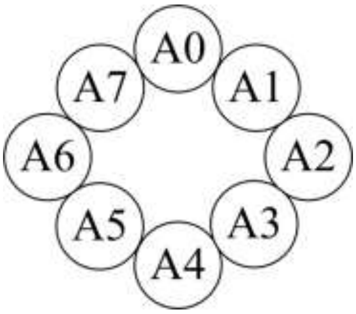

Figure 1. The position of antenna elements on the array.

The vector from the phase center of the array (its coordinates, in our case, are $(0\ 0\ 0)^{T}$) to the k-th element can be obtained as a difference between the coordinates of the circumference center and the array elements. In this case, this is, simply, the k-th column of matrix **A**, i.e. $\mathbf{A}^{<k>}$

Thus, the amplitude and phase distribution vector to the array elements, setting the direction of the beam to the i-th signal source, can be determined by

$$\mathbf{H}(\psi,\gamma) = \left(F_1(\psi,\gamma)\cdot\exp\left\{-2\pi j\cdot(R\mathbf{A}^{<1>}, L(\psi,\gamma))\right\}\ldots F_8(\psi,\gamma)\cdot\exp\left\{-2\pi j\cdot(R\mathbf{A}^{<8>}, L(\psi,\gamma))\right\}\right), \quad (4)$$

where $F_1(\psi,\gamma)$ is the amplitude and phase radiation pattern of the k-th array element; $(R\mathbf{A}^{<1>}, L(\psi,\gamma))$ is the scalar (dot) product.

The total output signal from all the antenna elements of the phased antenna array can be determined by

$$\dot{\mathbf{Y}}_{\Sigma}(t) = \dot{\mathbf{Y}}^{T}\left[\dot{\mathbf{\Phi}}^{-1}\dot{\mathbf{X}}(\alpha)\right] = \dot{\mathbf{Y}}^{T}(t)\dot{\mathbf{R}}(\alpha), \quad (5)$$

where $\dot{\mathbf{Y}}_{\Sigma}(t)$ is the output signal of the adaptive antenna array; $\dot{\mathbf{Y}}^{T}$ is the vector of the input signal of the array; $\dot{\mathbf{\Phi}}^{-1}$ is the inverse correlation of the interference matrix; $\dot{\mathbf{R}}(\alpha)$ is the vector of weighted coefficients.

The algorithm of spatial processing (5) is typically modified. This is done considering the requirements of a more convenient arrangement of the spatial processing unit. The modification of the algorithm is reduced to the multiplication of column vector of the received $\dot{\mathbf{Y}}(t)$ and expected $\dot{\mathbf{X}}(\alpha)$ oscillations by a transformation matrix **A** [6]. The transformation of the column vector can be determined using

$$\dot{\mathbf{Y}}_{tr}(t)=\dot{\mathbf{A}}\dot{\mathbf{Y}}(t),\quad \dot{\mathbf{X}}_{tr}(\alpha)=\dot{\mathbf{A}}\dot{\mathbf{X}}(\alpha). \tag{6}$$

Accordingly, the correlation matrix $\dot{\mathbf{\Phi}}$ and its opposite $\dot{\mathbf{\Phi}}^{-1}$ are modified, as is the weighted column vector $\dot{\mathbf{R}}(\alpha)$. Their modified values with considerations for (6) shall be equal to

$$\begin{gathered}\dot{\mathbf{\Phi}}_{tr}=M_{\Pi}\left[\frac{\dot{\mathbf{Y}}_{tr}(t)\dot{\mathbf{Y}}_{tr}^{*T}(t)}{2}\right]=\dot{\mathbf{A}}\dot{\mathbf{\Phi}}\dot{\mathbf{A}}^{*T},\\ \dot{\mathbf{\Phi}}_{tr}^{-1}=(\dot{\mathbf{A}}\dot{\mathbf{\Phi}}\dot{\mathbf{A}}^{*T})^{-1},\quad \dot{\mathbf{R}}_{tr}(\alpha)=\dot{\mathbf{\Phi}}_{tr}^{-1}\dot{\mathbf{X}}_{tr}(\alpha).\end{gathered} \tag{7}$$

Furthermore, the structure of modifying the spatial processing algorithm is identical to the modified algorithm

$$\dot{\mathbf{Y}}_{\Sigma tr}(t)=\dot{\mathbf{Y}}_{tr}^{T}(t)\dot{\mathbf{R}}_{tr}(\alpha)=\dot{\mathbf{Y}}_{tr}(t)\,. \tag{8}$$

