Revisiting the conducting of measurements from the board of International Space Station by decimeter synthetic aperture radar system

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Abstract. Nowadays the importance of using synthetic aperture radar (SAR) in the P and VHF bands for object recognition, as well as for surface and subsurface sensing of the Earth’s surface has been proven. However, the space experiment using P-band SAR has not yet been implemented. One of the most important reasons for this is destructive influence of the ionosphere on the quality of synthesized images. It is expected that the polarimetric radar survey of the Earth’s surface in the years to come will be provided by two spacecraft – "BIOMASS" and "ISS-SAR(P) (International space station-SAR(P))", operating at frequencies ~435 MHz.

Variety of phenomena related to radio wave propagation through the ionosphere, as well as the temporal and spatial inhomogeneities of its properties, has been the subject of research for many decades. In the case of the use of SAR of P and VHF bands for remote sensing of the Earth (ERS), the situation is aggravated by the fact that various processes in the ionosphere begin to concentrate, that reduces the unique properties of the performance of these devices to a minimum. As a result, a number of provisions concerning the application of the SAR of P and VHF bands for remote sensing require clarification and additional studies of the ionospheric influence on electromagnetic radiation passing the "Satellite – Earth – reflection from the Earth’s surface – Satellite" route. Such studies can be carried out directly in the course of the space experiment (SE) by creating specialized ground test sites, equipment of which works according to the program coordinated with the operation of SAR. The ISS-SAR(P) experiment in the area of a ground-based test site should primarily be considered as the development of methods for additional ionosphere research, and also as an improvement in methods for compensating the influence of the ionosphere on radar images.

Keywords: synthesized aperture radar, Earth’s ionosphere, oblique and track-range resolution, phase-gradient autofocus, active calibrator with specific capabilities.

1. Introduction

Radar stations with synthesized aperture of P(λ~70cm) and VHF(λ~2-5m) bands are considered as effective method of detecting objects under the vegetation cover and under the surface layer of the Earth [1–4]. Despite the fact that the technical capabilities make it possible to create space SARs even in the meter range, no experiments have yet been carried out in World practice. The
reason is the difficulty of compensating for the loss of coherence and polarimetric distortion of the received signal due to the effects of radio wave propagation in these ranges in the Earth’s ionosphere. Theoretical studies [2] have shown that the unique properties of P and VHF bands can be minimized due to the destructive influence of the ionosphere if used on spacecraft.

It should be noted that even high-quality averaged modern models of the ionosphere will have little effect on the performance of these devices. This is due to the fact that the resolution of SAR depends on the ionosphere characteristics that are actually rapidly fluctuating in space and time. In addition, some processes in the ionosphere that affect the formation of synthesized images are poorly understood. A number of examples are provided below to show the need for more detailed elaboration.

2. Peculiarities of radio wave propagation in the ionosphere

The ionosphere is a layer of the planet’s atmosphere, consisting of a mixture of neutral atoms and molecules of gas and quasi-neutral plasma. Ionospheric plasma is described by the concentration of electrons. The electron concentration profile varies with day, season, latitude, solar activity, magnetic storms, etc. The ionosphere usually has a number of local peaks of electron density called D, E and F layers. In each layer of the ionosphere, irregular thickening and rarefaction of the ionisation density occur continuously. A large number of studies have been devoted to the influence of the Earth’s ionosphere on the radio waves propagation and are primarily related to problems of information transfer and study of the ionospheric parameters [3, 4, 7–10].

The solution to the problem of broadband signals propagation in an inhomogeneous, unsteady ionosphere (dispersing medium) located in the Earth’s magnetic field remains relevant to the present day. Depending on the radio waves frequency the electrical properties of the ionosphere are different for various radio wave bands. In the proposed BIOMASS and International space station SAR(P) (ISS-SAR(P)) experiments radar stations would operate in \( f \sim 435 \text{ MHz} \) band. Frequency \( f(435 \text{ MHz}) \gg f_p, f_h \), where \( f_p(5-10 \text{ MHz}) \) is the plasma frequency (frequency of natural longitudinal oscillations of spatial charge in a homogeneous plasma in the absence of a magnetic field), \( f_h(5-10 \text{ MHz}) \) is the gyromagnetic frequency (frequency of rotation of the electron in a constant magnetic field \( H \) in the plane perpendicular to \( H \)). The magnetic field of the Earth makes the ionosphere anisotropic and as a result of the rotation of the polarization plane of electromagnetic emission (EME) is observed. At distribution of EME in the ionosphere dielectric permeability \( \varepsilon \) and conductivity \( \sigma \) have the form

\[
\varepsilon = 1 - \frac{\omega_0^2}{\omega^2 + \nu^2}, \quad \sigma = \frac{e^2 N_e \nu}{m(\omega^2 + \nu^2)},
\]

