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Calculation of the radar cross-section of complex objects for the problem of modeling a synthetic aperture radar

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Abstract. A synthetic aperture radar is usually a complex software and hardware package that allows obtaining images in the radio range comparable in resolution with optical systems. The advantage of radio waves is that high-quality photography takes place despite cloudiness and dark time of the day. The development of algorithms for this system type is rather complicated process; mathematical modeling is used for reducing its cost. This paper shows the applicability of approximation methods to calculate the scattered field for imaging of synthetic aperture radar. The disadvantages of these methods are also discussed.

1. Introduction

At present, mathematical modeling is an important element of the development of complex technical systems; it can reduce the cost of conducting real experiments, speed up of hypothesis testing and find previously unknown relationships. The advantage of mathematical modeling is evident for each experiment in the case of synthetic aperture radar (SAR), which is usually installed on board an aircraft. It should be noted that even a simple synthesis of a radar image requires a large computational power and/or processing time because of the large amount of processed data. It is necessary to solve the problem of the formation of a radio hologram, each line of which represents a reflected signal from all objects that fall into the antenna pattern at modeling in addition to the image synthesis.

As a rule, calculating method of the scattered field for the simulation task of a synthetic aperture radar must meet two requirements of the simulation task. First, a reasonably accurate scattering model is needed to observe diffraction, diffuse and specular reflection effects. Secondly, a model is required, which is capable of calculating large areas of the underlying surface in a reasonable time.

Vehicles and anthropogenic structures, which are of particular interest to SAR, usually consist of metal structures. Only ideal conductors can limit the exact calculating model; its scattered field is determined mainly by the geometry. One of the most well-known methods for calculating the scattered field is the method of physical diffraction theory (PTD), developed by P. Ya. Ufimtsev [1].

On the other hand, the underlying surface usually consists of dielectric materials, calculations for which are more complicated than for an ideal conductor. The area of the underlying surface is many times larger than the area of interest objects. In this case, a statistical description of the reflecting properties of materials is used, taking into account the polarization and the angle of irradiation.

Despite the fact that reflective models have been developed for a long ago, their use has not yet become widespread except for the calculation of the effective of a surface of scattering of radar cross-section (RCS). This paper presents an approach for modeling a radar scene with the formation of a radio hologram and the synthesis of a radar image from the simulation data.

2. Research Method

The calculation of metallic objects is a combination of methods based on physical optics. It includes physical optics and the physical theory of diffraction. The principles of these methods are described in [1–3]. In addition, it should be noted works [4–6]; the calculation equations for arbitrary polarization are given there.

The approach, described in [4], assumes that the resulting scattered field is a superposition of electromagnetic fields, caused by different surface currents:

$$\vec{E} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \vec{E}_4 , \tag{1}$$

where $\bar{E}_1$ is the vector of strength of electric field corresponding to the contribution from the smooth elements of the object; $\bar{E}_2$ is the vector of strength of electric field corresponding to the contribution from sharp edges; $\bar{E}_3$ is the vector of strength of electric field corresponding to the contribution from multiple reflections; $\bar{E}_4$ is the vector of strength of electric field corresponding to the contribution from underlying surface.

The facet surface model was used to simulate the reflection of a signal from the surface; it represents the surface as a set of elementary reflecting elements, namely plates of finite size, coinciding with the surface of large-scale irregularities. The Huygens-Kirchhoff's principle is the physical justification of such a model: each point of the surface, irradiated by an electromagnetic wave, is a source of a secondary spherical wave [7].

The use of the facet model is most appropriate for surfaces with multi-scale irregularities. The following conditions are necessary at dividing the surface into facets (reflectors) [8]:

- ✓ the sizes of the facet must be greater than the wavelength by several times;
- ✓ the signal, reflected from one elementary facet, does not depend on signals, coming from other reflectors;
- ✓ the radius of curvature of the average facet is larger than the facet sizes, i.e., the average facet level is almost flat;
- ✓ number of facets, forming the reflecting surface should be large, and their reflective properties are about the same.

The surface of the object should be represented by a set of reflecting areas (facets) of the same area, evenly distributed over the surface, to simulate the operation of the radar station with a given resolution in azimuth and inclined range. In this case, the size of the facets should be less than the parameters of the resolution of the radar station.

