Preliminary analysis of experimental cross-polarization images from polarimetric aircraft synthetic aperture radar of P-band

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Abstract. An analysis of polarimetric synthetic aperture radar (SAR) space observations usage for measuring Faraday rotation angle of plane-polarized electromagnetic radiation on the satellite-Earth-satellite route and calibrating the radar is performed. It is shown that technical characteristics of SAR, the radar movement during the survey and features of electromagnetic waves reflection from the rough Earth’s surface, as well as small-scale ionospheric inhomogeneities affect the results of comparison the radar images at HV and VH cross-polarizations. As a result, there is a problem of SAR signal polarization plane Faraday rotation angle measuring accuracy, which is needed for proper calibration of linearly polarized polarimetric long-wave band SAR using methods proposed by soviet and foreign specialists. Currently, there are no studies of Earth’s surfaces reflection properties carried out by means of space-based long-wave band polarimetric synthesized aperture radars at HV and VH polarizations. At the same time, the authors are not aware of any works, in which the reciprocity principle of cross-polarized HV and VH radar images is analyzed. An attempt to use aircraft P-band radar images at HV and VH polarizations for studying the reciprocity principle is performed in this work.

Keywords: synthetic aperture radar, radar specifications, Earth’s ionosphere, Faraday rotation angle of polarization plane, reciprocity of radar images on HV and VH polarizations.

1. Introduction
This study covers issues that are significantly connected to space polarimetric long-wave band synthetic aperture radar (SAR) surveys results analysis. However, the same issues occur when analyzing the results of the Earth’s surface polarimetric observations made by aircraft. It is supposed that the reciprocity principle is respected while studying the Earth’s surface and other objects reflections by means of polarimetric SAR, i.e. reflections from the surface at HV and VH polarizations are identical. This assumption is based on the findings of studies [1, 2]. If the experimental cross-polarized measurement results are not identical then this effect is explained by differences in characteristics of H-polarization and V-polarization tracts. In further consideration these differences are taken into account. It should be noted that authors of mentioned studies do not have any information to confirm the reciprocity principle compliance for aircraft radar.
systems. The theoretical modeling (with the help of certain authors of these studies) of reflection in case of probable re-reflection of electromagnetic radiation from elements of an object under consideration, when these elements are located at distances of more than tens of wavelengths, currently shows that in such cases the reciprocity principle requires further research.

Issues related to the rotation angle of SAR signal polarization in ionosphere due to Faraday effect are considered in [3-5]. In particular, knowing the rotation angle of polarization plane is necessary for calibration of linearly polarized polarimetric long-wave band SAR located on board of spacecrafts.

2. Reflection of electromagnetic radiation from the Earth’s surface

The authors of [3, 4] suggest to evaluate the Faraday rotation angle of polarization plane in case of polarimetric SAR by analyzing the experimental complex matrices of measurements in linear polarization basis \( s \) for various combinations of horizontal (\( h \)) and vertical (\( v \)) polarizations of signal during emission and reception

\[
s = \begin{pmatrix} s_{hh} & s_{hv} \\ s_{vh} & s_{vv} \end{pmatrix}.
\]  

The authors explain the differences in radar images received at HV and VH polarizations by:
(i) hardware distortions (different characteristics of \( h \) and \( v \) tracts of SAR);
(ii) distortions that emerge during the propagation of electromagnetic waves on satellite-Earth-satellite path;
(iii) distortions of survey geometry.

In the end, considering the results of matrix \( s \) components measurements:
(i) method for characteristics of \( h \) and \( v \) tracts differences compensation was suggested;
(ii) the reciprocity principle of reflection from the Earth’s surface was supposed to be respected, i.e.

\[
L = \begin{pmatrix} L_{hh} & L_{hv} \\ L_{vh} & L_{vv} \end{pmatrix}, \quad L_{hv} \equiv L_{vh},
\]

where \( L \) is matrix of reflection from the Earth’s surface;
(iii) it was also supposed that due to non-reciprocity of propagation medium the angle of Faraday rotation at signal propagation from satellite to the Earth’s surface and backwards is doubled.

