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Calculation of Antenna Gain via 3D Radiation Pattern and Estimation of Their Mutual Influence

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Abstract. The paper considers the task to determine the gain of the optionally beamed antenna on the set direction. It is necessary to solve the task when evaluating electromagnetic compatibility of radio engineering systems involving both receiving and transmitting segments equipped with their own antennas. The main attention is focused on the treatment and analysis of the form of the antenna radiation pattern appearing as a 3D rotation figure.

The determination of the intensity of the 3D interaction of receiving and transmitting antennas by means of simulating the radiation patterns considering their mutual orientation is one of the most important task of obtaining the degree of the influence of the transmitting segment on the reception devices of the radio engineering system.

The method given in the paper presumes a simple software realization and is slated to be applied in the special software product created for the analysis of the electromagnetic situation in radio engineering systems, as well as for evaluating electromagnetic compatibility of radioelectronic facilities.

Keywords: antenna radiation pattern, antenna gain, electromagnetic compatibility

Introduction

It is known that any equipment connected with information reception or transmission by means of electromagnetic waves is supplied with the antenna in this or that kind.

A great work has been done by engineers to achieve the required parameters from the created antennas, first of all, reducing power costs for transmission of useful electromagnetic signals in the necessary direction and also improving reception of useful signals from the directions of interest. One of such parameters is the antenna gain defined as the relation of density of a stream of the radiated energy in some direction by means of the considered antenna to the stream density which would be radiated in the same direction by the isotropic antenna (that is the imagined, ideal antenna radiating with uniform intensity in all directions). The display of antenna gains in the spherical system of coordinates where the intensity of radiation is displayed by the radial coordinate, and the direction by the azimuthal one, is called the antenna radiation pattern. Certainly, that each type of the antenna, each of its dimensions depending on the used frequencies of radiation or reception, has its specific form of the radiation pattern.

Forms of radiation patterns have various appearances. They can either possess the principal lobe and side and reversed petals (that is a characteristic of narrow-beam, for example, parabolic antennas, Fig. 1) or not possess them as, for example, radiation patterns of rod antennas (Fig. 2).

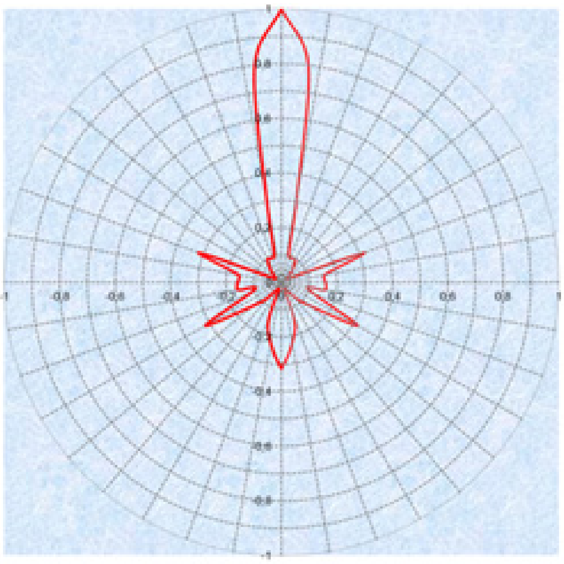

Fig. 1. Radiation pattern of a narrow-beam antenna.

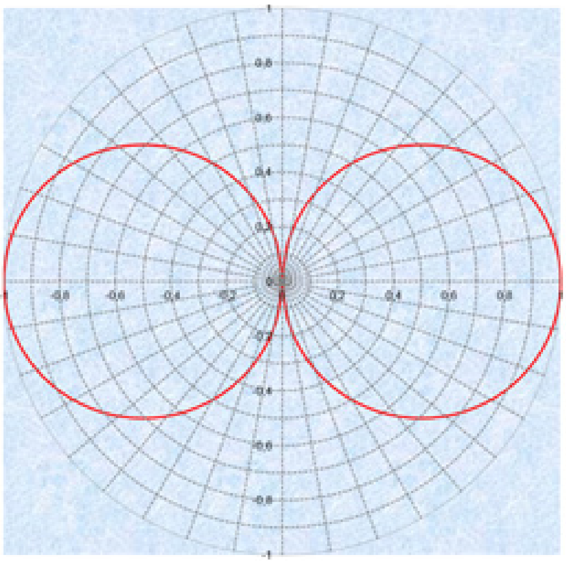

Fig. 2. Radiation pattern of a rod antenna.

