EURASIAN JOURNAL OF MATHEMATICAL AND COMPUTER APPLICATIONS
ISSN 2306–6172
Volume 4, Number 4 (2016) 44–53

NEW METHOD FOR THE SPATIO-SPECTRAL SENSITIVITY DOMAIN FILLING AND RADIOMETRIC IMAGING WITH HIGH RESOLUTION IN APERTURE SYNTHESIS SYSTEMS

Pavlikov V.V., Kiem Nguyen Van, Tymoshchuk O. M.

Abstract The classical method for filling the spatio-spectral sensitivity (SSS) domain in the quasimonochromatic aperture synthesis system is considered. Ultrawideband signal processing is widely used nowadays so according to this fact, this method should be corrected. It is necessary to know the essentialness of transformation from temporal to spatial frequencies . The new method for filling the SSS domain and radiometric imaging with high resolution in aperture synthesis systems with sparsed antenna array is proposed. It is shown that instead of shifting the bases of the antennas can be replaced by widening of the range of operating frequencies of the system. The method describes for the one-dimensional SSS domain but without any specifics it can be generalized for the two-dimensional SSS domain. Examples of simulation of SSS domain, ambiguity function and radiometric imaging corresponding to each method are shown.

Key words: spatio-spectral sensitivity; ultra wideband signal processing; passive radar; aperture synthesis systems; multi-element antenna array

AMS Mathematics Subject Classification: 35Q85, 43A45

1 Introduction

Aperture synthesis systems [1-5] are widely used in radio-astronomy and remote sensing. These imaging techniques have extremely high angular resolution and perform radio-interferometric signals processing, which are observed at the outputs of spatial distributed sparsed antenna systems. To achieve the unambiguous (in the sense of the spatial coordinates) measurements the spatio-spectral sensitivity (SSS) domain need to be expanded and tightly filled. To this end, in the middle of the XXth century methods of successively and parallel aperture synthesis have been proposed [1]. The first method presumes the signals processing received from a small number of antennas, part of which changes its position with respect to anothers. This method requires a long time of signals accumulation. The second method requires the large number of antennas and significantly increases the cost of aperture synthesis systems.

Until recently, such approaches to signal processing in the aperture synthesis systems had no alternatives. The last decade marked a breakthrough in the technology production of ultra-wideband (UWB) radio-components. This laid the foundation for the development of appropriate methods of UWB signal processing and by now new results on the statistical theory of radiometric systems with the ultra-wideband signals processing are obtained. In [6-15], algorithms of ultra-wideband signal processing in aperture synthesis systems are synthesized and their characteristics of directivity, fluctuation sensitivity of system are investigated. However there are absent research on the features of filling SSS domain.

In the article, the classical method for filling the SSS domain is considered and new method of its filling is offered by UWB radiometric signals processing. The method describes the one-dimensional SSS domain but without any specifics can be generalized for the two-dimensional SSS domain.

2 Filling the SSS domain by implementation of the classical method of aperture synthesis

The SSS domain in the aperture synthesis is filled by the use of a small number of moving (successively synthesis) or a large number of fixed (parallel synthesis) pairs of radio-interferometers implementing cross-correlation processing of spatio-temporal signals.