When comparing algorithms (5) and (8) it is easy to become assured in their total equivalence if the transformation matrix **A** has an opposite $\dot{\mathbf{A}}^{-1}$. Actually, if in (8) we replace values $\dot{\mathbf{Y}}_{tr}(t)$ and $\dot{\mathbf{R}}_{tr}(\alpha)$ from (6) and (7), we shall get

$$\dot{\mathbf{Y}}_{tr}(t)=\dot{\mathbf{A}}^{T}(\dot{\mathbf{A}}^{T})^{-1}(\dot{\mathbf{\Phi}}^{-1})^{*}(\dot{\mathbf{A}}^{*})^{-1}\mathbf{A}^{*}\dot{\mathbf{X}}(\alpha)=\dot{\mathbf{Y}}(t)\dot{\mathbf{R}}^{*}(\alpha)=\dot{\mathbf{Y}}_{\Sigma}(t)\,. \tag{9}$$

Matrix $\dot{\mathbf{A}}$ is used for building schemes with a main and (M – 1) compensating receiving channels, having near-omnidirectional features. The choice of the transformation matrix is determined by the decoupling of the primary and compensating channels via the desired signal. Here is one of the variants of such a matrix:

$$\dot{\mathbf{A}} = \begin{Vmatrix} \dot{\mathbf{X}}_1^*(\alpha) & \dot{\mathbf{X}}_2^*(\alpha) & \dot{\mathbf{X}}_3^*(\alpha) & \cdots & \dot{\mathbf{X}}_{m-1}^*(\alpha) & \dot{\mathbf{X}}_m^*(\alpha) \\ -\dot{\mathbf{X}}_1^*(\alpha) & \dot{\mathbf{X}}_2^*(\alpha) & 0 & \cdots & 0 & 0 \\ 0 & -\dot{\mathbf{X}}_2^*(\alpha) & \dot{\mathbf{X}}_3^*(\alpha) & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & -\dot{\mathbf{X}}_{m-1}^*(\alpha) & \dot{\mathbf{X}}_m^*(\alpha) \end{Vmatrix}. \quad (10)$$

The modified column vector $\dot{\mathbf{Y}}_{tr}(t) = \left\| \dot{\mathbf{Y}}_{tri}(t) \right\|$ of the received oscillation $\dot{\mathbf{Y}}(t)$ includes the strength of the primary channel

$$\dot{\mathbf{Y}}_{tr1}(t) = \sum_{i=1}^{M} \dot{\mathbf{Y}}_i(t) \dot{\mathbf{X}}_i^*(\alpha). \quad (11)$$

and the strength of the compensating channels

$$\dot{\mathbf{Y}}_{trki}(t) = -\dot{\mathbf{Y}}_i(t)\dot{\mathbf{X}}_i^*(\alpha) + \dot{\mathbf{Y}}_{i+1}(t)\dot{\mathbf{X}}_{i+1}^*(\alpha). \quad (12)$$

The anticipated oscillation $\dot{\mathbf{X}}(\alpha)$ are modified to

$$\dot{\mathbf{X}}_{tr}(\alpha) = \dot{\mathbf{A}}\dot{\mathbf{X}}(\alpha) = \begin{Vmatrix} M & 0 & 0 & \cdots & 0 \end{Vmatrix}^T. \quad (13)$$

where $M = \sum_{i=1}^{M} \dot{\mathbf{X}}_i^*(\alpha)\dot{\mathbf{X}}_i(\alpha)$.

The zero value of the elements of the column vector $\dot{\mathbf{X}}_{tr}(\alpha)$, starting from the second, confirm a decoupling of the primary and compensating channels via the desired signal. The latter is an instrument for forming compensating channels using difference schemes. Due to this, a null is formed in the combined characteristics of the directivity of the compensating channels. The angular position of the null corresponds with the anticipated input of the desired signal α.

