Flaw Detection Method for Radomes in Weakly Anechoic Conditions

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***Abstract* – To protect the antennas of radar stations from the external environment, various radomes are used. The main electrical requirementsfor these products is the requirement of introducing minimal distortion of electromagnetic waves (EMW) while maintaining strength and protective properties. It is important to identify and localize areas that do not meet the requirements for the magnitude of energy losses, to evaluate their sizes and boundaries. A new method for radomedefectoscopy is proposed, it includes a way for measuring losses under weak anechoic conditions, and for estimating the sizes and shapes of sections that do not meet the requirements for the magnitude of losses.**

***Keywords* – electromagnetic wave, magnitude of losses, radar station, radome, receptor model, transmission coefficient.**

1. Introduction

To protect the antennas of radar stations from the effects of external environment, various radomes are used. The main electrical requirementsfor these products is the requirement of introducing minimal distortion of EMW while maintaining strength and protective properties.

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The choice of the optimal constructive option of a radome includes the solution of the following tasks:

- selection of the optimal geometric shape, based on the layout solution of the entire structure of the object;
- selection of technological solutions when creating it;
- analysis of the strength component of the manufacture.

When choosing a technological solution in the process of manufacturing radomes at the stages of the output control, there is the task of detecting and localizing defects (flaw detection) with an analysis of their size, shape, etc.

There are well-known methods of non-destructive flaw detection of materials (acoustic, magnetic, vortex, thermal, etc.) [3], [6] capable of detecting a structural defect of the material [9], [16]. It is possible that within the framework of non-destructive testing, there is no detection of defects, or the detected defect is insignificant for the structural strength, while this area has a greater impact on the radio characteristics of the radome in comparison with its other areas [17], [19]. Therefore, to make a decision on the suitability of the product, it is necessary to perform a flaw detection based on the measurement of parameters regarding radio-frequency (electricity) engineering.

Methods based on electrical tests (resonance, wave) [15], are based on the measurement and analysis of the dielectric parameters of the materials. These parameters are convenient for describing the properties of homogeneous materials. For heterogeneous ones (layered, cellular, porous), it is necessary to find the field of electrical parameters (their distribution). In such cases, it is convenient to characterize the material not by dielectric (relative permittivity ε and dielectric loss tangent $tg\delta$), but by radio engineering parameters, in particular, transmission coefficient or loss [12]. The most informative way to use flaw detection is to use methods based on direct measurement of parameters of radio-frequency engineering of EMW.

The purposes of the article are the following:

- formalization of the flaw detection method in weak anechoic conditions based on the measurement of losses;
- study of known methods for measuring the magnitude of losses;
- formation of a method for measuring the magnitude of losses in weak anechoic conditions;
- formation of a method for localizing and assessing the size and shape of defects (areas with an increased value of the loss value).

To test the radomes, the substitution method in the field of a plane EMW is used. These tests are carried out as part of the antenna and antenna-feeder path of the radar, i.e. the object of research is the whole antenna-fairing system (AFS). These tests of AFS are described in detail in the specialized books [1], [18]. However, it is not always convenient to make the AFS of the product for which the radome is intended to be a workstation, including from an economic point of view. Moreover, the manufacture of the antennas and the radome are often divided in time and expanse (for example, specialized enterprise is engaged).

In the practical implementation of this method, it is necessary to ensure stable values of the radiated power level, characteristics of the receiving devices and the path, and exclude reflections from third-party objects. It is also desirable that the dimensions of the aperture and the standard radar antenna are close.

The method of measuring radio parameters (including the magnitude of losses) of radomes [2], [8] is based on the replacement method. The measuring antenna is located in the field of a plane EMW, and it is oriented in the direction of obtaining the maximum signal at the output [14]. Measurements are made at the operating frequency f_0 in two stages. At the first stage, the signal level of the incident EMW from the output of the measuring antenna without the radomeE_0 is measured, then (at the second stage) the signal level E_1 is measured from the output of the antenna with the radome. The ratio of the changed signals is used to calculate the magnitude of EMW losses:

$$d = \frac{E_1}{E_0}. \quad (1)$$

The disadvantages of this method is that the re-reflection of EMW from the radome introduce an error in the measurement of the value of E, and therefore in the calculated level d.

The method described in is different from the method described in [14], because in order to reduce the measurement error of the value of E, suppression of re-reflections from the radome is performed. The technical result is ensured by conducting a series of measurements of the signal level E_i when the phase of the reflected wave is varied between the measuring antenna-cowling, followed by mathematical processing of the results and calculating the value E. Phase variation is made by changing the position of the radome relative to the antenna.

