Modeling of synthetic-aperture radar in X and P-band

A N Leukhin¹, A A Voronin¹, V I Bezrodnyi¹, O V Galtseva²

¹Mari State University, Yoshkar-Ola, Russia
²National Research Tomsk Polytechnic University, Tomsk, Russia
E-mail: leukhinan@list.ru

Abstract. Synthetic-aperture radar is usually a complex software and hardware system. It allows obtaining images in radio range, comparable in resolution with optical systems. The advantage of radio waves is that the images are of high quality, despite cloudiness and dark time. The development of algorithms for such systems is a rather complex process. Mathematical modeling applied in purpose to reduce costs. In this paper, we give an overview of early created systems. We discuss the methods for calculating the scattered electromagnetic field. We choose methods that are most suitable for simulating a synthetic aperture radar. Combination of different approximation methods allows us to process large scenes. We take into account the various effects that arise when propagating radio waves. Also, we describe algorithms for a synthesis of radar images. In particular, we consider range-migration algorithm and time-frequency processing algorithm. We show that the frequency-time processing algorithm is preferable for synthesis a radio image in the X-band due to its speed. In opposite, the range-migration effect in P-band is too strong to ignore it. The time-frequency algorithm gives not focused image with serious artifacts. It is better to use the range-migration algorithm for P-band.

1. Introduction

Earth remote sensing with radio, infrared and optical waves is an integral part of the modern human activity.

Space and aerial remote sensing are used to solve practical problems of land use, agricultural and forest monitoring, land and sea ecology, control fishing areas, identifying preconditions of dangerous phenomena as: landslides, floods, critical changes in the geometry of natural and artificial objects and engineering structures, as well as technical and military intelligence tasks.

Remote sensing of the Earth’s surface started at the beginning of the 20th century and is still ongoing. There are two types of systems depending on the wavelength: optical and radio. The advantages of the optical remote sensing are high resolution and the relative simplicity of the onboard equipment. Disadvantages of this type of systems are dependence on meteorological conditions and time of day. In opposite to that, radar remote sensing is an effective method for obtaining operational and long-term information.

Historically, the implementation and development of space satellites with SAT can be characterized in 4 stages.

The first stage is the research stage, which includes the launch of the American SAR Seasat-A (1978), SIR-A (1981), SIR-B (1982) and Soviet Mech-K, Mech-KU, Kosmos-1870 (1987–1989), Almaz-1 (1991–1992). Also should mention SIR-C/X-SAR (1994) developed by USA and Germany. At this stage, a large amount of experimental material was accumulated. Developers have produced methods and software packages for processing and interpreting radar images. Methods for solving military intelligence tasks have appeared at that time.
The second stage is the refinement of the techniques for the processing of radar images applied to practical remote sensing problems in various fields of human activity. European satellites ERS-1 (1991–2000), ERS-2 (since 1995), Canadian Radarsat-1 (since 1995), Japanese JERS-1 (1992–1998), USA military satellites Lacrosse (launches 1988, 1991, 1997, 2000, 2005) have provided information for improvements of processing methods on this stage.

The third stage is the great leap in radar imaging which includes launches interferometric SAR in 2000. This type of SAR with rigid base allows creating relief height maps. Such SAR systems found its place in full-polarimetric Envisat-1 and PALSAR, that can cover 80% of Earth surface. Commercial use of SAR imaging has developed.

The fourth stage is an information explosion in the field of space radars, which occurred in 2007 when Germany, Italy, China, Japan, and Canada launched into orbit 9 satellites with radar systems.

Modern technologies make it possible to create satellite radars with a spatial resolution about few centimeters. The achieved high resolution of space-based SARs allows solving the problem of radio vision, having advantages not only in all-weather conditions but also in the possibility of detecting and recognizing objects of observation by radar contrasts and selection of moving ground objects.

Still, some important problems of radar imaging remain unsolved today. Tasks such as detecting, tracking, and estimating parameters of airborne targets are unaffordable for modern airborne radar systems.

