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Mathematical Models of Location Signals Reflected from the Underlying Surfaces of the Earth and the Sea Modeling SAR Images for Ecosystem Monitoring Task

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Abstract: When testing onboard equipment of aircraft using navigation radar maps for navigation, there is a need for mathematical models of signals reflected from the earth's surface and the sea surface. Traditionally, using theoretical constructions, such models were models of stochastic signals, the envelope fluctuations were described by the laws of Rayleigh and Rayleigh-Rice. These models were used both for simulating signals reflected from the earth's surface, and for signals reflected from the sea surface. With low resolution of airborne radars, these models described the statistical characteristics of fluctuating signals quite well. Modern onboard locators have high resolving power and the Rayleigh and Rice models can no longer be used in the synthesis and modeling of modern on-board navigation systems. In this study, we propose an approach to the construction of models of location signals that uses both theoretical construction and experimental data which allows us to take into account the features of the reflection of the location signals from small parts of the underlying surface of the earth and the sea, while taking into account both the correlation between the individual sections and the an isotropy of the reflections when observing areas from different angles. Reflections from the sea surface are approximated by a log-normal law, reflections from the terrestrial in view of the variety of surface types, Beckman and Weibull laws, particular cases of which are the laws of Rice, Hoyt and Rayleigh. These models can be used for high-precision mapping, monitoring environmental pollution, testing the operating modes of aircraft equipment.

INTRODUCTION

In recent years, the requirements for resolving power for the tasks of high-precision mapping of the earth's surface have been increasing every year. Therefore, the topic of mapping the terrain by synthesizing the aperture of the antenna from the aircraft's side remains relevant today where it is necessary to achieve high resolution of the generated radar image. This high resolution is determined by many factors, and in particular one of these factors are the fluctuations of the signal reflected from the underlying surface by the characteristics of which we obtain information for the formation of the radar image. Known works that are devoted to synthesizing the antenna aperture are mainly based on the average properties of the reflecting surface[1].

In calculating these properties, the average power of the re-reflected signals are calculated from the basic radar equation. In fact, depending on the type of surface, signal fluctuations occur which can worsen these characteristics. How much they get worse can be seen after the equipment is created. It is desirable for developers to have in advance a set of distribution laws for different types of surfaces and information on how they impair the potential characteristics of the elements of the resolution of the generated radar image, calculated in a theoretical way[2].

There is a considerable list of problems solved by radar survey. Important tasks of radar monitoring, performance solutions which due to improving prospects for radar image equipment includes the following: assessment of the characteristics of the environment and ecosystems (from regional to global), description of forest, agricultural and fishery ecosystems; Determination of the state of forest ecosystems, assessment of growth and condition of forest lands, detection of legal and illegal logging, assessment of the area and consequences of forest fires and floods, pyrogenic and post-identification of the size, nature and volume of water surface contamination, determining the area of leakage of combustible and liquid chemicals in disaster areas; Identification of zones of flooding and shallowing of the coasts of the seas and lakes; Monitoring in polar regions, including assessing the state of coastal ecosystems, assessing the state of marine areas; Production of cartographic works by land, sea surface, shelf, compilation, maintenance and updating of the land cadaster; Carrying out the cartography of sea ice and the evaluation of the ice deformation; Topology and lithological measurements;

The successful solution of this list of monitoring tasks is determined by the capabilities of information radio-electronic (primarily radar) systems capable of extracting information about the objects of observation contained in power engineering, the structure and polarization of the signal, and functioning in many frequency ranges of the electromagnetic spectrum[3].

MATERIALS AND METHODS

Methods for modeling the echo signal for the formation of sar images: There are two approaches to modeling the echo from the earth's surface. The first approach is the electrodynamic model when the re-scattered signal is calculated by the Maxwell equations. The second model which has found application in practice and which describes the fluctuations of the echo uses a statistical approach.

The first approach uses all possible approximations depending on the type of surface roughness, for example, small perturbation approximation by the Kirchhoff method by Rayleigh methods.

Another method, using the Feynman diagram method, requires cumbersome and complex mathematical computations and it is necessary to have a lot of prior information: about the reflecting properties of the signal, about the channel, etc.

In the second approach which is used for designing systems, in which a statistical model of the echo signal on a computer is modeled. Computer simulation uses all possible laws for the distribution of signal fluctuations of the elements of the resolution of the underlying surface which do not contradict the experimental data[4].

The simplest kind is a stable echo signal. The second kind, when there are many elements of the underlying surface or a digital map of the terrain in the simulation, fall into the elements of the resolution of the beam, then the fluctuations correspond to the Rayleigh distribution law. If there is a stable element in the signal, then Rayleigh-Rice. If the conditions of geometrical optics are not met, and there is a correlation between the elements, then there may be other laws. In particular, it very well approximates the experimental data-the Weibull distribution law and for the sea surface the log-normal law. In some cases, the log-normal law is also used for hilly or undulating types of earth's surface. Other laws are also used but we will limit ourselves to the following:

- Log-normal
- Weibull
- Rayleigh

Some laws are rarely found in the literature, or the amplitude of the echo is calculated at average power but there is no information on how many fluctuations in the envelope amplitude of the echo, coordinated with a certain distribution law, affects the quality of synthesis, the resolving power of the radar.