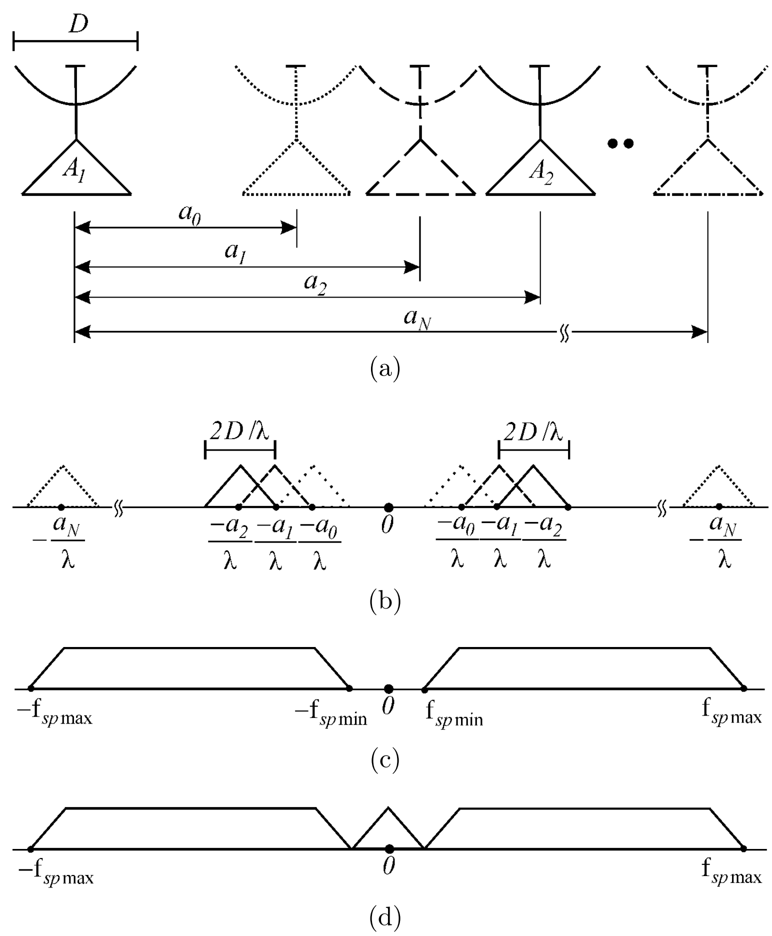


Figure 1: Filling SSS domain by successively aperture synthesis

We will consider the filling this domain by the example of successively synthesis using one radio-interferometer with movable base (Fig.1). In Fig.1a it is shown the geometry of antenna placements A_1 and A_2. Antenna A_1 is fixed and A_2 changes its position in step (for example, step of changing can be equal to the diameter of the antenna dish). In Fig.1a the dashed lines show the possible position of the antenna and the solid line is its current position.

The distance between the antenna phases center (base) is denoted by a_i ($i = 0..N$), and diameter of each antenna equals D. The signal accumulation time at each base equals T_{accum}. The total accumulation time consist of $T_{accum}(N+1)$ and the time $T_{ch}N$ spent on the base change N times.

In Fig.1b it is shown the SSS domain, which is obtained for bases which are shown in Fig.1a. The type of spatial sensitivity domain is given for the uniform amplitude distribution in antennas. Each base forms the SSS domain (it is shown as cone with its center at points $\pm a_i/\lambda$ and the diameter is $2D/\lambda$). The total SSS domain $[-f_{spmax}, -f_{spmin}] \cup [f_{spmin}, f_{spmax}]$ is shown in Fig.1c. The width of this frequency band defines the system ambiguity function (AF) structure.

In some problems, it is advisable to introduce the autocorrelation signals processing from the output of the antenna. In this case, the SSS domain will take the form, which is shown in Fig.1d (the domain $[-f_{spmax}, f_{spmax}]$ is filled almost completely).

Figures are shown in Fig.1 are also valid for aperture synthesis system of the parallel type. Wherein signals are received simultaneously from all of antennas, as are shown in Fig.1a.

Naturally, the presence of unfilled areas in the SSS domain generates the grating lobes in AF. The uniqueness condition of the AF main lobe will be given below.

3 The uniqueness condition of the main peak of the ambiguity function for one-dimentional SSS domain with unfilled central area

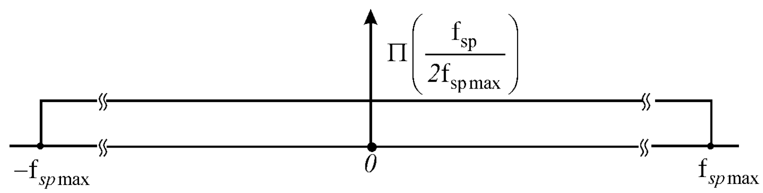
Let us consider the AF of two-antenna system of successively aperture synthesis as the Fourier transform (by spatial frequencies) from the SSS domain.

Let assume that initially the system provides a continuous and uniform filling of domain $[-f_{spmax}, f_{spmax}]$ (Fig.2). Then the ambiguity function will take the form:

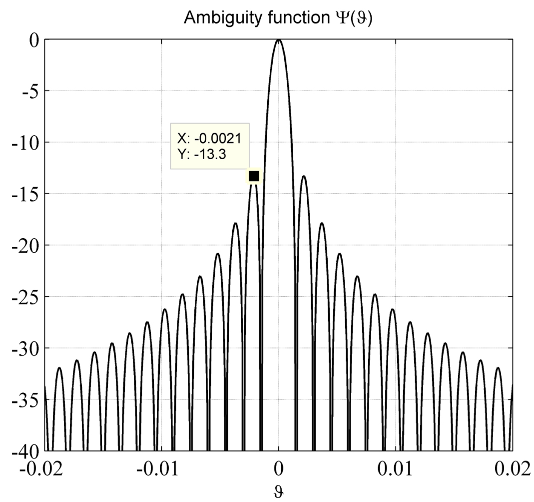
$$\Psi(\vartheta) = F\Big[\prod\big(\frac{f_{sp}}{2f_{spmax}}\big)\Big] = 2f_{spmax}\,\mathrm{sinc}(2f_{spmax}\vartheta), \tag{1}$$

where $F[\cdot\,]$ is the Fourier operator,
ϑ is the direction of cosine,

$$\prod\left(\frac{f_{sp}}{2f_{spmax}}\right) = \begin{cases} 1, & \text{if } |f_{sp}| \leq f_{spmax}, \\ 0, & \text{otherwise.} \end{cases}$$



(a)



(b)

Figure 2: The continuous and uniform filled SSS domain (a), module of the AF on the spatial coordinates in dB (b)

Now let $[-f_{spmax}, -f_{spmin}] \cup [f_{spmin}, f_{spmax}]$ (Fig.3). Then the AF will take the next form:

$$\Psi(\vartheta) = F\left[\prod\left(\frac{f_{sp}}{2f_{spmax}}\right) - \prod\left(\frac{f_{sp}}{2f_{spmin}}\right)\right] =$$
$$= 2f_{spmax}\,\mathrm{sinc}(2f_{spmax}\vartheta) - 2f_{spmin}\,\mathrm{sinc}(2f_{spmin}\vartheta). \tag{2}$$

From the analysis of the left side of expression (2) it follows that the AF is the difference of two functions $\mathrm{sinc}(\cdot)$ by different width. The amplitude of the first function in f_{spmax}/f_{spmin} times greater than the amplitude of the second function. The analogous dependence is maintained for the width of these functions, i.e. the width of first $\mathrm{sinc}(\cdot)$ in f_{spmax}/f_{spmin} times narrower than the width of second $\mathrm{sinc}(\cdot)$.

Let neglect the increasing of the AF sidelobe level (SLL) no more than 10 percents during the transition from the SSS domain, which is shown in Fig.3 and in Fig.4

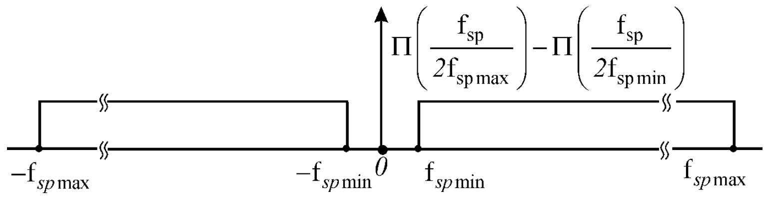


Figure 3: The SSS domain with unfilled areas

show modulus of AF (2) with different ratio f_{spmax}/f_{spmin}.Then we can introduce the condition

$$\frac{f_{spmin}}{f_{spmax}} \leq 0.02, \tag{3}$$

provided that the increasing of the first SLL is not more than 10 percents.

From the analysis of Fig.4 it follows that when $f_{spmax}/f_{spmin} = 0.02$, the first SLL has changed from -13.3 dB (for continuous SSS domain) to -12.7 dB. This change corresponds to 10 percents. The subsequent increase of the ratio f_{spmax}/f_{spmin} leads to the increase of the SLL. So for $f_{spmax}/f_{spmin} = 0.1$ the first SLL equals -9.4 dB, which corresponds to the increase of sidelobe by 60 percents in comparison with the filled SSS domain.

Fig.5 shows the change of the first SLL normalized to the maximum of AF modulus for the SSS domain with unfilled central area.

From the analysis of Fig.5 it follows that the maximum SLL for $f_{spmax}/f_{spmin} \approx 0.38$ equals 0.707 of the mainlobe maximum amplitude.

Accordingly we introduce appropriate criterion for uniqueness of the AF mainlobe in the following form:

$$\frac{f_{spmin}}{f_{spmax}} = 0.38. \tag{4}$$

The spectral filling method, the alternative to the classical method for filling the SSS domain is proposed.