2. Research Method

2.1 Time-frequency algorithm

The time-frequency algorithm assumes a transition from the calculation of a two-dimensional convolution to the execution of two one-dimensional operations of processing a radio hologram.

To do this, after compression of the signal in range, a transition is made to the frequency domain along the azimuth coordinate [1]. The dependence of the Doppler frequency on travel time is

$$f(t_x) = \frac{1}{2\pi} \frac{d\phi(t_x)}{dt_x}.$$  (1)

Function $\phi(t_x) = \frac{4\pi}{\lambda}(t_x)$ describes the phase modulation of the azimuth signal. Then we get

$$f(t_x) = f_x = \frac{V^2_n t_x}{\lambda r_0}.$$  (2)

The current increment of the slant range relative to the traverse channel as a function of travel time is

$$\bar{r}(t_x) = r(t_x) - r_0 = \frac{V^2_n t_x}{2r_0}, \quad t_x = -\frac{f_x \lambda r_0}{2V^2_n}.$$  (3)

The time is related to the Doppler frequency $f_x$ linearly. Therefore, substituting (2) into the range function (3), we obtain the following dependence of the current migration on Doppler signal frequency:

$$\bar{r}(f_x) = \frac{f_x^2 r_0}{8V^2_n}, \quad -\frac{\Delta f_x}{2} \leq f_x \leq \frac{\Delta f_x}{2},$$  (4)

where $\Delta f_x$ is spectrum width of the SAR trajectory signal.

Equation (4) expresses the parabolic law of changing the distance from the current frequencies. At the same time, the parabola curvature is proportional to the slant range $r_0$. With the help of the Fourier transform only along the coordinate $x$, the transition from the two-dimensional region “slant range –
path range” to the two-dimensional region “slant range-Doppler frequency \( f_x \)” is performed. At the same time, for all points of the surface that have the same traverse range, the dependence of the magnitude of migration on frequency will be the same. Consequently, the subsequent direct rectification allows you to move signals with the same traverse range into one channel and form a two-dimensional signal with no migration.

However, the dependence calculated with the help of (4) will have a different view for different slant ranges, therefore, along with the slant range, the Doppler shift correction will occur with an error. It is believed that it is advisable to perform the correction relative to the center point of the frame with an inclined range \( r_{oc} \), however, at the edges of the frame, the quality of compression will be lower, which leads to distortion and an increase in the level of side lobes. In addition, with the complex law of motion of the carrier, when the support function must be recalculated at each repetition period, the use of this algorithm is impossible.

In this regard, the use of the algorithm described above may be impractical for some applications.

2.2 Range migration algorithm

Range migration algorithm directly compensates the offset of the signal in range channels [2].

Range migration is estimated by

\[
\frac{\Delta R}{r_d} = \frac{\sqrt{R^2 + x^2} - R}{r_d}. \tag{5}
\]

Range migration at the edge of the antenna pattern is equal

\[
\frac{\Delta R_{\text{max}}}{r_d} = \frac{\sqrt{R^2 + (L_s / 2)^2} - R}{r_d}. \tag{6}
\]

Thus, during the synthesis of the aperture, a signal from a point reflector with a slant range \( R = 6000 \) m, \( r_d = 0.15 \) m, \( \Delta x = 0.3 \) m, \( L_s = 350 \) m will be observed in 17 channels of the range.

The range-migration effect greatly complicates the task of the synthesis of radar images. This is explained by the fact that the invariance of the sample line of the radio hologram to a shift along the \( X \) axis and, consequently, to a time shift is broken. Thus, the solution of the problem of compression in azimuth as a compression of the chirp signal using a matched filter in the frequency domain along a single line of the radio hologram is impossible. Therefore, compression in azimuth must be performed individually for each synthesized point of the image \( \hat{I}_{p,q} \) by calculating the scalar product

\[
\hat{I}_{p,q} = \sum_{n=-N/2}^{N/2} w_{n+p,m + \Delta m(q, r_d, n, r_d)} \cdot \hat{h}_{n,m}, \tag{7}
\]