When it concerns the maximum quality of signal transfer or its reception, so based on the given drawings, it is possible to understand intuitively that it is reached by orientation of the antenna so that the radial coordinate of the radiation pattern (in other words, antenna gain) was maximum in the direction of the receiver (in case of transmission) or a signal source (in case of reception).

This article offers to consider another task: **to determine the antenna gain of a known randomly directive antenna in the set direction.** The solution of such task is necessary, for instance, at the assessment of a problem of electromagnetic compatibility for the systems containing at the same time receiving and the transmitting segments equipped with their own antennas. In this case, it is meant that receiving and transmitting segments operate on the channels independent from each other. At the same time there is a need to estimate parasitic influence of the work of the transmitting segments on the reception channels. One of the components of such calculation is the assessment of mutual gain of transmitting and receiving antennas.

In the article the method of the assessment of mutual antenna gains for one pair of antennas, one of which is transmitting and another is a receiving one, will be considered. Of course, for the big system comprising several receiving and transmitting segments (for example, for a spacecraft), it will be necessary to carry out the paired analysis.

We will consider the necessary entrance data for the solution of this task:

- The coordinates of placement of transmitting and receiving antennas (the Cartesian coordinates *x, y, z* set in the random, but uniform system of coordinates for both antennas are meant).
- The rotation angles of axes of antennas: an azimuth and elevation (a zero azimuth is considered the *OX* axis and turn on an azimuth is the turn in the *XOY* plane. An elevation is the angle between an axis of the antenna and the *XOY* plane).
- The forms of radiation patterns of the considered antennas.

It is worth noticing that irrespective of a radiation pattern form, a straight line located on a zero corner of the diagram will be an axis. In the figures given above an axis is the vertical straight line passing through the center.

First, we will perform the calculation of antenna gain of any set transmitting antenna in the direction of any set receiving antenna.

Finding of an angle between the axis of the transmitting antenna and the direction on the receiving antenna will be the first step of our calculation (which in this case we simply consider a point).

The direction angle between the antennas is the angle between three points in space: t1 is the location of the antenna of the receiver; t2 is the location of the antenna of the transmitter; t3 is the random point on the axis of the antenna radiation pattern of the transmitter (if we look for an angle between the axis of the antenna of the transmitter and the direction on the antenna of the receiver, Fig. 3).

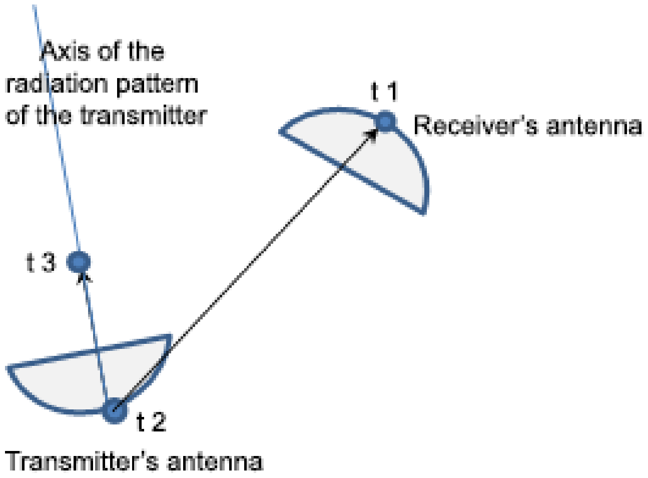

Fig. 3. A schematic image of the location of the antennas.