Some of these laws follow from physical representations and some laws are observed in practice and do not contradict real data. But in order to compare them one should calculate the signal-to-noise ratio (in terms of power) for each of the above distribution laws which should be the same. In addition, since, these are two-parameter laws, and the signal-to-noise ratio should be equivalent for all types of laws, it is necessary to show clearly how to specify the equivalence[5].

The method of forming a random matrix with a given

correlation function: We have an algorithm of a random signal with a given correlation function, we will form an algorithm for the random matrix. We form the vector $\eta_{i,j}$ the matrix of normally distributed independent random variables with zero means and unit variances $\eta_{i,j}$V N (0, 1), i =1, ..., n j = 1, …, m:

$$\eta_{i,j} = \begin{bmatrix} \eta_{1,1} & \eta_{1,2} & \eta_{1,3} & \cdots & \eta_{1,n} \\ \eta_{2,1} & \eta_{2,2} & \eta_{2,3} & \cdots & \eta_{2,n} \\ \eta_{3,1} & \eta_{3,2} & \eta_{3,3} & \cdots & \eta_{3,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \eta_{m,1} & \eta_{m,2} & \eta_{m,3} & \cdots & \eta_{m,n} \end{bmatrix}$$

From the matrix $\eta_{i,j}$ we form $x_{i,j}$ the matrix of normally distributed random variables, also with zero means and unit variances but with an exponential correlation over the columns. The following are the recurrent form of the formula of each j-th column of the matrix $x_{i,j}$:

$$\eta_{i,j} \Rightarrow X_{i,j} = \begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & x_{2,3} & \cdots & x_{2,n} \\ x_{3,1} & x_{3,2} & x_{3,3} & \cdots & x_{3,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{m,1} & x_{m,2} & x_{m,3} & \cdots & x_{m,n} \end{bmatrix}$$

From the matrix $X_{i,j}$ we form $Y_{i,j}$-the matrix of normally distributed random variable, also with zero means and unit variances but with the addition of exponential correlation in rows:

$$X_{i,j} \Rightarrow Y_{i,j} = \begin{bmatrix} y_{1,1} & y_{1,2} & y_{1,3} & \cdots & y_{1,n} \\ y_{2,1} & y_{2,2} & y_{2,3} & \cdots & y_{2,n} \\ y_{3,1} & y_{3,2} & y_{3,3} & \cdots & y_{3,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ y_{m,1} & y_{m,2} & y_{m,3} & \cdots & y_{m,n} \end{bmatrix}$$

Form two matrices $Y_{[n,m]}$ And from them to form two quadratures: $Y_{[n,m]} \Rightarrow U_{[n,m]}$ and $Y_{[n,m]} \Rightarrow V_{[n,m]}$:

$$U_{i,j} = \begin{bmatrix} u_{1,1} & u_{1,2} & u_{1,3} & \cdots & u_{1,n} \\ u_{2,1} & u_{2,2} & u_{2,3} & \cdots & u_{2,n} \\ u_{3,1} & u_{3,2} & u_{3,3} & \cdots & u_{3,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ u_{m,1} & u_{m,2} & u_{m,3} & \cdots & u_{m,n} \end{bmatrix} \text{and}$$

$$V_{i,j} = \begin{bmatrix} v_{1,1} & v_{1,2} & v_{1,3} & \cdots & v_{1,n} \\ v_{2,1} & v_{2,2} & v_{2,3} & \cdots & v_{2,n} \\ v_{3,1} & v_{3,2} & v_{3,3} & \cdots & v_{3,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ v_{m,1} & v_{m,2} & v_{m,3} & \cdots & v_{m,n} \end{bmatrix}$$

Set the variance matrices for two quadratures $\sigma_U = \sigma_V = \sigma$ where, $\sigma_{i,j}$ is the isotropic surface, with no shiny spots:

$$\sigma_{i,j} = \begin{bmatrix} \sigma_{1,1} & \sigma_{1,2} & \sigma_{1,3} & \cdots & \sigma_{1,n} \\ \sigma_{2,1} & \sigma_{2,2} & \sigma_{2,3} & \cdots & \sigma_{2,n} \\ \sigma_{3,1} & \sigma_{3,2} & \sigma_{3,3} & \cdots & \sigma_{3,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sigma_{m,1} & \sigma_{m,2} & \sigma_{m,3} & \cdots & \sigma_{m,n} \end{bmatrix}$$

Form a random Rayleigh field using two normally distributed quadratures, taking into account the dispersion matrix:

$$A_{[n,m]} = \sqrt{(\sigma U)^2 + (\sigma V)^2}$$

RESULTS AND DISCUSSION

There are different modes of mapping, we will consider the telescopic view mode in which the selected portion of the earth’s surface is irradiated multiple times and a high resolution is obtained from the angular coordinate. In this telescopic mode, there are difficulties. For example, if the aircraft is moving fast enough, it is possible to accumulate enough probing pulses but the elements of the underlying surface are shifted from the pulse to the probe pulse. Then we need to take into account their correlation properties. Therefore, we assume that the velocity of the carrier is such that the displacement of the elements of the underlying surface is insignificant when viewed from pulse to pulse[6].