There are the following disadvantages of the methods:

- the need to organize a suspension and movement system of the radome, which allows changing the distance of the antenna-radome without changing the spatial orientation of the radome;
- presence of a number of restrictions associated with the geometric size of the antenna and the radome, which do not allow movements.

A common disadvantage of the above methods is their noise immunity. The measurement result can be affected by any source of signal reflections located near the workstation (concrete or brick walls, floor, ceiling, metal and other non-transparent structures). To achieve high accuracy when applying these methods, the measurements have to be performed in an anechoic chamber (AC), which imposes additional restrictions on their applicability.

To measure the magnitude of losses under conditions of a large number of them, there is the method to combat reflections during measurements in weak anechoic conditions.

The influence of the reflected side wave on the generator of the measuring device will not be considered, because, firstly, the feeder paths (for example, coaxial lines) are decoupling attenuators, and secondly, in modern measuring instruments there is a decoupling of the generator from the reflected wave. Therefore, reactions are considered only in the gap between the transmitting and receiving measuring antennas and the receiving antenna and radome [7], [13].

The proposed method provides the registration of complex values of the amplitude at a number of frequencies and the subsequent Fourier transform of the data with a transition to the time domain. The use of nano- or picosecond pulses and a pre-selected window of time selection as a probe signal make possible to reduce the influence of spurious re-reflections and scattering.

2. Method of Measuring Losses in Weak Anechoic Conditions (Using Temporary Selection)

The following equipment is required for testing: transmitting and receiving measuring antenna, cable assemblies of fix length, vector network analyzer with time-domain function. The workstation is shown in the Figure 1.

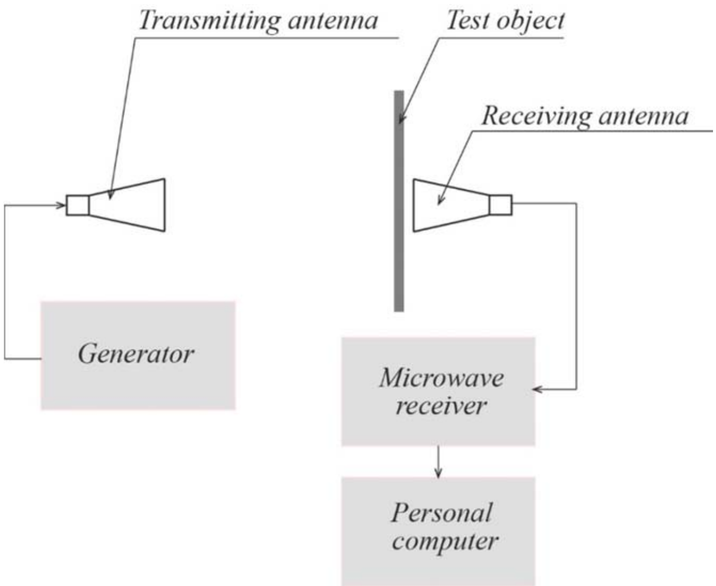


Figure 1. Workstation

The location of the measuring antennas at the polygon can be represented as follows (Figure 2):

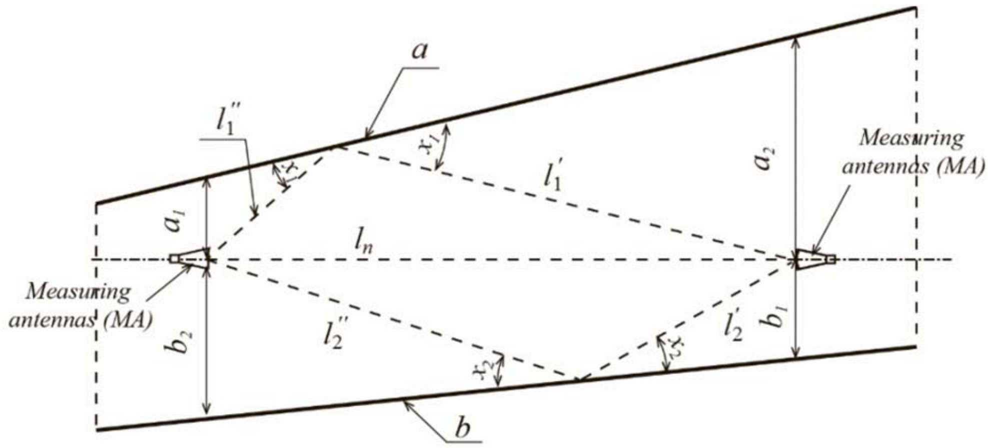


Figure 2. Measuring antennas location at the polygon. View from above

Here *MA* are the measuring antennas;