As it has been mentioned above, t1 is set by the Cartesian coordinates, t2 is also set by the Cartesian coordinates. The t3 point will be taken as a point on the axis of the radiation pattern of the transmitter remote from the point t2 by 1 unit (for example, 1 m, if the scale of the system of coordinates is set in meters). Thus, we know the coordinates of the points t1 and t2, and the coordinate of the point t3 is to be defined.

By means of simple trigonometrical transformations, we will obtain that the coordinates of the point t3 are in number equal to:

$$x_3 = x_2 + \cos(a) \cdot \cos(b), \tag{1}$$

$$y_3 = y_2 - \sin(a) \cdot \cos(b), \tag{2}$$

$$z_3 = z_2 + \sin(b), \tag{3}$$

where a is the azimuth of the transmitter's antenna;

b is the elevation of the transmitter's antenna;

x_2, y_2, z_2 are the Cartesian coordinates of the transmitter.

Now we have the coordinates of all three points. It is possible to find an angle between them as an angel between the vectors t2t1 and t2t3.

The cosine of the angle between the vectors is as the relation of a scalar product of vectors to the product of their lengths.

The angle itself (we will call it α) is found by the formula:

$$\begin{aligned}\alpha = \arccos\Big((x_3 - x_2)\cdot(x_1 - x_2) +& \\ + (y_3 - y_2)\cdot(y_1 - y_2) + (z_3 - z_2)\times& \\ \times (z_1 - z_2)\Big/\sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2 + (z_3 - z_2)^2}\times& \\ \times\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}\Big).&\end{aligned} \tag{4}$$

In the formula (4), the subtraction of the values *x2, y2, z2* from the coordinates of other points of interest shows a parallel transfer of the considered system in the beginning of the coordinates.

Thus, the angle between the axis of the transmitting antenna and the direction on the receiving antenna is defined. Now there is a problem to determine the gain of transmitting antenna corresponding to this angle. To do this, we need to carry out a certain analysis of the radiation pattern of the transmitting antenna.

For a mathematical task of a form of the radiation pattern, we will present it in the form of a two-dimensional table. The first field will reflect a deviation in degrees from the main axis. An interval, which needs to be considered in the interval, is 0–180°. Here we will make a certain assumption and consider the radiation pattern symmetric in relation to the antenna axis, and consider its section perpendicular to the axis the plane, respectively, circular.

The second field of the table will reflect the relative power radiated by the antenna in the direction corresponding to value of the first field. We will accept the maximum value of such relative power to be 1 (Table 1).

Table 1. Table of the rough description of the radiation pattern.

Angle between the axis of the antenna and direction (degrees)	Relative power (times)
0	1.00
20	0.79
40	0.32
60	0.40
80	0.32
100	0.50
120	0.32
140	0.50
160	0.32
180	0.79

For illustrative purposes, these table data can be displayed on the diagram and to designate the tops of the received figure (Fig. 4).

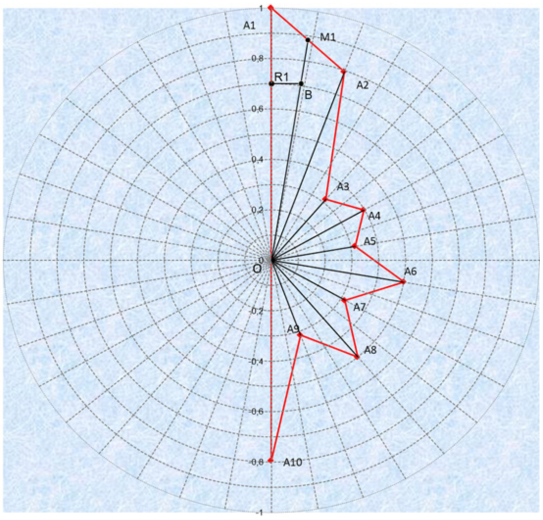

Fig. 4. A diagram display of the table data.