The reflected signal from the surface is the sum of the signals from all irradiated facets. Moreover, each partial signal has its own amplitude, determined by the orientation of the local diagram of backscatter (DBS), and its random phase.

The phase of the signal, reflected from the *k*-th elementary reflector (facet), is represented as

$$\phi_k = \phi_k^{(\mathrm{reg})} + \phi_k^{(\mathrm{rand})} , \tag{2}$$

where $\phi_k^{(reg)}=\omega\tau_k=(4\pi/\lambda)R_k$ is regular phase shift due to the time of wave propagation from *k*-th elementary reflector (facet) and back; h_k is ordinate of facet relatively to average surface level; $\phi_k^{(rand)}$ is random phase shift, caused by reflection from the facet and inhomogeneities along the propagation path (troposphere, ionosphere, etc.). It is usually considered that $\phi_k^{(rand)}$ has a uniform distribution law from 0 to 2π.

The signal on the input of the receiving antenna of radar station is the sum of the partial signals reflected from all facets in the irradiated area:

$$u(t) = \mathrm{Re} \sum_{k=1}^{N} A_k \dot{U}_M (t - \tau_k) \exp[i(\omega_0 t - \varphi_k)], \tag{3}$$

where A_k is amplitude of signal; $\tau_k = 2R_k/c$ is delay of the signal, reflected from the *k*-th facet; $\dot{U}_m(t)$ is law of modulation of probe signal; ω_0 is cyclical frequency of carrier oscillation.

The amplitude of signal, reflected from the facet, depends on the distance from the facet and the mutual orientation of diagram of antenna directivity and diagram of back scattering; it is defined:

$$A_k = \sqrt{\frac{2P_{\text{trans}} G_{\text{trans}} G_{\text{rec}} \lambda^2 \eta_{\text{a}} L_{\text{loss}}}{(4\pi)^3 R_k^4} g_{\text{trans}}(\theta_k, \alpha_k) g_{\text{rec}}(\theta_k, \alpha_k) \sigma_k^0 S_k}, \tag{4}$$

where P_{trans} is transmitter power; G_{trans}, G_{rec} are amplification factors of power of transmitting and receiving antennas respectively; $g_{trans}(\theta_k, \alpha_k)$, $g_{rec}(\theta_k, \alpha_k)$ are normal diagrams of directivities on power of transmitting and receiving antennas respectively $g(0,0)=1$; η_a is the efficiency coefficient of the antenna-feeder system for transmission and reception; L_{loss} is loss coefficient in the microwave paths and on the spread; R_k is distance from phase center of antenna to k-th reflector; σ_k^0 is specific RCS of k-th reflector; S_k is area of k-th reflector.

The power of a signal, entering in receiving antenna of radar station for given type of underlying surface, depends on the polarization of the radiation and the mutual direction of polarization during radiation and reception. If the polarization of radiation and reception coincide, the levels of the reflected signal for horizontal and vertical polarization are close for most surfaces (arable land, terrain covered with vegetation). Exceptions are smooth surfaces (concrete, asphalt, gravel, calm water surface). The reflected signal at horizontal polarization is less than at vertical (up to 16 dB at small slip angles) for them [9].

The reflectivity of underlying surface is characterized by the scattering coefficient, which is the specific effective area of scattering (SEAS): the ratio of the RCS of the permit element on the terrain to the value of its geometric area:

$$\sigma^0 = \frac{\sigma}{S}, \tag{5}$$

where σ is the value of the RCS of the element of resolution (facet), S is area of surface of the resolution element.

The RCS ratios in polarization channels (for example, $\sigma^0_{HV}/\ \sigma^0_H$ or $\sigma^0_{HV}/\ \sigma^0_V$), the ratio of RCS of polarization component to the averaged RCS $\sigma^0_{AVER}=(\sigma^0_H + \sigma^0_V + 2\sigma^0_{HV})/4$ or difference of phases between vertical and horizontal polarizations or between agreed and cross polarizations are informative features at working with different polarizations.

The strict solution of the problem of reflection from uneven surfaces faces with serious mathematical difficulties in interesting cases for practice. Therefore, the reflection characteristics are usually determined experimentally at certain conditions. Thereafter an empirical model of the surface is obtained so that the calculation of the reflected field is relatively simple; the calculated reflection characteristics were close to those obtained experimentally.

