Research of influence a physical carrier on the characteristics for four-element circular antenna array

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Abstract. The main problem arising in the development of mobile-based antenna arrays is the problem of taking into account the influence of the carrier body on the characteristics of such an antenna array. Pilotless vehicle are one of the most popular directions of modern aviation development. It is aimed to consider a quite simple in design four-element annular antenna array and to analyze the influence on the bearing direction finding characteristics of such a mobile carrier which is a pilotless vehicle. Theoretical consideration of the carrier body effect on the bearing direction finding errors is usually reduced to the problem of electromagnetic waves diffraction on conducting objects. Comparison of some absolute bearing direction finding errors obtained by the phase correlation method for the cases of placing the antenna array in free space and on the array carrier is given. The results of the calculation of the root-mean-square values dependence on the frequency, averaged over all the analyzed angles of the radio wave direction of arrival, are presented. The dependences of the root-mean-square value on the azimuth angle of the radio wave direction of arrival for the cases of the antenna array placement on the carrier body and in the free space averaged for all the analyzed signal frequencies were calculated.

1. Introduction
In mobile panoramic-direction finding systems, the antenna system is located on the carrier body [1]. In this case, as a result of secondary radiation when the radio waves are reflected from the carrier parts, the pattern of the antenna system is distorted [2]. This phenomenon, called radio deviation, leads to an increase in the direction finding error, which may in some cases exceed 20°-30° [3]. Theoretical consideration of the effect of the carrier body on errors in direction finding usually reduces to the problem of diffraction of electromagnetic waves on conducting objects [4].

The developers of vibrator antenna arrays used to solve the problems of radio monitoring and radio direction finding often use the apparatus of the Hallen integral equations [5] or the integro-differential Pocklington equations [6]. Such an approach allows us to estimate with a high degree of accuracy the systematic component of the direction finding error when performing numerical analysis, but it requires solving a system of equations with complex unknowns of a rather high order (up to several hundred for each discrete value of the azimuth angle of the radio emission source).
2. Materials and methods
As discussed earlier, the theoretical account of the effect of the carrier body on the errors of direction finding can be reduced to a simpler method – to the problem of diffraction of electromagnetic waves on conducting objects [4]. The main planes of the section of the cylinder (the principal curvature planes, Figure 1) can be chosen on the basis that the vector $\mathbf{U}_1$ is tangential to the cylinder in the XY plane, and the vector $\mathbf{U}_2$ is directed along the Z axis of the cylinder. The radius of curvature in the XY plane for an elliptical cylinder can be defined as:

$$a_1 = \left(\frac{a_2^2 \cos^2 \nu + a_1^2 \sin^2 \nu}{a_1 \cdot a_2}\right)^\frac{3}{2}.$$  

(1)

**Figure 1.** Radius of curvature in the main planes (planes of symmetry).

The plane of incidence can be defined as a plane containing the unit vectors $(\mathbf{s}', \mathbf{n})$. In the general case, the radius of curvature in the plane at an $\alpha$ angle from the basic surface axes is given by Euler’s theorem as:

$$\frac{1}{a_1} = \frac{\sin^2 \alpha}{a_1} + \frac{\cos^2 \alpha}{a_2}.$$  

(2)

For $a_1$ cylinder, equation (1) corresponds, for now $a_2 = \infty$. The angle $\alpha$ is calculated as:

$$t1 = -\mathbf{s}' \cdot \mathbf{U}_1,$$

$$t2 = -\mathbf{s}' \cdot \mathbf{U}_2,$$

$$\alpha = \tan^{-1}\left(\frac{t1}{t2}\right).$$  

(3)

Finding the length of the geodetic path (trajectory) can be produced as finding the distance along the surface of the cylinder from the elliptical angle $\nu1$ to $\nu2$ in the given direction. The arclength is calculated as:
where $\theta$ – the angle of elevation of the path traversed within $v_1$ and $v_2$.

In Figure 2 the appearance of the investigated carrier model and direction-finding antenna array is given. All elements of the model, except the protective covers of the screws and the screws themselves, are perfectly conductive. Rings of protective casings are made of material with $\varepsilon = 2.5$. Screws, which can also be made of plastic, are not shown, it is believed that their rotation averages the observed picture. Other design variants of pilotless vehicle are also possible [7].