4 The spectral method for the SSS domain filling

In contrast to the succesively and parallel aperture synthesis methods, this method does not change the antenna system bases. Filling the SSS domain occurs due to UWB signal processing, when the temporary frequency (continual or discrete) is converted into spatial frequency according to the expression a/λ (the denominator is changed but the numerator is not changed as before).

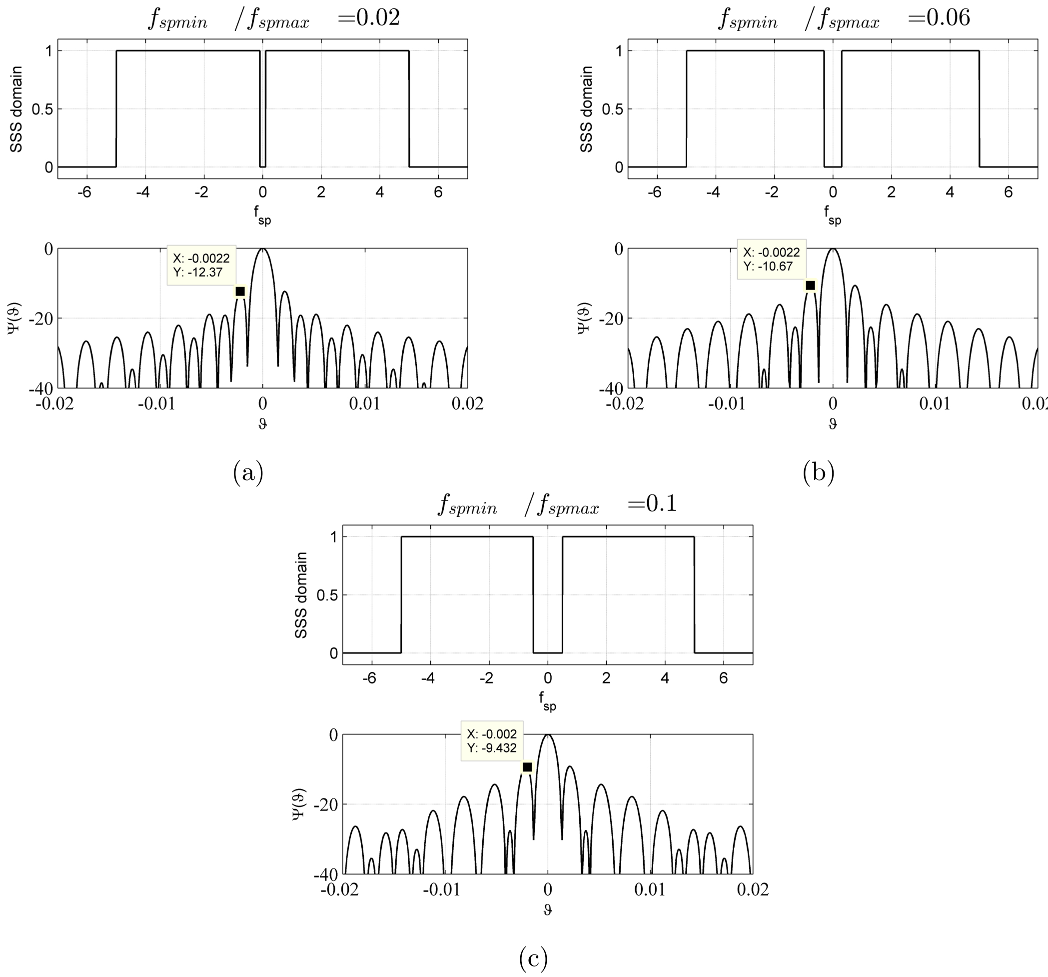


Figure 4: The type of SSS domain for different ratios f_{spmax}/f_{spmin} (top graphs) and the modulus of AF by angular coordinates in dB (bottom graphs).