The formula for modifying the weighted vector column of spatial processing $\dot{\mathbf{R}}_{tr}(\alpha)$ can be found using the matrix equation

$$\dot{\mathbf{\Phi}}_{tr}\dot{\mathbf{R}}_{tr}(\alpha) = \dot{\mathbf{X}}_{tr}(\alpha). \quad (14)$$

It is conveniently solved by writing $\dot{\mathbf{\Phi}}_{tr}$ and the vector column $\dot{\mathbf{R}}_{tr}(\alpha)$ as blocks

$$\dot{\mathbf{\Phi}}_{tr} = \begin{Vmatrix} \dot{\mathbf{\Phi}}_{tr11} & \dot{\mathbf{\Phi}}_{tr}^{*T} \\ \dot{\mathbf{\Phi}}_{tr1} & \dot{\mathbf{\Phi}}_{tr\kappa} \end{Vmatrix} \qquad \dot{\mathbf{R}}_{tr}(\alpha) = \begin{Vmatrix} \dot{\mathbf{R}}_1 & \dot{\mathbf{R}}_2 \end{Vmatrix}^T, \quad (15)$$

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where $\mathbf{\Phi}_{tr11}$ is the total dispersion of interference and noise at the output of the primary receiving channel

$$\dot{\mathbf{\Phi}}_{tr11} = M_{\Pi}\left[\frac{\dot{\mathbf{Y}}_{tr1}(t)\dot{\mathbf{Y}}^{*}_{tr1}(t)}{2}\right]; \tag{16}$$

$\dot{\mathbf{\Phi}}_{tr1}$ is the vector column of bilateral correlation moments of the interference voltage in the compensating and primary channels

$$\dot{\mathbf{\Phi}}_{tr1} = M_{\Pi}\left[\frac{\dot{\mathbf{Y}}_{trk}(t)\dot{\mathbf{Y}}^{*}_{tr1}(t)}{2}\right], \quad k = \overline{2M}\ ; \tag{17}$$

$\dot{\mathbf{\Phi}}_{tr\kappa}$ is the correlation matrix of the interference of the compensating channels

$$\dot{\mathbf{\Phi}}_{trk} = M_{\Pi}\left[\frac{\dot{\mathbf{Y}}_{trk}(t)\dot{\mathbf{Y}}^{*T}_{trk}(t)}{2}\right]; \tag{18}$$

$\dot{\mathbf{R}}_1$ and $\dot{\mathbf{R}}_2$ are elements of the weighted vector of the primary channel and the column vector of the weighted coefficients of the compensating channels.

Substituting (15–18) in the matrix equation (14), we deduce a system of two equations

$$\begin{cases} \dot{\mathbf{\Phi}}_{tr11}\dot{\mathbf{R}}_1 + \dot{\mathbf{\Phi}}^{*T}_{tr1}\dot{\mathbf{R}}_2 = M \\ \dot{\mathbf{\Phi}}_{tr1}\dot{\mathbf{R}}_1 + \dot{\mathbf{\Phi}}_{trk}\dot{\mathbf{R}}_2 = 0 \end{cases}, \tag{19}$$

Solving this system in relation to $\dot{\mathbf{R}}_1$ and $\dot{\mathbf{R}}_2$, we shall determine

$$\begin{cases} \dot{\mathbf{R}}_1 = \dfrac{M}{(\dot{\mathbf{\Phi}}_{tr11} - \dot{\mathbf{\Phi}}^{*T}_{tr1}\dot{\mathbf{\Phi}}^{-1}_{trk}\dot{\mathbf{\Phi}}_{tr1})}, \\ \dot{\mathbf{R}}_2 = -\dot{\mathbf{\Phi}}^{-1}_{trk}\dot{\mathbf{\Phi}}_{tr1}\dot{\mathbf{R}}_1 \end{cases} \tag{20}$$

It can be seen from (20) that the first element of the weighted vector is real value and serves as a normalization factor. This factor may be set to one without the loss of performance in detection, passing on to the normalized weighted vector $\dfrac{\dot{\mathbf{R}}_{tr}(\alpha)}{\dot{\mathbf{R}}_1}$. According to (20) the latter shall be equal to

$$\dot{\mathbf{R}}_{\Delta}=\frac{\dot{\mathbf{R}}_2}{\mathbf{R}_1}=-\dot{\mathbf{\Phi}}_{trk}^{-1}\mathbf{\Phi}_{tr1}, \tag{21}$$

The output voltage of the processing unit, having a designated primary channel, is determined by

$$\dot{\mathbf{Y}}_{\Sigma}=\dot{\mathbf{Y}}_{tr1}(t)+\dot{\mathbf{Y}}_{trk}^{*T}(t)\dot{\mathbf{R}}_{\Delta}^{*}, \tag{22}$$

The interference-compensating unit for interference received by the side lobes of a radiation pattern is built in accordance with the synthesized algorithm (Fig. 2).