![Figure 2. 4-element antenna array and carrier.](image)

3. Results and discussion

3.1. Analysis of absolute errors

In Figure 3, the solid line shows the dependence of the absolute errors for direction finding on the signal frequency for the azimuth angle of the electromagnetic wave arrival at 0 degrees, the points for the dependence at 10 degrees, the dashed line at 20 degrees, the dashed-dotted line at 30 degrees, solid thin line at 40 degrees. Other angles of arrival of the electromagnetic wave were not analyzed because the model is quasisymmetric with a period of 45 degrees horizontally. Based on the obtained data, it can be said that at almost all frequencies for all analyzed angles, except for the lowest frequencies (approximately from 100 MHz and below) for an azimuth angle of 20 degrees, the absolute error of direction finding does not exceed 5 degrees in the absence of an antenna array carrier. Those the intrinsic error of the antenna system of this type and size is approximately 5 degrees and, without complicating the construction a smaller error, it is apparently impossible to achieve. This is a rather strange and poor result, although it corresponds to the concept given in [8] that arrays with an even number of vibrators have a greater error relative to gratings with an odd number of them. The least error from the presented is characterized by a direction of 40 degrees, the phase on two vibrators of four for these angles of incidence should theoretically almost coincide, because the front of the electromagnetic wave reaches them almost simultaneously, and for the other two (conditionally "front" and "rear") to differ as much as possible. However, no complete coincidence is observed, this can be explained by the fact that the angle of full coincidence is 45 degrees. Here, except for frequencies below 100 MHz, the errors do not exceed 2 degrees.
In Figure 4, as well as on the previous one, a solid fat line depicts the dependence of the absolute errors for direction finding on the signal frequency for the azimuth angle of the electromagnetic wave arrival at 0 degrees, the points for the dependence at 10 degrees, the dashed line at 20 degrees, the dashed-dotted line at 30 degrees, the solid line – the dependence at 40 degrees. In the presence of a carrier, the situation is quite strong and changes quite unexpectedly. Errors, as in the case of the three-element lattice [9], begin to have a negative character, although the average value practically does not shift with respect to 0, and their maximum absolute value for all analyzed angles exceeds 5 degrees. In addition, the nature of the distribution of the error in frequency and angles of incidence is changing. The maximum error except for the lowest frequencies is achieved at frequencies of the order of 1450 MHz, as in the case of free space, apparently there is a resonance of the antenna system itself. In this case, the error value exceeds -12.5 degrees for the incidence angle of the electromagnetic wave on 30 degrees. Due to the influence of the carrier, there was a change in the angle with the maximum absolute deviation and the angle at 20 degrees, leading in the previous figure, is now only the second with an error of the order at -10 degrees. The minimum error of the order at -5.5 degrees from the maximum errors for a given frequency has a arrival direction of a wave at 10 degrees closest to the metal rod with the carrier motors. There are also two significant positive deviations, at frequencies at 1050 MHz the error does not exceed 4 degrees, at frequencies of about 1650 MHz the error does not exceed 6 degrees, and a number of smaller ones at lower frequencies. At frequencies below 100 MHz, unlike the previous case, only negative deviations up to -7.5 degrees are observed for the arrival angle of the wave at 20 degrees.

Based on the results of the analysis of absolute errors for the cases of the three-element and four-element antenna arrays, we can say the following: in the presence of a carrier with metal parts elongated in the direction of possible azimuth angles of an electromagnetic wave arrival, the measured bearing "distorts" towards these metal parts.
3.2. Analysis of root-mean-square value

In Figure 5, the solid line shows the dependence of the root-mean-square value error for bearing detection on the signal frequency for the case of antenna system placement on a carrier, dashed line – for the case of free space. The graphs generally repeat the dependence for the absolute errors of direction finding at frequency: for the case of placing the antenna array on the carrier, the root-mean-square value deviation of the frequency dependence for high frequencies is much higher than for the case of placement in free space and at frequencies of the order of 1450 MHz it reaches 9.5 degrees, subsidiary maximum at frequencies around 1050 MHz (~ 3.5 degrees, duplicated for the case of free space with a maximum of less than 2 degrees) and at frequencies of 1650-1700 MHz of about 4.5 degrees. For the case of placing the antenna array in free space, the maximum does not reach 4 degrees and is somewhat shifted in frequency (about 1500 MHz). An interesting effect is that at the frequency range 100-700 MHz, the antenna array placed on the carrier body has a much smaller mean square error than the same array, but located in free space, in this range of root-mean-square value of the array with the carrier does not exceed 0.5 degrees, unlike from values of 1 degree or more for a solitary case.
In Figure 6 as well as on the previous figure – solid line shows the dependence of the root-mean-square error of direction finding from the azimuth of the signal propagation for the case where the antenna system is placed on a carrier, the dashed line for the case of free space. When averaged over the angles of wave propagation there is a discrepancy RMS highs in the case of finding the antenna array in free space, the error maximum, equal to 3 degrees, is observed for the azimuthal angle of wave arrival at 20 degrees. For the case of finding the antenna array on the carrier, the maximum root-mean-square value is shifted towards one of the array elements and/or the angle of the carrier body on which it is mounted, and is slightly less than 4.5 degrees for the angle of wave arrival at 30 degrees.