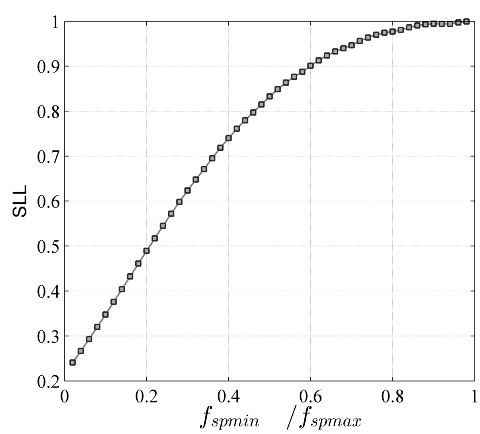


Figure 5: The increase of SSL by the increase ratio f_{spmax}/f_{spmin}

A more significant difference is the following. The size of the aperture of each antenna in wavelengths is changed, and accordingly, the base of cone in the SSS domain for one frequency (wavelength) will be changed by the following law: the changing frequencies causes the changing sizes of apertures in the wavelengths and SSS domain filling. In this case the radius of the base of cone in the SSS domain (Fig.6a) is changed according to a/λ. Therefore, the transition to the UWB signals processing allows to fill the SSS domain more effectively. Fig.6 shows the SSS domains and its corresponding

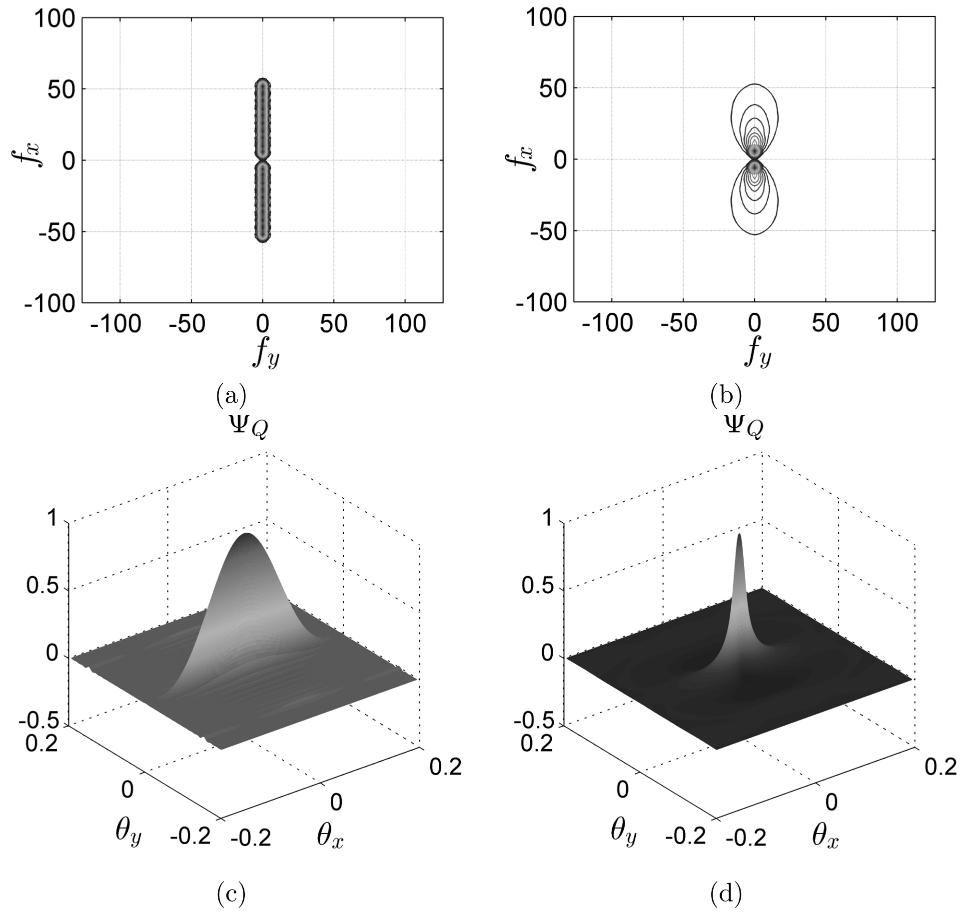
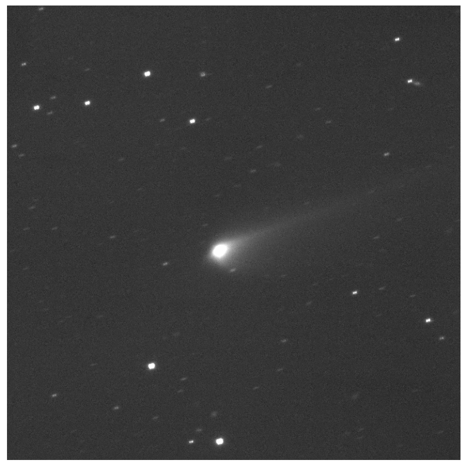


