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# 3D POSITION MEASUREMENT SIMULATION OF AIR TARGET'S SCATTERRERS IN INTERFEROMETRIC ISAR

*If one introduces an additional antenna spaced apart in height in inverse synthetic aperture radar (ISAR) it is possible to carry out an interferometric measurement of the scatterers heights. The theoretical relation for estimating the accuracy of the scatterer height measurement is obtained. A simulation model for obtaining the three-dimensional radar images (RI) of air objects in interferometric ISAR was developed. The comparison of the scatterer height measurements accuracy by theoretical relation and the results of simulation at different SNRs is performed.*

***Keywords***: *ISAR, interferometric measurement, 3D image, signal-to-noise ratio, measurement accuracy.*

**Introduction**. Capability of the air objects (targets) recognition is one of the requirements to future radars. This capability involves measuring of various radar characteristics of targets, the choice of informative and robust features, teaching the recognition device and subsequently making decisions about the affiliation of the objects being observed to a particular class (type).

The most informative are the signal signatures that are associated with the form of the target. Examples of such signatures are the high range resolution profile (HRRP) which is a one-dimensional target image, and a two-dimensional (2D) radar image (RI) that is obtained by processing of complex HRRP's consequence in the inverse synthetic aperture radar (ISAR) [1-4].

If reflections from target's bright points (BP) are located in space, then it is possible to obtain three-dimensional (3D) RI, which can improve the quality of the target recognition and study its reflectivity.

**Analysis of recent research and publications**

For today, the problem of 2D ISAR imaging with further measurement of the spatial coordinates of the separated BP is actively explored in the world. In order to solve the problem of 3D imaging of targets in ISAR, a considerable attention has been paid in recent years to the study of the possibility of applying a phase measurement method in the interferometric ISAR (InISAR) [5-13, 14-18]. To measure the height of the BT, this method requires at least two antennas spaced in height. The results of simulation and field experiments confirming the fundamental feasibility of measuring the height of BT which were previously separated by ISAR imaging technique are known [9-13].

In the classic scheme of the ISAR to obtain the high cross-range resolution the discrete Fourier transform (DFT) is used. Before performing the Fourier transform, it is necessary to align HRRPs by range along the line of sight (LOS) and eliminate the random phase term in the reflected signal caused by the radial motion of the target and the instabilities of the transmitter and receiver [1, 9, 15, etc.].

An important task of InISAR is the correct implementation of phase measurements between peaks on complex 2D RI obtained by several channels with corresponding antennas. The relative shift of peaks leads to significant errors in the measurement of phase differences between two RI and, accordingly, the measuring of BT's spatial coordinates. In [5, 15], the possibility of a comprehensive account of BT's shift differences in different channels is investigated and bringing to the position of one reference channel to compensate for the differences in scatterers motion on different RI, or 3D focusing. In [16], simulation of the target motion effect is performed at the interferometric restoration of ISAR images in the realistic scenario of the marine target movement with complex dynamics. In [16], simulation of the target motion influence at the restoration of InISAR images is performed in the realistic scenario of the marine target movement with complex dynamics. However, the interpretation of ISAR images remains problematic for several reasons. One of them is the fact that the image plane can't be determined by the user, but depends on its own motion of the target and its position relative to the radar. In order to overcome the problem of interpretation of 2D ISAR images in [17] a method was presented for 3D reconstruction of moving objects. This method is based on the use of an InISAR with a system of antennas spaced in vertical and horizontal planes.

In [18] is offered processing of multichannel data fusion for ISAR imaging, which improves the performance of the height estimate unlike the case of independent processing.

When using a phase (interferometric) method, much attention is paid to the measurement accuracy of the harmonics phase difference. It is also necessary to take into account the possible impact of neighboring harmonics (scatterers) on one another. A separate issue is the choice of the method of spectral analysis to measure the phase difference in the case of the BP convergence.

However, the influence of various destabilizing factors on the measurement accuracy of the BP height remains insufficiently investigated. Among such factors, the most important are the influence of noise and interference and the influence of the spectral analysis procedure in the ISAR, depending on the location of the BT relative to other bright points. In ISAR, the most common method of spectral analysis is the DFT, which has computational advantages, especially in the application of fast algorithms for its implementation.

**The aim of the article is** developing the model for measuring the spatial position of bright points and obtaining 3D radar images of air targets, and assessing the accuracy of BP positions measurement under the influence of destabilizing factors.

