On the efficiency of defocusing a large satellite multi-beam hybrid parabolic antenna

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Abstract. The article is devoted to the evaluation of the desirability of defocusing a large-sized multi-beam hybrid parabolic antenna (MBHPA). Defocusing means displacement of the antenna array (AA) from the focus, in the interests of rarefaction of the AA. Calculation of the MBHPA characteristics was carried out using a no strict but high-speed simulation program, the consistency of which was confirmed by comparison with the data of other authors. The results of our multivariate calculations with two strategies for the formation of feed clusters show that the idea of defocusing, which is tempting at first glance, does not benefit in the gain factor of the beams in comparison with un-displaced AA with the same spacing of the array elements. Therefore, in this capacity, defocusing is not effective.

1. Introduction

Large-scale MBHPA is widely used in satellite communication systems in a geostationary orbit. The very strict requirements are imposed on stability of the antenna radiation patterns (ARP) and gain factors of their beams. During operation, the antenna reflector is subject to a number of factors (primarily uneven heat flow), resulting in deformations of the reflector. Therefore, it is not surprising that there are many publications, for example, [1-9], devoted to the problem of stabilizing the characteristics of satellite antennas against deformation of the reflector caused by external conditions. Increasing the energy and throughput requirements of the corresponding telecommunication systems leads to the need to use the MBHPA with a large and increasing number of beams. Accordingly, the number of antenna feeds and processing channels increases, the structure becomes more complicated and its cost increases.

In this connection, technical solutions aimed at minimizing the number of AA elements. In [10], the authors consider the displacement of the AA plane from the focal plane, called defocusing of the reflector, as a means of increasing the stability of the MBHPA characteristics in the conditions of failures of individual channels. The idea is clear: when AA is displaced from the focal plane, focal spots expand and, consequently, the region of intensely excited elements of AA participating in the formation of a particular beam expands. Therefore, the role of each individual antenna element is reduced and its failure to a lesser extent degrades the parameters of the antenna. At first glance, the expansion of the focal spot can be useful in another way, namely, to increase the AA spacing that
leads to the rarefaction of the array and the corresponding reduction in the number of its elements. The present paper is devoted to an analysis of this possibility.

2. MBHPA and the modeling program

Figure 1 shows the geometry of the MBHPA and the coordinate systems used. The beams are formed by the reflector of offset geometry with focal length $F = 7.4 \text{m}$, diameter $\varnothing = 12 \text{m}$ and clearance $H = 3 \text{m}$. Operating frequency is $2 \text{GHz}$. The antenna array is within a rectangle of $2 \text{m}$ by $1 \text{m}$ and is nominally formed by feeds located at the nodes of a grid having a honeycomb structure with a hexagon’s side of $100 \text{mm}$. Its center is aligned with the focus $F$ of the reflector, and its plane is deviated from the normal to the optical axis of the reflector by an angle of $62^\circ$.

In figure 1, we present the global coordinate system $\{x, y, z\}$, in which the surface of the mirror is recorded; $\{\xi, \eta\}$ – the coordinate system for the antenna array centered in the focus $F$; and, finally, the local coordinate system $\{x', y', z'\}$ of the observation region for ARP $\mathcal{F}(\theta, \phi)$, whose axes are oriented relative to the mirror in such a way that the plane $x'y'$ is the plane of the azimuth angle $\phi$, and the angle $\theta$ measured not from the polar axis $0z'$, but from the plane $x'y'$, is the elevation angle.

Within the MBHPA service area, the solid angle of which takes units of degrees at both angles, it is not necessary to go over to the generalized angular coordinates $u = \cos \theta \sin \phi$ and $v = \cos \theta \cos \phi$, which is traditionally used in the calculations of the radiation pattern of a plane aperture. Within the region of interest, the angular grid $\{\theta = \text{const}, \phi = \text{const}\}$ forms an almost rectangular grid, which facilitates the image of the amplitude relief of ARP $|\mathcal{F}(\theta, \phi)|$.
irradiating field are practically tangent to the surface of the reflector. Finally, it is sufficient to study the ARP within a small solid angle around the optical axis of the mirror.

The combination of these factors allows us to use the "acoustic" approximation, which reduces the computation time by hundreds of times and includes the following.

The reflector is represented by a sufficient number of points \( \{x_p, y_p, z_p = (x_p^2+y_p^2)/4F\} \), which emit spherical waves induced by a plane wave incident from the direction \( \{\theta_0, \phi_0\} \) or by a cluster of sources with excitation distribution \( \{W_n\} \). This leads to the following very close expressions, respectively, for focal spots \( \{S(\xi_n, \eta_n)\} \) (more precisely, signals receiving by the AA) or for ARP \( F(\theta, \phi) \) forming by the cluster:

\[
S(\xi_n, \eta_n) = \sum_p \exp(k \Delta r_p(\theta_0, \phi_0)) f_0(\psi_{n,p}) \exp(k \rho_{n,p}) / \rho_{n,p}
\]

\[
F(\theta, \phi) = \sum_p \exp(k \Delta r_p(\theta, \phi)) \left[ \sum_n W_n f_0(\psi_{n,p}) \exp(k \rho_{n,p}) / \rho_{n,p} \right]
\]