We confine ourselves to mathematical modeling of the mapping process under different types of distribution laws and visually compare them. The modeling algorithm is implemented in the MATLAB package. And there is an appropriate interface which allows you to set all kinds of mapping modes (side, line and telescopic), set the initial parameters of modes and select the type of echo.

We will simulate the mapping process by synthesizing the antenna aperture using a telescopic view. During the observation of the site by the earth's surface, the center of the beam shifts to the center of the observation zone, at each radiation period of the probe signal pulse.

Now in order to observe the characteristics of the elements of the radar image resolution after the synthesis, we introduce a test image where the echo from the elements of the underlying surface will fluctuate according to the equivalent distribution laws or will be stable.

Results of computer modeling: It is necessary to simulate a random field distributed according to the Rayleigh law arbitrary size by the algorithm given above. The results can be represented as (Fig. 1-3):

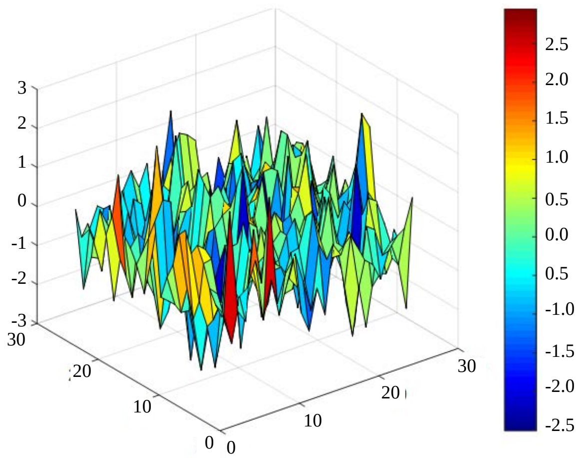

Fig. 1: Random normal field

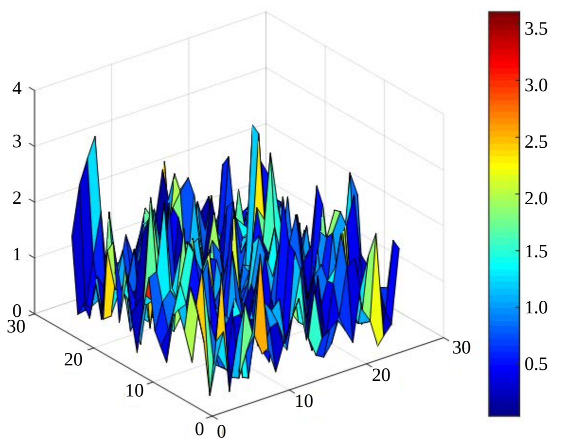

Fig. 2: The random Rayleigh field corresponds to reflections from the earth's surface

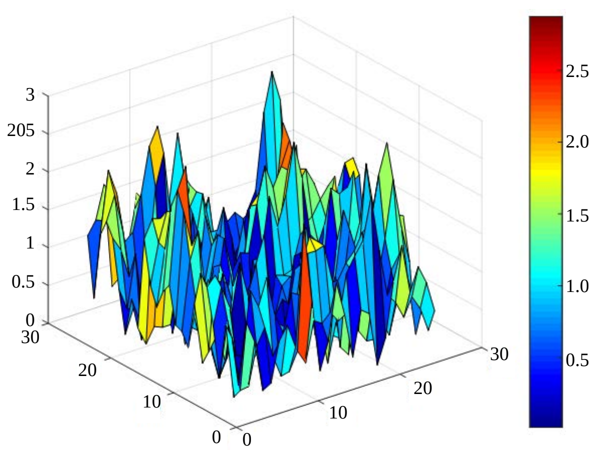

Fig. 3: The random log-normal field corresponds to reflections from the sea surface

According to the results of computer simulation, it is visually evident that the stable characteristics of the resolution elements after the operation of the radar image formation algorithm have been obtained with fluctuations of the echo signal according to the Rayleigh-Rice and Weibull distribution laws and the worst resolution characteristics were obtained with the log-normal distribution law. Under the Rayleigh law, the results of the study were of a satisfactory nature.

CONCLUSION

Based on the results obtained, two conclusions should be drawn. From the first conclusion, it follows that the worst result is obtained with the log-normal distribution law, the best with a stable signal, whereas under the Weibull law, the particular case of which are the laws of Rayleigh and Rayleigh-Rice, the resolving characteristics are approximately the same.

Therefore if a person wants to calculate his mapping system without even knowing the synthesizing algorithms, simulating an echo signal according to the log-normal law knows that this will give him the worst result of the radar image resolution performance, because the dispersion law is large but it will be better if there will be other distribution laws of its characteristics.

The second conclusion is that, since some of the laws give the same result, and the Weibull law has invariance under reflections from the ground, the Weibull distribution is an excellent model for describing the echo signal.

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