a, b are the polygon walls;

a_1, b_2 is the distance from the transmitting antennas to the walls *a* and *b*;

a_2, b_1 is the distance from the receiving antenna to the walls *a* and *b*;

l_n is the direct signal path (distance between transmitting and receiving antennas);

x_1 is the angle of incidence (reflection) of re-reflection of a signal of the first kind from the wall *a*;

x_2 is the angle of incidence (reflection) of re-reflection of a signal of the first kind from the wall *b*;

$l_1 = l_1' + l_1''$ is the path of the reflection of a signal of the first kind from the wall *a*;

$l_2 = l_2' + l_2''$ is the path of re-reflection of the signal of the first kind from the wall *b*.

To perform temporary selection, it is necessary to select the size of the temporary window. First of all we need to consider the paths of re-reflections of the first kind l_1 and l_2. Reflections of the second kind will not be taken into account, since the signal path in them is potentially larger than in reflections of the first kind. It was experimentally obtained that for measurements it is optimal to choose the time window Δl so that it satisfies the following conditions:

$$\Delta l = l_r - min(l_1, l_2). \qquad (2)$$

To configure the organization of the workplace and the setup of measuring equipment it is necessary to do the following:

1. To install the measuring antennas as in the Figure 1. By turning the antennas in azimuth and elevation we can find the maximum signal.
2. To calculate the value of x1 and x2 from the expressions:

$$a_1 \cos\cos\left(x_1 + 3\arccos\frac{a_2-a_1}{\sqrt{(a_2-a_1)^2+l_п^2}}\right) + a_2 \cos\cos\left(x_1 + \frac{a_2-a_1}{\sqrt{(a_2-a_1)^2+l_п^2}}\right) - a \text{‰}in \sin x_1 = 0; \quad (3)$$

$$b_1 \cos\cos\left(x_2 + 3\arccos\frac{b_2-b_1}{\sqrt{(b_2-b_1)^2+l_п^2}}\right) + b_2 \cos\cos\left(x_2 + \frac{b_2-b_1}{\sqrt{(b_2-b_1)^2+l_п^2}}\right) - b \sin\sin x_2 = 0; \quad (4)$$

3. To calculate the values l_1 and l_2 from the expressions:

$$l_1 = \frac{a_1^2+a_2^2}{\sqrt{(a_2-a_1)^2+l_п^2 x_1}}; \quad (5)$$

$$l_2 = \frac{b_1^2+b_2^2}{\sqrt{(b_2-b_1)^2+l_п^2 x_2}}. \quad (6)$$

4. To calculate the value Δl by the formula (2).
5. To measure the signal $E(f_n)$ at discrete frequencies $f_n = f_0 + n * \Delta f$, where $n = 0, 1, \dots, (N-1)$
6. To do the following operation at each point $n = 0, 1, \dots, (N-1)$: $E(f_n) = E(f_n) * K(n)$,

where $K(n) = 0.40217 - 0.49703 \cos\cos\left(\frac{2\pi}{N}\right) + 0.09392 \cos\cos\left(\frac{4\pi}{N}\right) - 0.00183 \cos(\frac{6\pi}{N})$ is Blackman-Harris weight window.

7. To make the Fourier transform:

$$E(t_m) = \sum_{n=0}^{N-1} E(f_n) exp(-\frac{i2\pi nm}{N}), t_m = \frac{m}{N * \Delta f}, m = 0, 1, \dots, (N-1)$$

8. To do the following operation at each point $m = 0, 1, \dots, (N-1)$: $E(t_m) = E(t_m) * D(t_m)$,

Where $D(t_m) = exp(i\pi(t_m - t_0)\Delta f)\frac{sinsin(\pi(N/k)(t_m-t_0)\Delta f}{sinsin(\pi(t_m-t_0)\Delta f}$,

t_0 is the time of arrival of the useful signal, k is the width of the weight window, located at $k = \frac{\Delta l}{c}$, is the speed of light in air.

9. To make the inverse Fourier transform:

$$E(f_n) = \frac{1}{N}\sum_{m=0}^{N-1} \mathrm{E}(t_m) exp(\frac{i2\pi nm}{N}).$$

As a result, we obtain the values of the reconstructed signal E at N discrete frequencies: $f_n = f_0 + n * \Delta f$, $n = 0, 1, \dots, (N-1)$. The frequency step and the number of frequencies are selected based on the above ratios, considering the required width of the domain and the step.