**Main part**

The general case of the target irradiation by signals from two antennas is shown in Fig. 1, where $H$ is the height of the target, $h$ is antenna height (distance between two antennas), $R_{11}$ and $R_{21}$ is distance from the first and second antennas to the first BP along the line of sight.

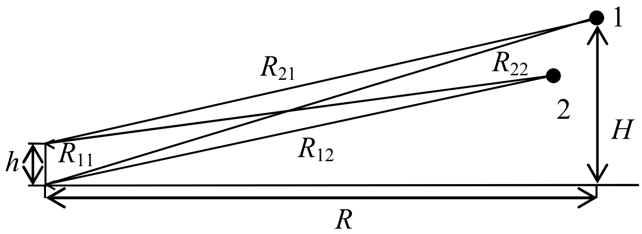



Figure 1 – Observation of two BP with two antennas

In this case the point's height can be expressed through the phase difference of the reflected signals

$$H = \frac{\lambda(\varphi_{11} - \varphi_{21})}{4\pi} \frac{(R_{11} + R_{21})}{2h} + \frac{h}{2} \qquad (1)$$

where $H$ is the height of BP, $\lambda$ is the radar wavelength, $\varphi_{11}$ and $\varphi_{21}$ is the measured initial phases of the BP for the first and second RI. It is taken into account here that the phase difference of the received signals depends on the difference of ranges to the BP from the upper and lower antennas as

$$(\varphi_{11} - \varphi_{21}) = \frac{4\pi}{\lambda}(R_{11} - R_{21}).$$

When measuring the height of BP, this method requires measuring a very small phase difference (units of degrees). The accuracy of measurements of phase difference will be significantly influenced by the signal-to-noise ratio (SNR) of the received signal.

To find the mean squared errors (MSE) of the BP heights measurement, we introduce the vector of the current values of the measured quantities

$$\mathbf{B} = (\varphi_1 \quad \varphi_2 \quad R_1 \quad R_2)^T$$

and the absolute errors vector of measurements

$$\Delta\mathbf{B} = (\Delta\varphi_1 \quad \Delta\varphi_2 \quad \Delta R_1 \quad \Delta R_2)^T$$

in relation to their true values

$$\mathbf{B}^0 = (\varphi_1^0 \quad \varphi_2^0 \quad R_1^0 \quad R_2^0)^T.$$

In this case, the value of height can be represented as a function $H(\mathbf{B})$, which is decomposed into a Taylor series, with the preservation of only the first term of expansion as follows

$$H(\mathbf{B}) = H(\mathbf{B}^0 + \Delta\mathbf{B}) \approx H(\mathbf{B}^0) + \mathbf{J}_0(B - B^0) \qquad (2)$$

where $\mathbf{J}_0$ is the Jacobi matrix at the point $\mathbf{B}^0$. In this case, it is a column vector of partial derivatives

$$\mathbf{J}_0 = \left( \frac{\partial H}{\partial \varphi_1} \quad \frac{\partial H}{\partial \varphi_2} \quad \frac{\partial H}{\partial R_1} \quad \frac{\partial H}{\partial R_2} \right)^T.$$

Elements of the vector $\mathbf{J}_0$ we find by the differentiation of expression (1).

Proceeding from the approximation (2), and, denoting a probability distribution of the phases and ranges measurements $P(\varphi_1, \varphi_2, R_1, R_2)$, the estimate of $H$ variance near the point $\mathbf{B}^0$ can be written as

$$\sigma_H^2 = \int_{-\infty}^{\infty} \Delta H^2 \cdot P(\varphi_1, \varphi_2, R_1, R_2)\, d(\varphi_1, \varphi_2, R_1, R_2).$$

In the assumption of the measurement errors independence as applied to values $\varphi_1, \varphi_2, R_1, R_2$, the obtained expression may be integrated. As a result of the integration, we obtain the variance of the height measurements $H$

$$\sigma_H^2 = \left(\frac{\sqrt{2}\cdot\lambda}{8\cdot\pi\cdot h}\right)^2 \cdot \left(\sigma_\varphi^2 \cdot \left(R_2 + R_1\right)^2 + \sigma_R^2 \cdot \left(\varphi_2 - \varphi_1\right)^2\right).$$

According to this expression, with a constant phase difference $\varphi_2 - \varphi_1 = 0,03638$, which corresponds to the expected value of the BP height # 1 $H = 8$ м (for the following target conditions of observation), we construct the theoretical graph of the change in the standard deviation (SD) of the BP height from the signal-to-noise ratio (Fig. 2).