The entire underlying surface is marked by one of the prepared materials, such as asphalt, concrete, dry dirt, wood, etc. Description of the materials is built on the works [9, 10], in which the experimental evaluation of the scattering characteristics is carried out. Below is a radar image, which shows the scene with the underlying surface (Figure 1).

3. Results and Discussion

Objects with well-known estimates were selected as test objects with a complex geometry: heavy V-52N bomber and BGM-109 Tomahawk cruise missile. Result of calculation of research model is below (Figure 2).

A rather old model of the V-52N bomber is best suited for estimating the RCS calculation. This is due to the fact that at the time of the release of the aircraft the methods of lowering radio-visibility were rather weakly developed. The all-metal body is well suited for calculation in accordance with the physical theory of diffraction. A typical estimate of RCS of V-52N is about 100 m^2 [11], which is equivalent to 20 dB and has an average value of 15.33 dB. In this case, the deviation is less than 5 dB.

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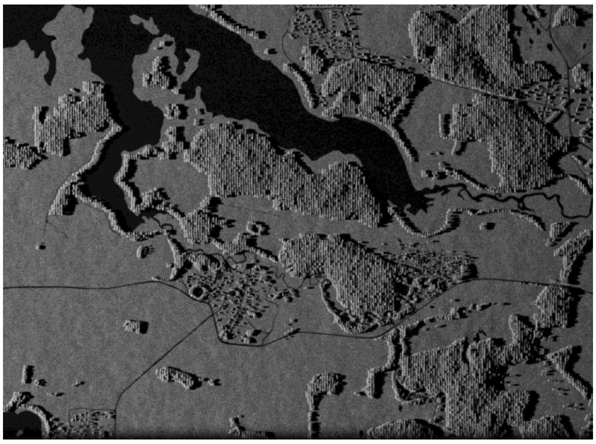


Figure 1. Radar image of the underlying surface.