Here, \( p \) and \( n \) are the indexes of the reflector points and antenna sources, respectively; \( \{W_n\} \) are the complex excitation amplitudes of the cluster; \( \Delta r_p(\theta_0, \phi_0) = \sin \theta_0 (x_p \cos \phi_0 + y_p \sin \phi_0) + z_p \cos \theta_0 \) is the path difference to the observation point \( (\theta_0, \phi_0) \); \( \rho_{n,p} \) is a distance between the \( p \)-th reflector point and \( n \)-th point of AA: \( \rho_{n,p} = \sqrt{(\xi_n \sin \beta_0 - y_p)^2 + (\eta_n - x_p)^2 + (F + \xi_n \cos \beta_0 - z_p)^2} \) where \( \beta_0 \) is the angle of inclination of the antenna plane to the optical axis \( \theta_0 \) of the reflector. Projections \( \{x_p, y_p\} \) of the reflector points are distributed evenly within the circle of radius \( R \) as shown in Figure 1(b). The radiation pattern \( f_0(\psi) \) of the feeds was taken as \( \cos^{1/2} \psi \) of the angle \( \psi \) between the normal to the antenna array and the radius vector to the reflector point, i.e.

\[
f_0(\psi_{n,p}) = \sqrt{(\xi_n \sin \beta_0 - x_p \cos \beta_0 + (F + \xi_n \cos \beta_0 - z_p) \sin \beta_0) / \rho_{n,p}}
\]

To validate the program, the results of calculations were compared with the data given in [10]. Figure 2 shows the ARP of the MBHPA the geometry described above. The beams, similarly to [10], are formed by single elements arranged with spacing of 100mm along the longitudinal axis \( \xi \) of the AA: (a) without displacement from the focal plane; (b) when the AA is displaced along its normal onto the wavelength \( (\lambda = 150\text{mm}) \) towards the reflector. The colors of the curves, for the sake of clarity, alternate cyclically: black, gray, light gray.

![Figure 2. MBHPA beams: in modeling without (a) and with (b) displacement towards the reflector; presented in [10] without (c) and with (d) displacement towards the reflector.](image_url)
Figure 2 (c) and (d) reproduces the graphs from [10, figure 2] for MBHPA of the following geometry: focal length 10m, reflector diameter 15m, clearence 5.5m, angle of AA inclination to the optical axis 66°, operating frequency 1.25 GHz, grid space equal to wavelength. Comparison of the curves shown in Figure 2 confirms the correctness of our modeling program, since the main regularities coincide: the shape of the beams, their alteration caused by the defocusing of the reflector. There could not be a complete coincidence, because although the optical scheme in the compared MBHPA are similar, but the frequencies, reflector sizes and AA differ.

3. Reflector defocus effects
Since our interest in defocusing is related to the hope of forming the required set of beams with a reduced number of AA elements, the simulation was limited to a sparse AA with a cell side of 125 mm (instead of a "nominal" cell size of 100 mm). Due to this, with the AA boundary of 2m per 1m, the total number $N$ of AA elements is reduced to $N = 153$ against the "nominal" their number $N = 231$.

Two variants of the geometry of clusters were compared: a fixed seven-element hexagonal structure and structures adapted to the configuration of focal spots for the corresponding beams. In the first variant, the cluster forming the certain beam is determined as follows. The intensity of signals receiving by AA elements if MBHPA is irradiated from the direction of the corresponding beam, is analyzed and the position of the element with the maximum signal is taken as the center of the corresponding cluster. Then the central element is completed by six elements of the hexagonal surroundings. The weight coefficients of the cluster are set proportional to the complex conjugate values of the received signals. This ensures the formation of the maximum of the beam in the desired direction.

The dependences of the gain factor for a set of beams that are oriented in the elevation plane in the range $-3.5^\circ < \theta < 3.5^\circ$ with a discrete of $d\theta = 0.7^\circ$ are shown in Figure 3: (a) azimuth $\phi = 0^\circ$ (middle of the working zone) and (b) the azimuth $\phi = 1.8^\circ$ (the periphery of the working zone). The parameter of the curves is the value $dn$ of the reflector displacement in the range from 0m to 1.5m in increments of 0.25m. A bold line indicates the situation without defocusing ($dn = 0$), when the center of the AA locates in the focus of the reflector.

![Figure 3](image-url)

**Figure 3.** Gain of beams formed by clusters of 7 elements: (a) azimuth $\phi = 0^\circ$, (b) azimuth $\phi = 1.8^\circ$.

As follows from the data presented, when using clusters of a fixed hexagonal structure, defocusing results in a decrease in the beams' gain.

The second way of forming clusters involves arranging clusters taking into account the relief of focal spots from the corresponding directions. The logic of the adaptive composing the cluster structure is as follows. The intensity of the signals on the elements of AA is analyzing. The element having the maximal intensity is selected as the first element of the cluster and is supplemented by
those elements whose signal intensity exceeds the threshold level $U_0 = -13$ dB relative to the maximum. Figure 4, in a similar manner to Figure 3, shows the gain factor dependencies for the beams formed by adaptively configured clusters at various displacements $d_n$ (the parameter of the curves). In receive mode, the gain characterizes a part of the energy from the incident wave that is captured by the cluster.

As defocusing increases, the focal spots of the corresponding beams expand. This leads to an increase in the number of elements involving in the cluster. Therefore, the gain of peripheral beams increases that result in substantial decreasing the gain alteration. Accordingly, the limits of the ordinate axis in Figure 4 are narrowed in comparison with Figure 3.

4. Conclusion
The simulation results suggest that the displacement of the antenna array from the focal plane is hardly useful in a practical sense.

First, with any strategy of forming clusters, defocusing does not lead to a noticeable gain in comparison with the arrangement of the antenna array in the focal plane.

Secondly, it is clear that reducing the gain of the beams due to the rarefaction of the antenna array can be compensated by changing the elements intended for the 100mm cell by elements adapted to the increased size of cells. However, the relative changes in gain of beams when the plane of the antenna array is shifted do not depend on the factor noted above.

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