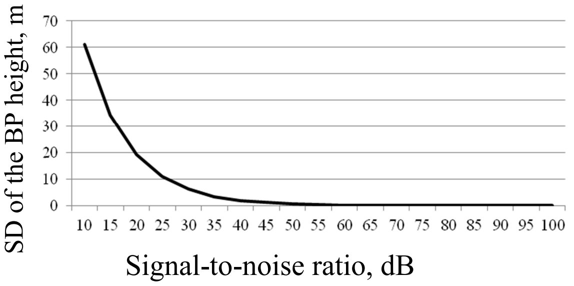



Figure 2 – Theoretical dependence of the standard deviation of the BP height of the SNR

When constructing this graph of SD, a measurement of the phase $\sigma_\varphi$ was calculated as follows

$$\sigma_\varphi = 1/q$$

where $q$ is the signal-to-noise ratio for the selected BP.

The SD of the range measurement to BP has the form

$$\sigma_R = \sqrt{\sigma_{Rp}{}^2 + \sigma_{Rd}{}^2}$$

where $\sigma_{Rp}$ is the potential component of the error, which depends on the effective width of the signal spectrum $\Pi_{eff}$. When calculating we assumed that a chirp pulse with frequency deviation $\Delta f = 150$ МГц, $\Pi_{eff} = 1,8\Delta f$ is used

$$\sigma_{Rp} = \frac{c}{2\cdot q\cdot \Pi_{eff}},$$

where $c$ is a speed of light, $\sigma_{Rd}$ is sampling error $\sigma_R = \frac{\Delta r}{2\sqrt{3}}$, where $\Delta r$ is the discreteness of range samples with taking into account that the resolution of the signal about 1 m, was set to 0.5 m.

Simulation of BP heights measurements and estimation of their errors are also carried out. For simulation of BP height measurements, and BP placement on the 3D target's image, the model [19] was supplemented by the block of the RI recovery unit and the block of the BP phase difference measurement on the RI and the calculation of their heights.

As the first simulation model, a cube was chosen, with a 16 m edge, which had two point scatterers on the front face, two on the back and one in the geometric center. The initial of the object to radar was 110 km, the height 8 km, the observation angle was 90°, the target flight speed was 750 km/h, and its observation time was 8 s. During the observation, 1024 complex HRRPs were taken; the antenna height was chosen 1.75 m. Two 2D RI were obtained using the ISAR with the following parameters: the wavelength is 3 cm; chirp probing pulse with rectangular envelop (pulsewidth was 13.65 μs, frequency deviation was 150 MHz); the signal-to-noise ratio was set to 100 dB; the signal-to-noise ratio was set to 100 dB; the signal processing included a matched filtration and additional using of the Hamming filter both in cross-range and in range. The radar images of the two antennas were restored using a fast Fourier transform to store the phase information of each BP. For a better choice of BP under conditions of destabilizing factors for the restoration of RI it is possible to use parametric methods, for example, the method of maximum entropy or the Capon method. Before obtaining of RI, the procedure for finding the dominant scatterer (the dominant scatterer algorithm (DSA) by Steinberg [20]) is used. Relatively to BP in the selected distance separation element, both RIs are focused. After this procedure, on this BP the perpendicular is directed from a point in the middle between two radar antennas.

In the simulation a scatterer in the geometric center of the cube was selected as the reference. In this case the results of BP heights measuring are obtained not in relation to the ground, but in relation to the focusing center of the image. Examples of two-dimensional RI and placement of BP in space based on phase measurements are presented in Fig. 3, a and Fig. 3, b, respectively.

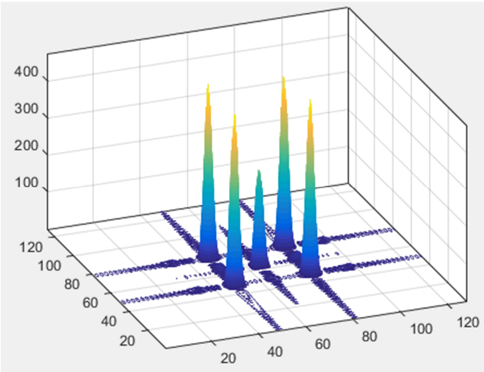
They are obtained with a signal-to-noise ratio of 100 dB per HRRP. When the target model approaching to the radar, the projections of the BP on the line of sight are converge, which may affect the accuracy of the measurement of phase differences (Fig. 3, b, c).