The process of measuring the test object (TO) is carried out in two stages: measuring the level of the restored signal without TO (E_0) and at the output of the antenna with TO (E_1). So, we can calculate d_i at *i*-th point of the radome.

The Figure 3 shows three graphs of the loss value for the same sample of radiolucent material (teflon, the wide is 20 mm). The theoretical color graph of the losses calculated on the basis of reference values (relative permittivity ε and dielectric loss tangent *tg(α)* is shown in blue. Yellow color is the amount of losses measured by the "Method for measuring losses in radomes". Red one is the magnitude of losses measured by the method proposed above. Based on the results, the application of the proposed method allows increasing the stability of measuring the magnitude of losses compared to the previously known method.

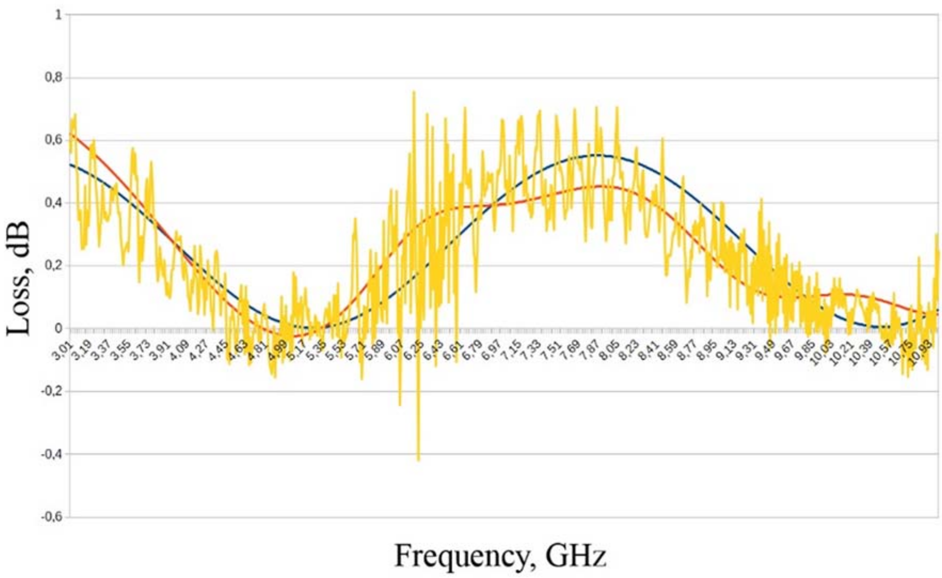


Figure 3. Loss graphs for teflon, 20 mm wide

3. Mathematical Analysis of the Resulting Data Array in the Framework of Flaw Detection. Geometric Aspects of Processing Measurement Results in the Object With the Adjusted Shape

The above-mentioned method allows measuring the magnitude of the energy loss in the radome in a wide frequency band and can be used for flaw detection. Radomy flaw detection is not only the search for inhomogeneities (seams, seals, cracks, delaminations, moisture accumulations) on its surface, but also the assessment of their potential impact on the amount of losses with the aim of subsequently deciding on the possibility of further application of the radome under study in the final product or refinement of defects.

The value of the level of reconstructed signal at the output of the antenna with the E_{1xiyi} radome is measured for each geometrical point with the coordinate $[x_i,y_i,z_j]$ ($i=1,2,...,m;\ j=1,2,...,k$) with the step Δh and Δz (Figure 4-6). The choice of the optimal step for the arrangement of geometric points on the surface of radome$\Delta h$and Δz depends on the expected size of the detected inhomogeneities directly.

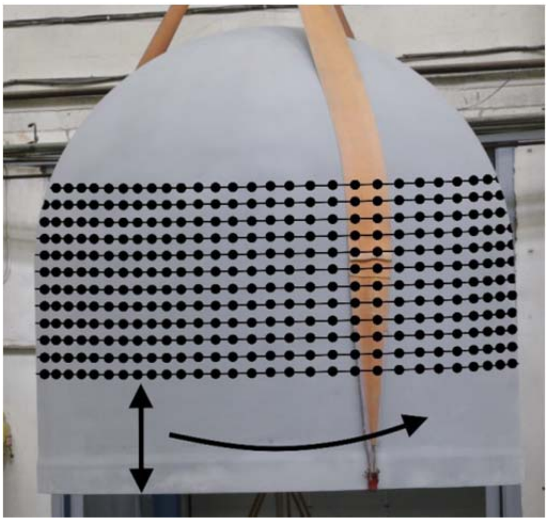


Figure 4. Example of the shape of the investigated radome with measuring points E_{xiyi}

This radome consists of combination of a cylindrical part and a sphere.