For the considered P-band in most of the ionosphere the ratio \( \omega_2 \gg \nu_2 \) is true and the refractive indices \( (n) \) and absorption depend on the frequency

\[
n = \sqrt{\varepsilon} = \sqrt{1 - \frac{\omega_0^2}{\omega^2}} \approx 1 - \frac{1}{2} \frac{\omega_0^2}{\omega^2}, \quad \chi = \frac{2\pi \sigma}{\omega \sqrt{\varepsilon}}.
\]

As a result, the impulses are distorted when passing through the ionosphere [11]. A characteristic feature is that the distortion depends on the distance passed by the radio wave.

3. Radio impulse distortions in the ionosphere

Dispersion properties of ionospheric plasma cause distortions of signals propagating in it:

a) due to dependence of the phase speed on the frequency – the pulse duration changes;

b) due to the Faraday effect (each frequency component of a complex signal rotates at its own angle) – the rotation of the signal polarization plane is observed;
c) due to the dependence of the absorption coefficient on the frequency – the shape of the pulse changes.

The project "ISS-SAR(P)" is supposed to use the signal with linear frequency modulation (LFM). As a result, the type of time-frequency dependence of the signal differs from the linear one. A detailed consideration of the propagation of the LFM signal in the ionosphere is considered in [12]. Studies have shown that the dependence of the change in frequency on time within the pulse varies. If plane polarized radiation is used, the shape of the pulse at both polarizations will also change due to Faraday rotation [3]. This distortion depends on the characteristics of the ionosphere state, the angle between the Earth’s magnetic field line and the direction of signal propagation [3, 4]. As an example, in figure 1 from [3] the transformation of the pulse envelope and the type of frequency filling depending on the orientation of the beam with respect to the Earth’s magnetic field are shown.

![Figure 1. The envelope and frequency field of convolution of a broadband signal in an anisotropic ionosphere: 1-3 depending on the orientation of the beam with respect to the Earth’s magnetic field 0°, 45°, 90°](image)

If the parameters of the ionosphere change and the satellite moves, the appearance of these dependencies also changes. This example shows the complexity of synthesizing a signal over a range. The following uncertainties exist for performing the synthesis of the reflected signal: a) the change in signal duration, b) changes in the shape of envelope, c) changes in the shape of frequency filling of the signal convolution. In addition, the question of the probing pulse reciprocity on the ISS–Earth and Earth–ISS routes remains. One of the reasons for the reciprocity violation may be a change in the radio wave propagation conditions on the ISS–Earth and Earth–ISS routes due to the movement of the ISS and also the transformation and movement of heterogeneities over certain period of time.

As already noted, the ionosphere is an anisotropic medium due to the presence of the Earth’s magnetic field. In particular, the change in electromagnetic wave polarization in the ionosphere is explained not only by the Faraday effect, but also by the Cotton-Mouton effect [13]. The Cotton-Mouton effect has influence on the polarimetric properties of an electromagnetic wave at frequencies less than about 150 MHz. The order of magnitude of the effect decreases with increasing frequency (this effect is assumed to be negligible at frequencies greater than 300...
MHz). However, the value of the polarization angle due to this effect depends on the reflecting properties of the underlying surface. The principle of calibration of polarimetry SAR (computing the polarization scattering matrix) is based on the fact that its cross-polarizing components in the ionosphere for a linearly polarized SAR are equal to (VH=HV) [14]. When the influence of the Cotton-Mouton effect on the polarization matrix cannot be ignored, it is impossible to recover the true scattering matrix from measurements [13]. For successful use of polarizing SAR of P and VHF ranges, the proof of reciprocity principle of cross-polarizing components is required, in other words, that the radar images (RLI) on cross-polarizations are the same.