To estimate the position of scatterers, based on geometric transformations, we obtain the relations:

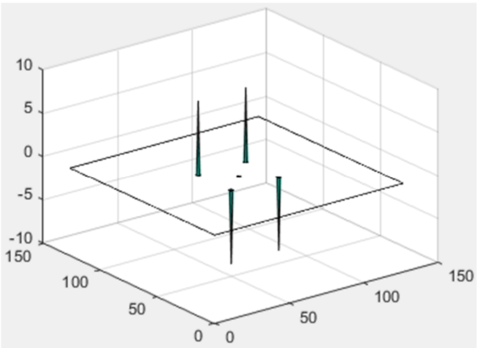
$$h_s = \frac{\sqrt{2}}{2}\cdot H\cdot\cos\left[\frac{\pi}{4} - \text{arctg}\left(\frac{H}{R}\right)\right];$$

$$r = \frac{\sqrt{2}}{2} \cdot H \cdot \cos\left[\frac{\pi}{4} + \mathrm{arctg}\left(\frac{H}{R}\right)\right]$$

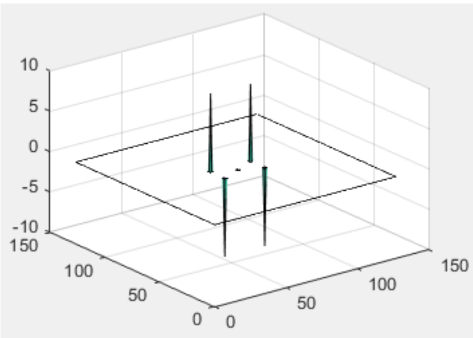
where $h_s$ is the height of the BP over the plane perpendicular to the plane of sight (plane of sight includes the line of sight and the vertical line, $r$ is the distance between the projection of the BP and the focusing center on the line of sight; $H$, $R$ is the height of the target relative to the horizontal plane and the range to the target along this plane.




a)




b)

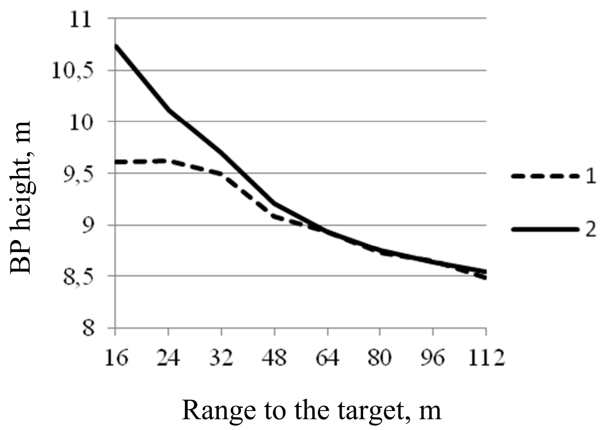



c)

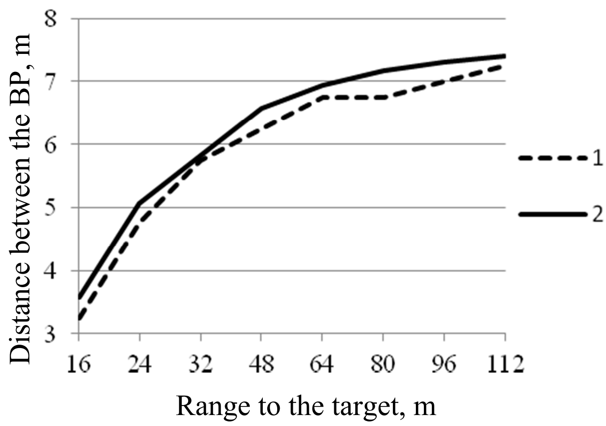
Figure 3 – Focused two-dimensional image (a) and placement of BP in a range of 64 km (b) and 16 km (c) distances (scale points on the axes in the horizontal plane go through 0.5 m)

The verification of these formulas was carried out under the following conditions: the target flight height of 8 km, the range to the target varied from 16 to 112 km through every 16 km. The heights of the BP were measured by the phase method, the distance between the BP of cube was calculated according to the numbers of the resolved elements by range (Fig. 4).