For the cylindrical coordinate of any point on the surface, it is determined by a system of equations (Figure 5)

$$\begin{cases} x = \rho cos\varphi \\ y = \rho\, sin\varphi. \\ z = z \end{cases} \qquad (7)$$

Here ρ is the outer radius of the cylindrical shell and φ is the angle of rotation between adjacent points in a given section.

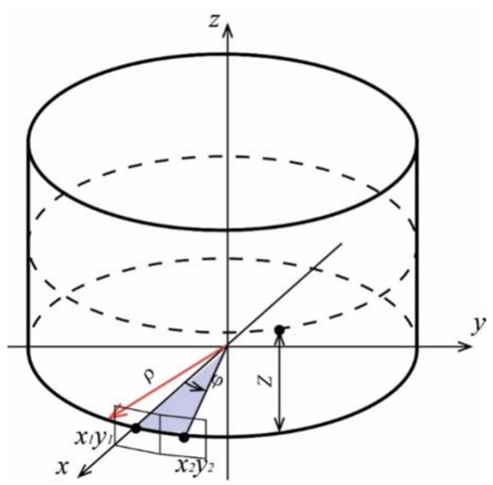


Figure 5. Determining points on the cylindrical part

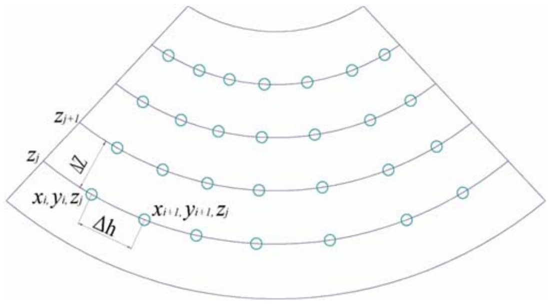


Figure 6. Layout of the points on the scan cylinder

Δh determines the measurement step E_{1xiyi} and it is determined by the dependence $\Delta h = \frac{2\pi\rho}{\varphi}$.

According to the measurements obtained at two stages, the magnitude of the losses in the entire frequency range for each geometric point is calculated.

Thus, as a result of data processing, there is an array [*x,y,z,d*], which contains the energy loss d_i for each geometric point [x_i, y_i, z_j] at each frequency f_k.

In the Figure 7 there is the graphical display of d_i in a separate portion of the radome for a single frequency. There will be *k* graphic mappings. This example has been processed using *MatLab* for an EMW frequency of 10 GHz.

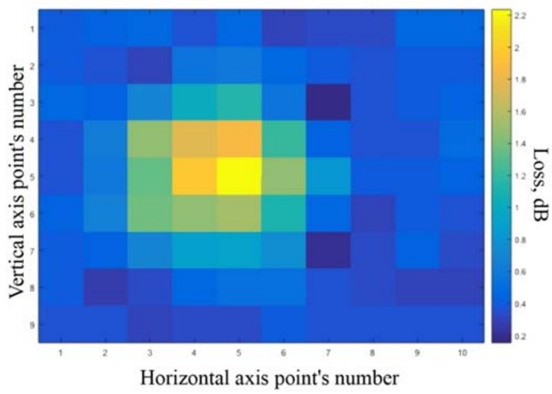


Figure 7. Example of visualization of data

To determine the geometric coordinates of cells with d_i exceeding the allowable d_A value, the theory of receptor models is used [4].

The mathematically receptor model is described by the set $A = \{a_{ij}\}$, where

$$a_{ij} = \begin{cases} 1, if\ d_i \geq d_A \\ 0, \text{otherwise.} \end{cases} \quad (7)$$

The resulting matrix with «*1*» allows estimating the boundaries and the area of the plot with cells where d_A excesses occur [5], [10].

In the Figure 8 there is an array of coordinates of a product fragment with the presence on them of several sections with excess d_A. It is important to identify the geometric parameters of each individual section, which allows studying changes in its shape when analyzing data at different test frequencies, which is important when creating a general picture of the radome manufacturing quality [11].