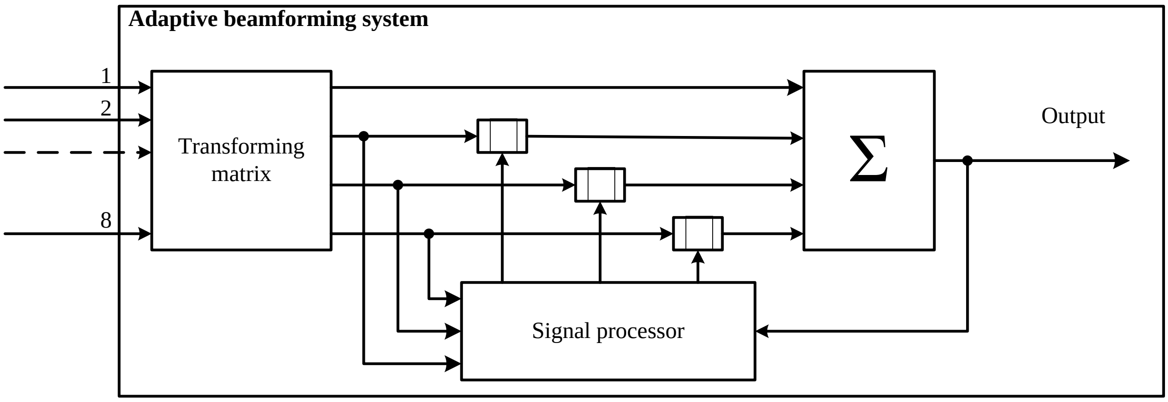

Figure 2. An adaptive beamforming system of a phased antenna array.

The analog section of the adaptive phased antenna array consists of 8 antenna modules with 8 connected radio signal paths. The signals from the radio signal paths are received by the analog-to-digital converter, after which they are transmitted to the digital unit, which consists of a beamforming arrangement and a digital signal processing channel. The beamforming arrangement is a weighted summer of signals, transmitted from 8 analog paths. The weighted coefficients are calculated by a signal processor in accordance with the desired radiation pattern. Particularly, in a high precision measuring mode, the weighted coefficients are selected so as to be capable of compensating the difference between the pass of the desired signal between antennas, i.e. the desired signals, transmitted to the summer, have one phase. This mode of the adaptive phased antenna array has been inquired in [7].

3. Conclusion

In conclusion it should be said that we have synthesized an interference-suppressing algorithm for an 8-element phased antenna array; this algorithm enables us to implement a close to optimal output effect of the adaptive unit. The formation of maximums in the radiation pattern in the direction of the signal source increases the signal-to-noise ratio, which, in its turn, improves interference immunity; the general increase in sensitivity aids receiving signals from satellites in difficult conditions.

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References

[1] Radioelektronnie sistemy: osnovy postroeniia i teoriia [Radio-electronic systems: the fundamentals of design and theory (in Russ.)] 2007 Ia.D. Shirman (ed.) Moscow: Radiotekhnika.

[2] Tyapkin V N, Dmitriev D D, Fateev Y I, Kremez N S 2016 The synthesis algorithm for spatial filtering to maintain a constant level of the useful signal, *Journal of Siberian Federal University. Mathematics & Physics* **9(2)** pp 258–268.

[3] Kartsan I N, Tyapkin V N, Dmitriev D D, Goncharov A E, Zelenkov P V, Kovalev I V 2016 Synthesis of an algorithm for interference immunity *IOP Conference Series: Materials Science and Engineering* **155**

[4] Tyapkin V N, Kartsan I N, Dmitriev D D, Goncharov A E 2015 Spatial filtering algorithms in adaptive multi-beam hybrid reflector antennas, *International Siberian Conference on Control and Communications (SIBCON) – proceedings*

[5] GLONASS. Printsipy postroeniia i funktsionirovaniia [GLONASS: arrangement and functioning principles (in Russ.)] 2010, A I Perov, V N Kharisov (eds.), Moscow: Radiotekhnika

[6] Almazov V B, Manzhos V N 1985 Poluchenie i obrabotka radiolokatsionnoi informatsii [Receiving and processing radar data (in Russ.)] Kharkov

[7] Sharfunova T G, Tyapkin V N, Dmitriev D D 2013 Tochnost’ izmereniia navagatsionnykh priborov v navigatsionnoi apparature potrebitelei sputnikovoi radionavigatsionnoi sistemy “GLONASS”, osnashchennoi antennoi reshetkoi [The accuracy of navigation parameters measurements in GLONASS systems with an antenna array] *Radiotekhnika* **6** pp 22–25