where

\[
\Delta m(R_m, x_n) = \frac{\Delta R}{r_d} = \frac{\sqrt{R^2 + x_n^2} - R_m}{r_d}, \tag{8}
\]

\[
\hat{h}_{n,m} = \exp\left(-j \phi(n \cdot T \cdot R_m)\right), \tag{9}
\]

\[
\phi(t, R_m) = \frac{4\pi}{\lambda} \sqrt{R_m^2 + x_n^2} = \frac{4\pi}{\lambda} \sqrt{R_m^2 + \left(V(t - t_0)\right)^2}, \tag{10}
\]

where \( w_{n,m} \) is an element of the radio hologram after compression by the slant range, \( \hat{h}_{n,m} \) is a filter impulse response for the \( m \)-th channel slant range \( R_m \).
3. Results and Discussion

In our case, we decided to use two mathematical models for calculating the scattered field, the results of calculations from each of them we combine according to the principle of superposition.

Vehicles and man-made structures that are of particular interest in SAR are usually composed of metal structures. Thus, we can restrict the exact model of the calculation to only perfect conductors, the scattered field from which is determined mainly by the geometry. A similar situation applies in the military aviation radar. One of the most well-known methods for calculating the scattered field from a polygonal model is the method of the physical theory of diffraction (PTD), developed by P. Ya. Ufimtsev [3]. In the best way, the formulas for calculating the scattered field in accordance with the PTD are shown in [4–6].

On the other hand, the underlying surface usually consists of dielectric materials, calculations for which are more difficult than for an ideal conductor. It remains for us only to apply the statistical description of the reflective properties of materials, taking into account the polarization and angle of irradiation. The entire underlying surface is marked with one of the prepared materials such as asphalt, concrete, dry dirt, wood, etc. Description of materials built on the works [7–10] in which produced the experimental evaluation of scattering characteristics.

In order to compare the previously described approaches to the synthesis of radar images, we produce a mathematical modeling of the synthetic-aperture radar. The radar scene is represented by a forest road with different density of trees, and there are also open areas of terrain. In addition, there are 5 vehicles in various locations on the scene.

Figures 1 and 2 represent the result of work range-migration algorithm. The scene for modeling the P-band is an exact copy of the X-band, with the exception of the material properties of the scene.

![Figure 1. Range-migration algorithm (X-band).](image1)

![Figure 2. Range-migration algorithm (P-band).](image2)

The cross along azimuth and slope range (Figure 3) in both sides of the vehicle appears because of high brightness of vehicles in P-band (Figure 4). Side lobes after matched filtration along with slant range and azimuth are brighter than underlying surface.
First of all, it should be noted that with time-frequency processing, vehicles are not focused enough. This is due to the fact that for the formation of radar images in the P-band, a significantly larger synthesized aperture is needed and, therefore, the effect of migration in range will be stronger. It should also be noted that in the P-band, due to the radio transparency of the foliage, it is possible to detect targets under the cover of the forest.

Figures 5 and 6 represent a difference between the two algorithms in different bands. As it can be seen in Figure 5, there is no much difference between range migration and time-frequency algorithm (Figures 1 and 3). But there is a small difference to the left and right sides of the image, which appears as it been discussed in section 2 because the time-frequency algorithm focused only in the middle of the image. Due to a larger size of the aperture in P-band and brightness of the vehicles, this effect yields a stronger difference (Figure 6).

It can be seen that the time-frequency processing algorithm creates an image that does not differ
much from the result obtained using the range migration algorithm. In this case, the method of frequency-time processing is preferred, since it allows you to implement an FFT procedure to increase the speed of synthesis.

4. Conclusion
The calculation of the scattered field usually meets with two requirements in the simulation problem. First, a sufficiently accurate electrodynamic model is needed to observe diffraction, diffuse and specular reflection effects. Secondly, a model is needed that is capable of calculating large areas of the underlying surface in adequate time.

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