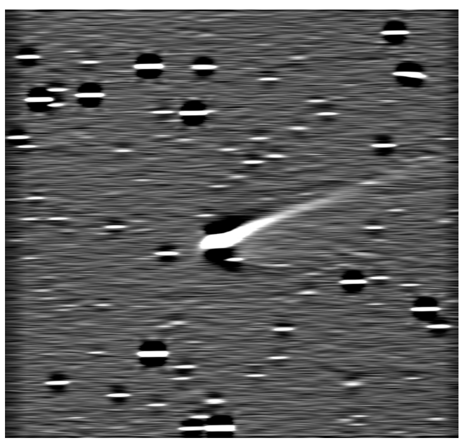
Figure 6: The SSS domains and its corresponding AF in succesively aperture synthesis by changing bases of antenna system (changing numerator of radio a/λ)(left graph) and by changing wavelength (changing denomirator of ratio a/λ) (right graph).

AF in succesivelly aperture synthesis by changing bases of antenna system (changing numerator of radio a/λ)(left graphs) and by changing wavelength (changing denomirator of ratio a/λ) (right graphs).

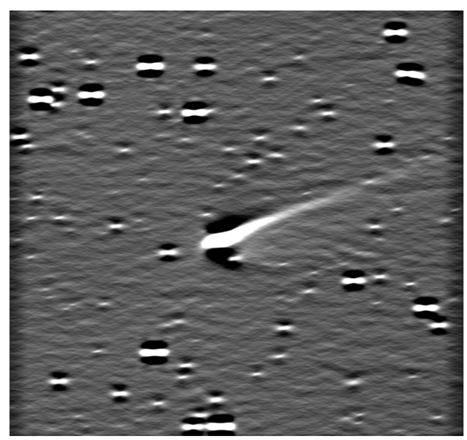
From the analysis of Fig.6a and Fig.6c it follows that in spectral method of aperture synthesis (changing the wavelength) the SSS domain has been expanded not only along spectral frequency f_x but also along spectral frequency f_y. The wavelength changing (changing of denomirator of ratio a/λ) leads to the change of the cone base (the base of cone is not round but leaf shape-look at Fig.6b). Initial cone becomes not-standard cone. This leads to the narrowing of corresponding ambiguity function and increase the resolution in restoring radiometric images.



(a)



(b)



(c)

Figure 7: The original image (a), the reconstructed image by succesively aperture synthesis (b) and the reconstructed image by spectral method (c).

Fig.7 shows the restoring of radiometric image. From the analysis of Fig.7b and Fig.7c it follows that the resolution of reconstructed image by spectral method is better than by succesively aperture sysnthesis. We can see that in the classical method (classical succesively aperture synthesis) the reconstructed image is distorted, and distortion of the reconstructed image in the spectral method has been reduced. Thus the use of the spectral method have great significance in the reduction of radiometric system cost, no need to displace the system, increasing resolution of obtained radiometric images.

5 Conclusion

The new method of aperture synthesis by the SSS domain filling is proposed. Unlike classic (set of moving bases between the antennas in the antenna system), the new method suggests to fill the SSS domain by UWB spatio-temporal signals processing. A feature of the method is simultaneously filling SSS domain in the spatial frequency f_x, f_y through the use of even an one base. The simulation results, which confirm the usefulness of the new method and, accordingly, the transition to the UWB signals processing in aperture synthesis systems are shown.

References

[1] Burke B. F., and Graham-Smith, *Introduction to Radio Astronomy*, 3rd ed., F. 2009.

[2] J. Font, A. Camps, A. Borges, M. Martin-Neira, J. Boutin, N. Reul, Y. H. Kerr, A. Hahne, S. Mecklenburg, *The Challenging Sea Surface Salinity Measurement From Space*, Proceedings of the IEEE, Vol. 98 Issue (2010), pp. 649 - 665.

[3] M.Peichl, H.Suess, M.Suess and S.Kern, *Microwave imaging of the brightness temperature distribution of extended areas in the near and far field using two-dimensional aperture synthesis with high spatial resolution*, Radio Science, Vol. 33 Issue (1998), pp. 781-801.

[4] M. Ishiguro, *Atacama Large Millimeter/submillimeter Array (ALMA)*, Antennas and Propagation (ISAP), 2012, pp. 1268-1268.

[5] 14. J. Martinez, A. Turiel, V. Gonzalez-Gambau and E. Olmedo, *Spatial Correlations in SMOS Antenna: The Role of Effective Point Spread Functions*, IEEE Transactions on Geoscience and Remote Sensing, vol. 54, no. 8, pp. 4906-4916.