4. Influence of the heterogeneities ionosphere

The phase distortion of the signal passing through the ionosphere is of great importance in obtaining a RLI in the P-band. In the ionosphere, irregular thickenings and rarefactions of the ionization density occur continuously, both over time and from point to point. In addition, the inhomogeneous structure of the ionosphere move. Heterogeneities are presented by regions with an electron density different from the average value at a given ionospheric height. The deviation of the electron density of heterogeneities from the average value is (0.1÷1)%. The speed of movement of heterogeneities is assumed to not exceed 1÷10 m/s [15]. When probing the Earth’s surface from the ISS, the radio wave crosses regions of heterogeneities with dimensions comparable to the distance traveled by the ISS over the probing pulses repetition period, as well as heterogeneities up to several kilometers in size. Despite the fact that the deviation of the electron density of heterogeneities from the average value is (0.1÷1)% of the total concentration, fluctuations in the phase of the wave passing through these heterogeneities can reach significant values. The analysis of the influence of small-scale non-stationary heterogeneities on the formation of synthesized images requires very close attention.

![Figure 2. Explanation of the problem of double wave propagation in randomly inhomogeneous media.](image)

During the propagation of electromagnetic waves in real media a variety of fluctuation effects occur due to the random heterogeneities. It was found that when waves pass through the same heterogeneities twice, qualitatively new fluctuation effects can be observed[16]. At first glance, it may seem that the fluctuation properties of the wave entering the receiver in the experiment (figure 2a) are similar to the properties of a wave that has passed twice the distance 2L in a straight line (figure 2b), since in both cases the wave passes through a randomly inhomogeneous medium along a path of the same length 2L. However, in the experiment (figure 2a), the reflected wave passes through the same heterogeneities as the incident one, while on the track (figure 2b), the wave propagates through various heterogeneities. This is what leads to specific fluctuation effects, in particular, doubling the phase dispersion of a normally reflected wave (figure 2a) compared to the phase dispersion of a wave propagating on the 2L track (figure 2b). Due to the satellite movement and movement of ionosphere, the question arises: through which of heterogeneities does the wave propagate on the satellite–Earth and Earth–satellite routes? Are
heterogeneities the same or different ones? If the wave propagation on the satellite–Earth and Earth–satellite routes occurs through the same heterogeneities, the phase fluctuations increase twice [16]. This issue is not considered in the works devoted to the P-band satellite operation.

5. Problems of EMR reflection from the Earth’s surface
When an electromagnetic wave is reflected from a rough dielectric surface, there are features that can affect the interpretation of the P-band SAR results. For example, consider the reflection of circular polarization from a metal surface and from a three-sided angle reflector. Due to the reversibility of the phase during reflection, the direction of rotation of the circular polarization changes to the opposite. In this case, the Faraday angle of the polarization plane rotation on the ISS–Earth–ISS route would be equal to twice the value. However, the behavior of rotation of circular polarization from a rough dielectric surface remains in question.

It is known that when a plane-polarized wave is reflected from a rough surface, cross-polarization components appear. In particular, the reflection model can be represented as a set of various dihedral and trihedral corner reflectors.

Three-sided corner reflectors do not change the plane of polarization when reflected. But since there is a cross-polarizing component in reality, it is necessary to add a set of two-sided corner reflectors to the surface model. The edges of these reflectors is to be rotated at some angle relative to the propagation plane. In this case, the matrix of reflection from them has the form

\[
S = S_0 \begin{pmatrix} 
\cos(2\alpha) & \sin(2\alpha) \\
\sin(2\alpha) & -\cos(2\alpha)
\end{pmatrix}
\]

(3)

and when \( \alpha = \pm 45^\circ \) the matrix is visible

\[
S = S_0 \begin{pmatrix} 
0 & \sin(2\alpha) \\
\sin(2\alpha) & 0
\end{pmatrix}
\]

(4)

Depending on the number and size of angle reflectors, the value of the rotation angle of circular polarization may become unclear. As a result, the polarization plane rotation angle when passing through the ionosphere on the ISS–Earth–ISS route may be equal to zero. And as an example on figure 3 the phase image of a section of the Earth’s surface in an airplane experiment is presented.

![Figure 3](image_url)

**Figure 3.** Fragment of a radar phase image of the underlying Earth’s surface in an airplane experiment (the phase difference between the lightest and darkest value corresponds to 360°).
As expected, the phase of reflection from a rough surface changes chaotically. This leads to rapid fluctuations in the rotation of the polarization plane and further complicates the image synthesis.