Now the radiation pattern set by Table 1 can be given as a body of rotation of the figure represented in Fig. 4 around the direct line OA_1. As it is easy to see, the figure consists of the triangles (A_1OA_2, A_2OA_3, A_3OA_4, etc.), and for each such triangle the lengths of the sides equal to relative powers, and the angle between them are known (equal to the difference of the angles set in Table 1).

The general power of the transmitter radiated by this antenna can be interpreted as radiation pattern volume (that is the bodies of rotation of the considered figure). To find the volume of a body of rotation, we will use the second Pappus–Guldinus theorem, which says that:

The volume of the body formed by rotation of a flat figure around the axis located in the same plane and which does not cross the figure is equal to the area of the figure multiplied by the length of a circle, which radius is the distance from a rotation axis to a figure barycenter.

Thus, it is possible to draw a conclusion that the total amount of a body of rotation will represent a composition of the bodies of rotation of the triangles stated above.

Let us take the first triangle A_1OA_2.

Its square is easily calculated by the formula:

$$S_1 = 1/2 \cdot OA_1 \cdot OA_2 \cdot \sin(A_1OA_2). \tag{5}$$

Now it is necessary to find a barycenter (center of mass) of the triangle. As geometry says, the barycenter of a triangle lies on the crossing of medians, and medians cross in 2:1 ratio.

First, the length of the side A_1A_2 should be found by the cosine theorem:

$$A_1A_2 = \sqrt{(OA_1{}^2 + OA_2{}^2 - 2 \cdot OA_1 \cdot OA_2 \cdot \cos(A_1OA_2))}. \tag{6}$$

Knowing the sides of the triangle, we can determine the length of the median leading to A1A2 by the formula:

$$OM_1 = 1/2 \cdot \sqrt{(OA_1{}^2 + OA_2{}^2 - A_1A_2{}^2)} \tag{7}$$

and then multiply this length (OM_1) by 2/3 determining the position of the barycenter (B) on the median. Now it is necessary to define the distance from the barycenter to the axis OA_1, because for calculation of the volume it is necessary to know the length of a circle, which the barycenter traces at rotation. The radius of this circle is the length of the perpendicular lowered from the barycenter on the axis OA_1.

Understanding that the median halves the area of the triangle and knowing the area of the triangle OA_1A_2 (S_1), we find the angle between the median and the axis OA_1:

$$A_1OM_1 = \arcsin\left(1/2\,(S_1/(1/2 \cdot OA_1 \cdot OM_1))\right). \quad (8)$$

Then we determine the distance from the axis OA_1 to the barycenter (Fig. 4):

$$R_1 = 2/3 \cdot OM_1 \cdot \sin(A_1OM_1). \quad (9)$$

Applying the second Pappus–Guldinus theorem, we receive that the volume of a body of rotation of the triangle A_1OA_2 is equal to:

$$V_1 = S_1 \cdot 2 \cdot \pi \cdot R_1. \quad (10)$$

By same way we can find the volumes of bodies of rotation of other triangles of a figure and then, making an addition, we receive the total amount of a body of rotation of the figure (*V*).

At the emission of the same power, the isotropic antenna (we will remember that the isotropic antenna is the ideal antenna radiating evenly in all directions), the radiation pattern would be as a sphere of the same volume *V* with a radius being equal to:

$$\mathrm{R_i} = \sqrt[3]{3/4 \cdot \mathrm{V}/\pi} \quad (11).$$

Thus, we geometrically have interpreted the power of isotropic radiation by the value R_i and have had an opportunity to define the gain of the antenna in the direction which angle is calculated by the formula (4). For this purpose, it is necessary to find the value of the radial parameter *R* according to Fig. 4 for this angle (*α*). It is possible to do by means of a simple linear calculation by proportions. At first, the triangle where the angle beam α falls, is determined and then the following formula is used:

$$R = (\alpha - A_1OA_n) / (A_1OA_n{+}1 - A_1OA_n) \times \\ \times (OA_{n+1} - OA_n) + OA_n, \quad (12)$$

where *n* is the number of the triangle where the angle beam *α* falls.