Thus, with respect to averaging over all frequencies for certain angles of wave arrival, the mean square error for the case of placing the array on a carrier body increases by 1.5 times with respect to the free space. It should also be noted that, despite significant emissions (the order of 10 degrees) at high frequencies, the standard deviation at averaging over the angles of wave arrival is not so large and not large in comparison with the array of 3 elements placed on the carrier body [9].
Let's try to reduce the root-mean-square value for the case of averaging over the angles of wave arrival, by narrowing the range of analyzed frequencies and cutting off the peak value at high frequencies. For the frequency range 50-1300 MHz (Figure 7), the corresponding dependence of the root-mean-square value is not exceeded 4.5 degrees, we get an approximate error alignment for the cases of the antenna array on the carrier and in the free space. Root-mean-square value in both cases does not exceed 2 degrees, which is quite acceptable for the direct application of the antenna array as a direction-finding device.

![Figure 7](image_url)

**Figure 7.** Dependence of the root-mean-square error for direction finding from the azimuth of the signal arrival a bandwidth at 50-1300 MHz.

Next, try to minimize the range of analyzed frequencies to 50-1000 MHz, in which the root-mean-square value definition of the bearing for the case of finding an array on a carrier is less than for the case of free space. Indeed, as can be seen from Figure 8, with averaging over a given frequency range for all the analyzed azimuthal angles of signal arrival does root-mean-square value in the case of finding the antenna on the carrier does not exceed 1 degree and approximately 2 times less than the case of free space. Regarding the dependence of the root-mean-square error of bearing detection on the frequency of the signal and applicable without additional adjustments to the frequencies bands of the antenna array on the carrier, it can be noted that the error does not exceed 1 degree in the frequency band of approximately 100-950 MHz, which is significantly smaller than the root-mean-square value for the grating in the free space. Higher frequencies, for example, around 1400-1450 MHz, are not generally applicable for direct operation, since here the root-mean-square value practically reaches 10 degrees, this can be explained by the resonant effect of the antenna array / carrier system.

Based on the results of the analysis of the dependence of the root-mean-square error of direction finding from the azimuth of the signal arrival, we can state the fact that for the case of placing a four-element antenna array on the carrier, the errors are small enough even for averaging over the whole range of analyzed frequencies. They do not exceed 5 degrees, which is somewhat less than in the case of a three-element array [9], but also does not allow the use of a four-element array directly for direction finding without further error correction. In this case, in order to use the antenna array together with the carrier, we can directly recommend a narrower bandwidth at 50-1300 MHz, the root-mean-square value in which does not exceed 2 degrees, or even bandwidth at 50-1000 MHz, the root-mean-square value within which does not exceed 1 degree, if of course such a range will satisfy other system requirements.
Figure 8. Dependence of the root-mean-square error for direction finding from the azimuth of the signal arrival a bandwidth at 50-1000 MHz.

4. Conclusion
Regarding the absolute errors for the case of the four-element antenna array being analyzed, one can say about the unusualness of their values at high frequencies relative to the case of a three-element array, most likely this is related to the design of the antenna system itself and the aggravation of the resonance in the presence of the carrier. In consequence of this, the dependence of the root-mean-square value at the frequency has a similar character with a sharp increase in errors at frequencies of the order of 1400 MHz. The root-mean-square value, depending on the azimuth of the signal arrival, varies within 2.5-4.5 degrees for the case of finding the array on the carrier during averaging over the whole analyzed frequency range, which is relatively small. By reducing the range of operating frequencies, it is possible to pick up variants with a root-mean-square value of less than 1 degree in both cases.

Within the framework of this publication, a comparison is not made between antenna array patterns for the angles being analyzed when it is in free space and on a carrier. Moreover, the errors for different vertical angles of signal arrival have not been taken into account, the effect of screw rotation and the instability of the position of the aircraft in the air has not been taken into account. It is also desirable to analyze the errors for the vertical and horizontal angles of arrival of an electromagnetic wave under all the above conditions, taking into account the noisy signal spectrum [10].

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