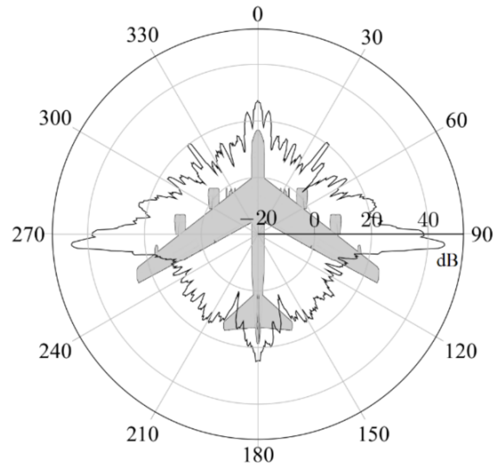
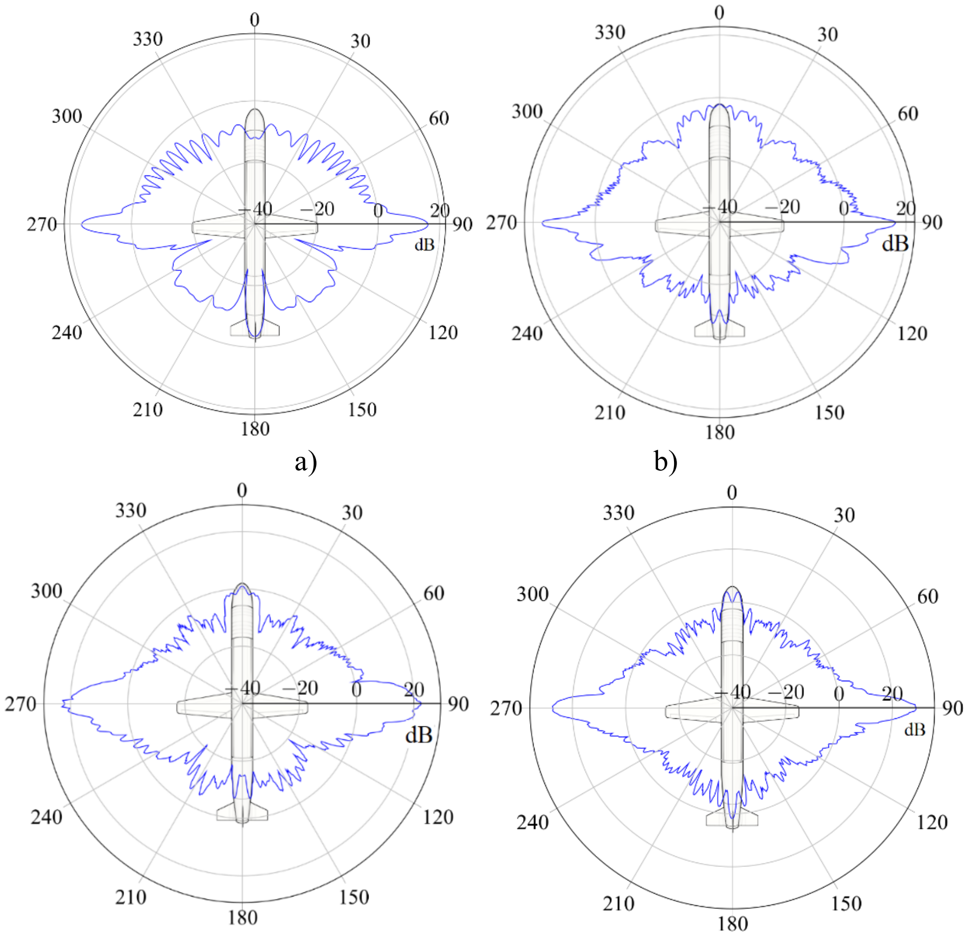
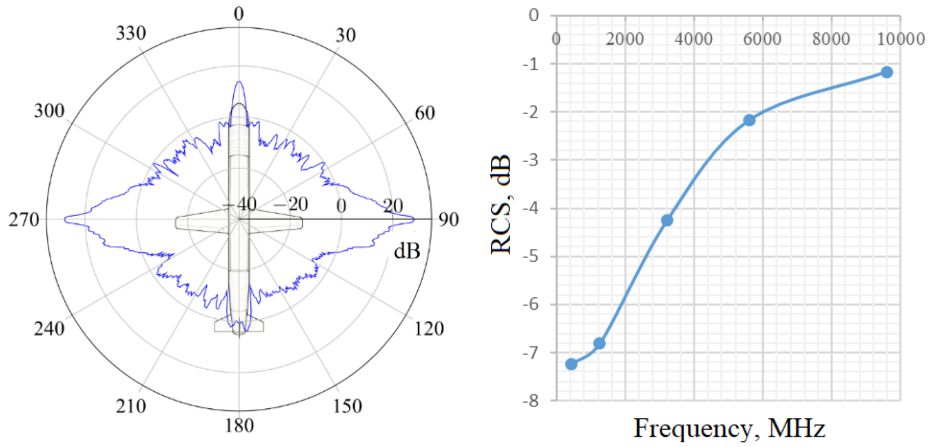


Figure 2. An example of calculating the RCS of V-52N bomber) at frequency of 1250 MHz.

Figures 3*a*-*e* show the diagrams of back scatter for different wavelengths. It can be said for each of them, that irradiation from the lateral direction increases the probability of irradiation of a cruise missile. At the same time, the rear hemisphere is also characterized by a smaller RCS. It looks rather unnatural because of the real cruise missiles are characterized by extremely low RCS in the direction of motion. In this case, the model may give an erroneous result due to the lack of the ability to calculate dielectric materials. Figure 3*e* shows the general dependence of the RCS [12, 13].



c) d)



e) f)

Figure 3. The RCS of the BGM-109 Tomahawk cruise missile at a different frequencies, where a) 430 MHz; b) 1 250 MHz; b) 3 200 MHz; d) 5 600 MHz; e) 9 600 MHz; and f) dependence of the average RCS on frequency.

In turn, the real cruise missile has more developed means of lowering radio-visibility. The body is covered by radio absorbing materials. In addition, the modification of BGM-109 block 4 uses carbon-fiber aerodynamic surfaces. Characteristic estimates of the RCS of BGM-109 Tomahawk cruise missile is 0.05–0.001 m^2 [todo], depending on the angle of shooting. The simulation results are in the range from -7 to -1 dB. The error is approximately two orders of magnitude in this case.

4. Conclusion

Using the example of two air objects, it was shown that the developed model shows the expected result for the problem of basic modeling of metal objects; however, this model shows itself to be insufficient for the task of modeling objects with a multilayer radio absorbing coating.

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