From the graph on Fig. 4, a it is clear that when the target is matched to the locator, the results of measurements differ from those calculated. The reason for this may be the overlap of the side lobes of one BP with the main peak of the other with their convergence, which distorts the measurement results. Also we received dependences of the BP height deviation from the true value when the signal-to-noise ratio is changed from 10 dB to 100 dB for alone HRRP. When receiving RI, a DFT with a Hamming window and without it was used (Fig. 5).




a)




б)

Figure 4 – Dependences of the points height relative to the line of sight (a) and the distance between the BP in the direction of the line of sight (b) on the range to the radar (1 – theoretical calculations, 2 – the results of simulation of measurements)

In the absence of a reference point, instead of the DSA, it is possible to focus the image using a multiple scatterer algorithm (MSA) [1]. After focusing the image to correctly measure the heights of the BP, one of them must be selected as reference, and the height of other BP will be calculated relative to it. Verifying the measurement of BP heights using the MSA algorithm on the model described above showed similar results to the use of the DSA algorithm.

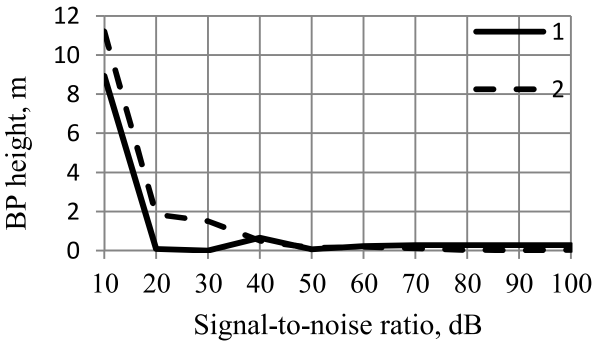



Figure 5 – The dependence of the difference between the BP height of the SNR based on the results of simulation and theoretical calculation: 1 – without Hemming filtration; 2 – with Hamming filtration

Radar Target Backscattering Simulation (RTBS) [21] was used to test the technique on models that were closer to real targets. It allows simulating reflected signals from several types of air targets in straight-line motion under the influence of atmospheric turbulences at irradiation of targets with wideband chip signal. As a research object, the B-52 bomber was selected.

Its parameters of motion and monitoring parameters were chosen similar to the previous point model of the target, the range of observation was set to 100 km. To calculate the heights of the BP and the errors of their measurements, simulation of 10 measurements under unchanged conditions of observation was performed. The obtained BP heights are shown in Fig. 6, a. Fig. 6, b shows the approximate location of the BP in the aircraft drawing.

Based on the obtained heights, the mean values of the heights of the points were calculated, and the absolute errors were measured (Fig. 7).

Also, based on the obtained data, the graphs of the dependencies of the BP heights standard deviation were constructed, analysis of which showed their proximity to the theoretical dependencies (Fig. 8).

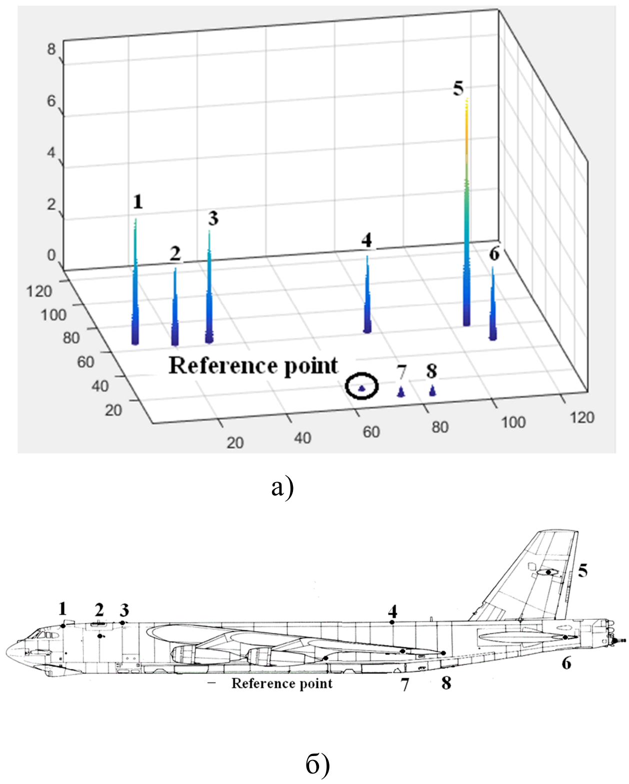



Figure 6 – The radar image of the B-52 (a) and the bright points in his drawing (b)