It must be noted here that features which affect the interpretation of SAR results may occur at reflection of electromagnetic wave from the rough dielectric surface [6, 7]. Reciprocity principle in matrix \( L \) may be violated because the cumulative scattering matrix is formed in two steps: in the first stage, a horizontally polarized signal (H) is emitted while the receiver registers both horizontal and vertical polarization; in the second stage, a vertically polarized signal (V) is emitted and both horizontal and vertical polarization signals are received again, that is, radar images at HV and VH are received at different points in time with an interval of \( T \) (impulses repetition interval). In the meantime, the aircraft moves at a distance \( L = w \cdot T \), where \( w \) is aircraft speed. Additionally, signals that are relevant to HV and VH polarizations pass through various small-scale fluctuations of ionospheric inhomogeneities. Thus, calculation of the angle of Faraday rotation of linearly polarized wave using the results of radar reflection matrix \( s \) measurements depends on the aircraft speed, small-scale ionospheric inhomogeneities spectrum [6, 7] and technical characteristics of the construction of SAR. Deterrent to the validation of theoretical studies was the fact that until now there was no space experiment held by means of long-wave band SAR.
3. SAR image formation
The information obtained from radar sensing is formed on the basis of electromagnetic signals, which are complex in their nature. When using SAR, a complex radar image consists of a real and an imaginary image component. After some processing only it is presented in a format convenient for us, as a rule, that is amplitude or intensity format (see figures 1, 2).

Figure 1. Real (a) and imaginary (b) part of the Earth’s surface SAR image; amplitude (c) and intensity (d) format of SAR image obtained by processing of real and imaginary components. Taken from [8, 9].

Figure 2. Real (a) and imaginary (b) part of the Earth’s surface SAR image, (c) the image in amplitude format (our experiment). Grayscale is inverted.

As noted in [8], it is difficult to see useful information in real and imaginary components of the radar image. However, complex components make it possible to obtain radar images in the amplitude format as shown in figure 3 (a, b), as well as radar images in the phase format shown in figure 3 (c, d).
At first glance, radar images both in amplitude and phase format at HV and VH polarizations are identical and, one might say, mutual. However, close examination shows that radar images at HV and VH polarizations in amplitude format are not identical. For comparison, figure 4 shows the same fragments of P-band radar images obtained at HV and VH polarizations almost simultaneously in one run with a time difference equal to the period of sounding impulses repetition. If the dissimilarities in small elements of the radar images could be attributed to the influence of the aircraft movement during this period, then the change in the outlines of inhomogeneities does not fit such an explanation (figure 4).

Elements of $L$ matrix and experimentally measured radar images (1) are the complex values. At this stage of the study, we assumed that the reciprocity principle for complex radar images $s_{hv}$ and $s_{vh}$ can be extended both to radar images in the amplitude format ($A$) and in the phase format ($\varphi$). This assumption was put forward in order to simplify the consideration of the results obtained and for better understanding. But in fact, these components should be analyzed in the format of complex values $A_{hv} \cdot \exp (i\varphi_{hv})$ and $A_{vh} \cdot \exp (i\varphi_{vh})$. The correlation coefficient in this case will also be complex. Further comparison will have to be done on the basis of real and imaginary parts.

Before proceeding to the analysis, it was agreed to explore the obtained radar images in
amplitude and phase formats. Briefly about the parameters of images in the P-band: pixel size is 8 meters in both range and azimuth; the repetition rate of impulses was changed in such a way that images of HV and VH polarizations due to the movement of the aircraft were obtained every $l=0.68m = 2$ meters.

4. Radar image analysis technique

Pixel-aligned images were taken as the initial data in the amplitude and phase format. On the fragments of the radar images in the amplitude format, an area of arbitrary size and shape was selected at any place, see figure 5. The relative position of the area is the same for both images.

![Figure 5.](image)

As a result, we can calculate:

(i) the value of correlation coefficient of images in the selected area;
(ii) correlation functions in $x$ or $y$ while moving the selected area on one of the images in range ($x$) or azimuth ($y$) with fixed area position on the other image;
(iii) correlation functions while moving the selected area along both radar images simultaneously in one direction.

Computation of the correlation function while simultaneous movement of the selected area along both radar images makes it possible to reveal fluctuations in the correlation coefficient of HV and VH images in range and azimuth. This operation allows to find out the possible influence of the type of underlying surface on the reciprocity of cross-polarized images.