[6] Volosyuk V. K., Kravchenko V. F., *Statistical Theory of Radio-Engineering Systems of Remote Sensing and Radar*, Fizmatlit, Moscow (in Russian), 2008.

[7] Volosyuk V. K., Kravchenko V. F., and Pavlikov V. V., *Development of the theory, methods and algorithms for optimal wide- and ultrawideband spatiotemporal signal processing of radio-thermal radiation*, Antenna theory and techniques ICATT'2013: proc. of the IX Intern. conf., Sept. 16-20, 2013, Odessa, Ukraine, pp. 74-79.

[8] Volosyuk V. K., Kravchenko V. F., Kutuza B. G., and Pavlikov V. V., *Review of modern algorithms for high resolution imaging with passive radar*, Antenna theory and techniques ICATT'2015: proc. of the X Intern. conf., Apr. 21-24, 2015, Kharkiv, Ukraine, 2015, pp. 45-50.

[9] V. V. Pavlikov, S. S. Zhyla, Kiem Nguyen Van and O.V. Odokienko, *Optimal signal processing for radiometric imaging with multi-antenna and multi-band passive radars*, Antenna theory and techniques. ICATT'2015 : proc. of the X Intern. conf., Apr. 21-24, 2015, Kharkiv, Ukraine, pp. 179-181.

[10] Pavlikov V. V., Kiem Nguyen Van, *Optimal algorithm for estimation of radio brightness of an extended source of radio thermal radiation in the ultra-wideband radiometric complex with a three element-antenna system*, proceedings of the XIIIth international conference TCSET'2016, Feb. 23-26, 2016, Lviv-Slavske, Ukraine, pp. 236-239.

[11] Kiem Nguyen Van, Tymoshchuk O.M., *Investigation of ambiguity function of ultra-wideband, multi-band and narrow-band radiometric complex with a three-element-antenna system*, proceedings of the XIIIth international conference TCSET'2016, February 23-26, 2016, Lviv-Slavske, Ukraine, pp. 240-242.

[12] Pavlikov V. V., Kiem Nguyen Van, Tymoshchuk O. M., *Optimal structural synthesis of multi-antenna ultra-wideband radiometric complex*, 9th international kharkiv symposium on physics and engineering of microwaves, millimeter and submillimeter waves MSMW'2016, Jun. 20-24, 2016, Kharkiv, Ukraine, section G-53.

[13] V. K. Volosyuk, Kiem Nguyen Van, V. F. Kravchenko, K. N. Nezhalskaya, *Investigation of ambiguity function of ultra-wideband radiometric complexes with multi-antenna system*, 9th international kharkiv symposium on physics and engineering of microwaves, millimeter and submillimeter waves MSMW'2016, Jun. 20-24, 2016, Kharkiv, Ukraine, section G-41.

[14] Pavlikov V. V., Kiem Nguyen Van, Tymoshchuk O. M., *Spectral Method for the Spatio-spectral sensitivity domain filling in aperture synthesis system* , International conference on ultrawideband and ultrashort impulse signals UWBUSIS-2016, sep. 5-11, 2016, Odessa, Ukraine, pp. 124-127.

[15] Pavlikov V. V., Kiem Nguyen Van, Tymoshchuk O. M., *Algorithm for radiometric imaging by ultrawideband systems of aperture synthesis*, 2016 IEEE Radar methods and systems workshop, sep. 27-28, 2016, Kyiv, Ukraine, pp. 103-106.

Pavlikov Vladimir Vladimirovich,
National Aerospace University named after N. Ye. Zhukovsky "Kharkiv Aviation Institute", Ukraine.
17 Chkalova St, Kharkiv, 61070, Ukraine
Email: v.pavlikov@khai.edu

Kiem Nguyen Van,
National Aerospace University named after N. Ye. Zhukovsky "Kharkiv Aviation Institute", Ukraine
17 Chkalova St, Kharkiv, 61070, Ukraine
Email: kiemxai@gmail.com

Tymoshchuk Olena Mykolaivna,
Kyiv State Maritime Academy named after hetman Petro Konashevych-Sahaydachniy, Kyiv, Ukraine
Dmytrivska St, 80, Kiev, 02000, Ukraine
Email: tymoshchukom@gmail.com

Received 12.11.2016, Accepted 30.11.2016