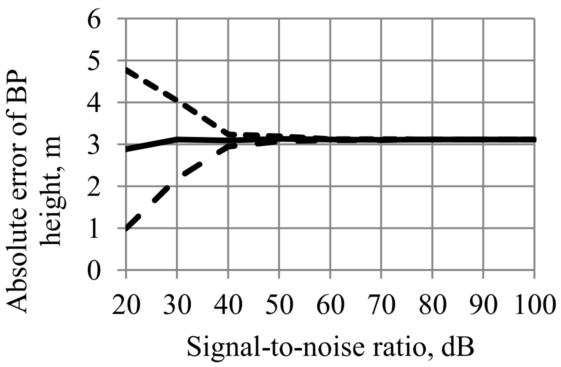



Figure 7 – Absolute error of BP # 2 height measurement in relative to its average value in dependence of the SNR per alone HRRP

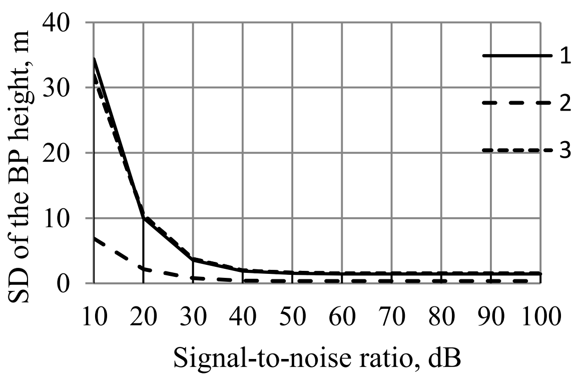



Figure 8 – Calculated values of the BP #1 – #3 height SD

**Conclusions**

The simulation model of interferometric ISAR are developed. The dependences of standard deviations and absolute errors of measurements of the BP height on the signal-to-noise ratio were obtained based on the obtained theoretically correlation and standard deviation the results of simulation. They are close. Sufficient accuracy of measurements by the phase method for BP on RI is achieved when SNR ratio for one HRRP is about 40 ... 50 dB.

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## ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ ВИМІРЮВАННЯ ПРОСТОРОВОГО ПОЛОЖЕННЯ БЛИСКУЧИХ ТОЧОК ПОВІТРЯНОЇ ЦІЛІ ФАЗОВИМ МЕТОДОМ В РЛС З ІСА

*В РЛС з інверсним синтезуванням апертури (ІСА) при введенні додаткової антени рознесеної за висотою існує принципова можливість застосування фазового метода для вимірювань висоти блискучих точок (БТ). Отримане теоретичне співвідношення для оцінювання точності вимірювань висоти БТ. Розроблена імітаційна модель відновлення тривимірних радіозображень (РЗ) повітряних об'єктів в РЛС з ІСА із застосуванням фазового метода вимірювань. Виконане порівняння точності вимірювань висоти БТ за теоретичним співвідношенням та за результатами імітаційного моделювання при різних відношеннях сигнал-шум.*

***Ключові слова**: РЛС з інверсним синтезуванням апертури, фазовий (інтерферометричний) метод вимірювань, тривимірне радіозображення, відношення сигнал-шум, точність вимірювань.*

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## ИМИТАЦИОННОЕ МОДЕЛИРОВАНИЕ ИЗМЕРЕНИЯ ПРОСТРАНСТВЕННОГО ПОЛОЖЕНИЯ БЛЕСТЯЩИХ ТОЧЕК ВОЗДУШНОЙ ЦЕЛИ ФАЗОВЫМ МЕТОДОМ В РЛС С ИСА

*В РЛС с инверсным синтезированием апертуры при введении дополнительной антенны разнесенной по высоте существует принципиальная возможность применения фазового метода для измерений высоты блестящих точек (БТ). Получено теоретическое соотношение для оценки точности измерений высоты БТ. Разработана имитационная модель восстановления трехмерных радиоизображений воздушных объектов в РЛС с ИСА и применении фазового метода измерений. Выполнено сравнение точности измерений высоты БТ по теоретическим соотношением и по результатам имитационного моделирования при различных отношениях сигнал-шум.*

***Ключевые слова**: РЛС с инверсным синтезированием апертуры, фазовый (интерферометрический) метод измерений, трехмерное радиоизображение, отношение сигнал-шум, точность измерений.*