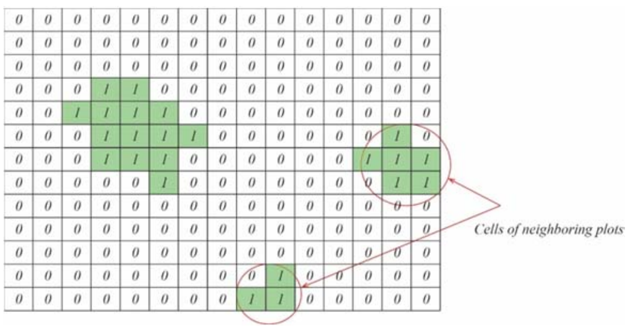


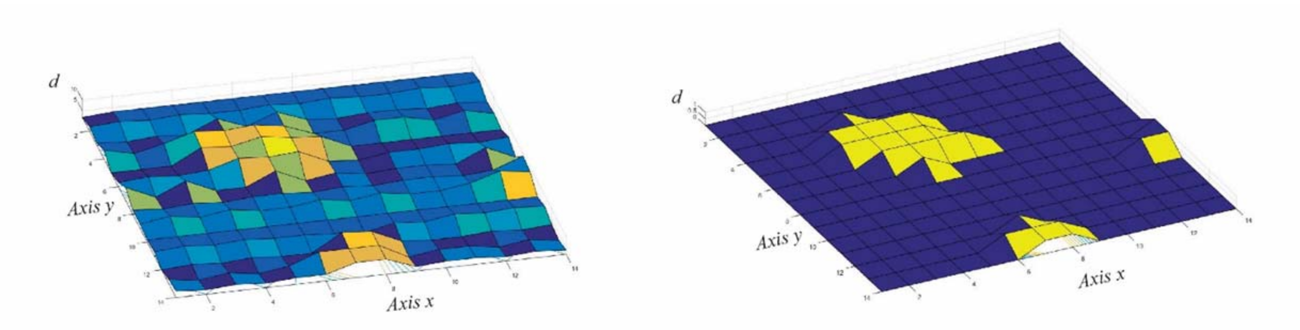
Figure 8. Receptor model of the 2-D site of the object with a given value of the range d

When comparing data for two frequencies f_i and f_j of the test, there are two arrays of measurements of the same section $A(x,y,f_i)$ and $A(x,y,f_j)$ processed using the receptor model.The identification of the plots consists in determining the difference between these arrays by the parameter d. In cells where d_i has a maximum difference equal to "1", it characterizes the zone of movement (expansion, contraction) of the defective region, where there is no change, we have "0".

There are the following conditions:

$$a_{ij} = \begin{cases} 1, if \ |A(x,y,f_i) - A(x,y,f_j)| \\ 0, \text{otherwise.} \end{cases} \quad (8)$$

The display of the values of real data of d_i losses over a given area is shown in the Figure 9a. The Figure 9b shows the graphical picture in accordance with the fulfillment of condition (7).



a) b)

Figure 9. Graphical display of the value of d in the coordinate system 0xy (*a*) and the corresponding display of areas with excess level d_A(*b*)

To analyze the contour of the studied areas with excess values of d_A, it is advisable to use contour analysis. It is the external shape (contour) of the given sections. The transition to consideration only of the contours of sections allows getting away from the image space, to the contour space, which reduces the complexity of the algorithms and calculations. The contour of the plot is determined by the coordinates of the vertices of the cells that make up the contour (boundary points). To determine the boundary points, it is advisable to use contour coding with the Freeman chain code [5], [11].

Based on the results, it is possible to localize zones with defects on the radome surface for further opening and / or refinement.

4. Conclusion

1. In order to search for defects in the working area of radomes, the defectoscopy method based on measuring energy losses was proposed.
2. In order to increase the stability of measurements of the magnitude of energy losses in radomes, one method for measuring the magnitude of energy losses in weak anechoic conditions based on temporary selection was proposed. So as to test it, measurements of the energy loss in a teflon sheet with a wide of 20 mm were carried out with a normal EMW drop. The results were compared with the calculated theoretical values for this material and by a previously known method. The measurements showed that the application of the obtained method allows increasing the stability of measurements in weak anechoic conditions.
3. A defectoscopy of a sphere-cylindrical radome was carried out. Using the theory of receptor models, the geometrical coordinates of cells with an increased value of the loss value (defects are localized) were determined, and their graphical model was constructed. An autopsy of the detected areas showed the compaction in the detected areas caused by the accumulation of the compound in the unit cells.

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