6. Justification for the need to create specialized ground polygons

Problems of overcoming the destructive influence of the ionosphere on the performance of space radars with synthesized aperture (SAR) operating in the P and VHF bands are being studied by both foreign and Russian specialists [2, 20, 21]. As a basis, the method of phase gradient autofocus is used, which is successfully applied in obtaining synthesized images from aircraft SAR complexes when compensation of fluctuations in carrier movement is necessary. The authors [20, 21] focused on azimuth convolution. At the same time, amplitude fluctuations, as well as fluctuations in the pulse duration, were not considered. According to the authors of this paper, the most advanced method for compensating the influence of the ionosphere on the radiolocation images (RLI) is presented in [2, 17, 18]. In [2, 17, 18] a two-dimensional adaptive iterative method for compensating the ionospheric destructive influence on the formation of RLI was considered. The study was carried out under the assumption that LFM pulses with circular polarization of EMI rotation are used. In these studies fluctuations in the experimental phase were introduced into the holograms obtained in airplane experiments [19]. It was shown that the formation of the synthesized image by range and azimuth should be considered as a single whole. As a result, the authors [2, 17, 18] showed that the destructive influence of the ionosphere can be minimized. However, when considering compensation for ionosphere influence, possible amplitude distortions and fluctuations in the pulse duration are not taken into account. The influence of the double EMI passage through the same ionosphere heterogeneities, the influence of possible features of reflection from the Earth’s surface on the phase fluctuation, the principle of reciprocity of EMI passage on the satellite–Earth and Earth–satellite routes are not considered. In addition, questions about the frequency and magnitude of oscillations of Faraday rotation angle of the polarization plane \( \Omega \) and phase fluctuations in the image synthesis interval along the azimuth remain open.

As an example, we can use data analysis [19]. In [19] the results of measuring phase fluctuations for P-band signals of circular polarization over a time interval of \( \sim 10 \) sec are presented (figure 4a), as well as the results for the first 5-sec. part (4b) and the second 5-sec. part (4c).

Using the obtained dependencies, we can calculate the spectrum of fluctuations over an interval of 10 seconds and on two nearby 3.7-sec. intervals \( S_1(f) \) and \( S_2(f) \). The results show: a) that the phase fluctuation spectra exceed the Doppler frequency spectrum of the RSA, b) the correlation coefficient \( S_1(f) \) and \( S_2(f) \) is close to zero \( R \sim \) 0.016. In figure 5 the comparison of spectra after averaging by a sliding window over 4 dimensions is shown. The analysis shows that it is possible to distinguish two frequency bands \( \Delta f_1(0-0.05 \) Hz) and \( \Delta f_2(0.05-0.14 \) Hz). In the frequency band \( \Delta f_1 \) the correlation coefficient \( R_1 \sim 0.65 \) and in the frequency band \( \Delta f_2 \), \( R_2 \sim 0.01 \). Thus, the results obtained [19] correspond to the passage of EMI both through large heterogeneities of the ionosphere and through small-scale ones.

Therefore it is necessary to develop a method for compensating the ionosphere destructive effect of radar surveys of an extended area of the surface. This is due to the fact that the proposed method must continuously adapt itself to the random time dependence of the phase fluctuation. In addition, it is necessary to find out the laws of rotation of the polarization plane of the signal from a rough surface. It should also be noted that phase-gradient autofocus can be effectively used in the presence of individual small-sized objects with increased reflectivity on the ground.

For more successful use of the ISS-RSA(R) complex of scientific equipment during the space experiment, it is planned to conduct additional experiments to study the influence of the
Figure 4. Dependence of fluctuations caused by small-scale heterogeneities of the ionosphere in a monochromatic signal at a frequency of 417 MHz when receiving a circular polarization signal. The correlation coefficient for the results shown in (b) and (c) is $R = 0.016$.

Figure 5. Spectra of the phase fluctuations of the two parts and their comparison.
ionosphere and the characteristics of reflection from the underlying surface on synthesized radar images. Such research can be carried out by creating ground polygons (test sites). Ground equipment must operate in different modes according to the program coordinated with the operating mode of the P-band SAR. The joint work of onboard and ground-based equipment should be aimed at studying the influence of the ionosphere, reflection from the Earth’s surface and performing the external calibration of the SAR.