The analysis of radar images reciprocity at cross polarizations is based on methods of correlation signal processing. This approach excludes the influence of technical differences in the H and V tracts with the same processing of the holographic data at HV and VH polarizations. As a result, the reciprocity of cross-polarization components of radar images can be influenced by

(i) Aircraft movement. Images at HV and VH polarizations are obtained not simultaneously, but with a time shift equal to the impulse sending period. Images at HV and VH polarizations are from different parts of the Earth’s surface, shifted by a distance corresponding to the SAR movement during one period of impulses emission. It can be assumed that the maximum value of the correlation coefficient will decrease with reduction of the overlapping area of images.
(ii) The fact, that the reciprocity principle for cross-polarized images itself is not strictly proven. This can be verified by measuring the values of the correlation coefficient from various objects located at various range distances for the same fragment of images. Comparing images at HV and VH polarizations in amplitude format over a very small selected area will lead to large fluctuations. Therefore, the average size of selected area corresponded to the window of 1000 to 3000 pixels.

5. The analysis results
As mentioned above, the analysis was performed on the radar images in amplitude and phase formats. Correlation functions for the range direction (x-axis) of HV and VH images in amplitude (a, b) and phase (c) formats are shown in figure 6 (about 3000 pixels in the selected area). The correlation functions are calculated while moving the selected area on the VH image in range direction with azimuth fixed, and in HV image the position of area remains fixed in both range and azimuth.

![Figure 6. Pearson correlation functions of HV and VH images for the range direction: (a) amplitude format, initial scale; (b) amplitude format, enlarged scale; (c) phase format. Selected area is \( \sim 3000 \) pixels in size.](image)

The shape and intensity of the obtained dependencies varies with the type of surface. The maximum value of the considered correlation coefficient in the amplitude format did not exceed \( \sim 0.83 \) all over the image, and in the phase format the absolute value was less than 0.3. According to Chaddock table [10], there is no phase correlation between radar images at HV and VH polarizations.
Figure 7. Real and imaginary parts (a) of complex Pearson correlation function and its amplitude (b). Correlation of HV and VH images for the range direction. The selected area is fixed for HV image and moving in VH image.

Figure 8. (a) Two azimuth positions are fixed and corresponding areas are selected; (b) the dependence of complex PCC amplitude (modulus) and non-complex PCC value on range distance in case of direction 1, (c) in case of direction 2. The selected area is moving in both HV and VH images simultaneously.
Since the received signals are complex in nature, the assessment of the cross-polarization components reciprocity can be carried out directly by calculation of complex Pearson correlation coefficient (PCC). The correlation function will become complex with corresponding real and imaginary parts (see figure 7a). Similarly to the way the radar image in the amplitude format is constructed out of real and imaginary values, the amplitude of complex correlation function of the cross-polarization components is calculated, see figure 7b. The real (non-complex) correlation function for the images in amplitude format (as in figure 6) is also shown for comparison.

In figure 8 the dependencies of real correlation coefficient value (for amplitude format images) and complex correlation coefficient amplitude (for complex images) on range distance are presented at two azimuth positions (direction 1 and 2). Despite the qualitative coincidence, they differ quantitatively. The selected area is moving here in range direction in both HV and VH images simultaneously.

6. Conclusion
The analysis of formation of the Earth’s surface images obtained by long-wave band SAR from space shows that the real value of Faraday rotation angle of the polarization plane for linearly polarized radiation on the satellite-Earth-satellite path is more complex than described in [3, 4]. The main limiting factor in verifying the correctness of theoretical studies is that nowadays there have not been performed any space experiments using SAR of long-wave band. At the same time, there is a compelling need to create ground polygons equipped not only with two-sided and three-sided corner reflectors, but also with special radio technical equipment working in conjunction with SAR [7]. When using aircraft polarimetric SAR, there is no Faraday rotation of the polarization plane of linearly polarized signal, no effects associated with inhomogeneities of ionosphere. The main factor for violation of the reciprocity principle in the back reflection matrix, presumably, should be the aircraft movement during HV and VH images acquisition time interval (equal to impulses repetition period). And the main unclear question remains: is the principle of reciprocity fulfilled at HV and VH polarizations when reflected from rough surfaces? The main disadvantage of studies related [3, 4] is that theoretical considerations are carried out in isolation from the conditions of measurements, possible features of electromagnetic radiation reflection from the Earth’s surface and technical characteristics of radar systems.

The preliminary analysis of reciprocity of experimental radar images at HV and VH cross-polarizations has shown that the images are not identical. The difference is explained, firstly, by the movement of the aircraft. As a result, the correlation coefficients do not reach the maximum value of 1. Secondly, the correlation coefficient depends on the type of underlying surface. The results obtained require further study. This work was supported in part by the State Assignment of Ministry of Science and Higher Education of the Russian Federation theme no. 0030-2019-0008 “Space” and in part by RFBR under Grant 20-02-00703/21.

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