Now we have an opportunity to find the ratio of the radial parameters *R* and R_i and, thus, to define the gain of the transmitting antenna in the direction of the receiving antenna:

$$GER = R/R_i. \quad (13)$$

The designation GER is based on the English words gain, emitter, and receiver and shows the considered direction of gain ("from the transmitter to the receiver" contrary to GRE, that is the gain of the receiving antenna in the direction of the transmitter).

The gain of the receiving antenna in the direction of the transmitter is in the same way calculated. It is worth reminding that the received GER and GRE values are measured in "times", therefore the gain of power transfer from the transmitter to the receiver can be considered as GER×GRE. In certain cases, the GER and GRE values are given in decibels, and then the gain of power transfer from the transmitter to the receiver represents their sum of GER+GRE.

Conclusion

The advantages of the described method can be an opportunity to record a 3D radiation pattern of the antenna in the form of a circular section that is most widespread and the simplicity of its implementation by electronic computing machines. The method does not demand difficult software and is easily implemented in such common applications as, for example, Excel.

The disadvantages are the simplification of models of radiation patterns (a rotation figure). However, the method is opened for further modernizations. In future the method can be functionally expanded to the calculation of the radiation charts of the elliptic section. It is also simple to develop this method before recording the apertures of the interacting antennas. For this case, the mechanism of the integrated calculation for space angles and comparison of the received values with conic volumes, which are the segments of an isotropic sphere, will be created.

References

1. Elektromagnitnaya sovmestimost' sistem sputnikovoy svyazi [Electromagnetic compatibility of satellite communication system]. Eds. Kantor L.Ya., Nozdrin V.V. Moscow, NIIR, 2009, 280 p. (in Russian)
2. Badalov A.L., Mikhaylov A.S. Normy na parametry elektromagnitnoy sovmestimosti RES [Norms for electromagnetic compatibility parameters of radioelectronic facilities]. Moscow, Radio i svyaz', 1990, 272 p. (in Russian)

3. Teoriya i metody otsenki elektromagnitnoy sovmestimosti radioelektronnykh sredstv [Theory and methods of evaluating electromagnetic compatibility of radioelectronic facilities]. Ed. Feoktistov Yu.A. Moscow, Radio i svyaz', 1988, 216 p. (in Russian)
4. Upravlenie radiochastotnym spektrom i elektromagnitnaya sovmestimost' radiosistem [Radio frequency spectrum and electromagnetic compatibility of radio systems]. Ed. Bykhovskiy M.A. Moscow, Ekotrendz, 2006, 377 p. (in Russian)
5. Goncharenko I.V. Antenny KV i UKV [SB- and USB-antennas]. Moscow, Radiosoft, 2016, 744 p. (in Russian)
6. Ustroistva SVCh i antenny [Microwave devices and antennas]. Ed. Voskresenskiy. Moscow, Radiotekhnika, 2006, 378 p. (in Russian)
7. Elektromagnitnaya sovmestimost' radioelektronnykh sredstv i radiokontrol'. Metody otsenki effektivnosti [Electromagnetic compatibility of radioelectronic facilities and radio control. Effectiveness evaluation methods]. Ed. Saiy P.A. Moscow, Radiotekhnika, 2015, 400 p. (in Russian)
8. Galimov G.K. Antenny radioteleskopov, sistem kosmicheskoy svyazi i RLS [Antennas of radiotelescopes, space communication systems, and radars]. Moscow, Advanced Solutions, 2013, 392 p. (in Russian)