As a rule, ground polygons are equipped with a set of angle reflectors and/or active calibrators that allow receiving signals from the SAR, amplifying and radiating them back after a time delay. If linear polarizations are used, the receiving and transmitting devices of the active calibrator must be equipped with two orthogonal channels. In each channel a digital signal is registered at the carrier microwave frequency, the received signal is processed and further re-radiated in accordance to the operating mode. The type of transmitting microwave signals of the active calibrator should change depending on the task in sync with the operation of the SAR. The frequency components of the LFM of the probed signal propagate in the ionosphere at different speeds, in addition, they are attenuated in different ways. Such the signal form and the law of frequency filling undergo some changes. Despite the fact that the frequency band of the probed signal is relatively narrow (6-50 MHz), the distance from the ISS to the Earth and back is about 900 km. Therefore, the effective duration of the probed pulse changes when it passes through the ionosphere, the law of frequency modulation changes, and the amplitude form of the pulse changes. In addition, the ISS is shifted from pulse to pulse, as well as the EMI polarization plane.

The Earth’s ionosphere is heterogeneous in space and non-stationary in time. Spatial heterogeneities have scales from meters to tens of kilometers, which change over time (this issue is not sufficiently studied). The speed of movement of small-scale components, their relaxation time and the relation of sizes of heterogeneities and the height of their location above the Earth’s surface are not completely clear. The ionospheric heterogeneity leads to fluctuations in the phase of the received signal both due to the fluctuations in the rotation angle of the polarization plane and the dispersion properties of the ionosphere. High-frequency phase fluctuations are the most important part for obtaining azimuth images of high resolution.

Thus, it is clear that for the successful application of P-band SAR it is necessary to conduct research of the ionosphere at least in certain areas of radar survey. At the same time this polygon must be equipped with three-sided corner reflectors, which are designed not only as just reflectors, but also to perform specific functions. It should be noted that the operational features of the angle-reflector and active calibrator for the P-band are different. In particular, it is noticeable that for circular polarization, when reflected from a flat surface, the direction of rotation of the polarization plane changes to the opposite. For a conventional active calibrator, the rotation direction of the polarization plane does not change, i.e. when EMI propagates on the Earth–satellite section, the Faraday rotation angle is to be compensated. In this case, SAR of P-band and the ground segment operate as a single complex. It should also be noted that the study of the ionospheric influence on the work of polarization PCAs was currently carried out on the results of measurements obtained in the L-band [20, 21], where the influence of the ionosphere is small.

7. Requirements for ground segment hardware
In this experiment the active calibrator is designed:

a) for receiving signals from the SAR (P) transmitter, forming a packet of reflected signals based on them, simulating the reflection from a point target (change in amplitude and delay time);

b) to change the delay time from 1.2 to 6 μsec of the pulse duration (the duration of the LPM pulse is 50 μsec);
c) to provide radiation of several pulses during the time of repetition of the probing pulse;
d) to provide a mode when the polarization of the signal at the active calibrator output is the
same as at the input or rotated by the angle, that is set by the program.

When flying over the polygon, the shape of the signal envelope on the Earth’s surface at the
V and H polarizations is determined for each sounding pulse of the RSA V/H polarization. As
a result, for each pulse on the satellite–Earth route, as well as on the Earth–satellite route, it is
possible to measure its duration, envelope, the law of frequency filling, the value of the Faraday
angle of the polarization plane rotation, and to study the time interval at which the reciprocity
principle is observed.

The data obtained during the flight of the ISS over this device allows us to determine the
intensity of fluctuations in the angle of the polarization plane rotation and the fluctuations
in the signal parameters caused by the passage of EMR both on the satellite–Earth and the
Earth–satellite route.

When reflected from the Earth’s surface, the rotation of the polarization plane of the reflected
signal changes. The possibility of changing the polarization plane at the output of the active
calibrator makes it possible to study the effect of rotation on the quality of the RLI.

8. Conclusion
For the successful implementation of space experiments with P-band SAR planned for 2022-
2025, fairly complex research aimed at analyzing and compensating the destructive influence of
the ionosphere on the results of radar surveys is required.

Conducting a space experiment with the SAR of the P-band currently fits the status of
a complex study that requires a large amount of diverse interdisciplinary research involving
specialists in various fields of knowledge.

Analysis of the ionospheric influence on the operation of P-band space radar showed the need
to create a specialized ground polygon equipped not only with three-sided corner reflectors, but
also a modified transponder with hardware and software for information processing, that works
in accordance to the equipment on the ISS. The joint coordinated operation of the P-band SAR
with the ground segment makes it possible to carry out double-significant research: 1) study of
ionospheric parameters and 2) developing a technique for processing the holographic SAR data
to obtain high-quality radar images necessary for interpreting the reflective properties of the
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