UDC 621.396.96

ANALYTICAL MODELS OF STOCHASTIC RADIOTHERMAL SIGNALS

KIEM NGUYEN VAN, K. N. NEZHALSKAYA, O. M. TYMOSHCHUK

The analytical models of stochastic radiometric ultra-wideband signals at the outputs of directional and omnidirectional multi-antenna arrays are developed. Such arrays are typical for radiometric complexes, which provide high resolution on angular coordinates. Examples of simplification of multi-dimensional signals in the case of using a single antenna (directional or omnidirectional) are shown. The statistical characteristics of developed models are investigated. Heuristic algorithms of signal processing for radiometric imaging which follow from analysis of these characteristics are studied. Examples of constructing likelihood functionals are given which are necessary to solve the problems of synthesis of the optimal algorithms.

Keywords: analytical model of signal, radiometric signal, passive radar.

INTRODUCTION

The knowledge of analytical models of radiometric signals plays a key role in the synthesis of algorithms of signal processing for solving problems of Earth remote sensing, radio astronomy, radiolocation [1-4], etc.

These signals depend on many factors such as electrical parameters and physical conditions of observation objects, antenna system and predetection sections of receiver. The important stage in the creation of analytical relationships between the parameters and characteristics precedes the solution of many radiometry problems. This result forms the adequate analytical models of signals, analysis of which in the following are isolated the main processing operation.

It is known [5] that radiothermal radiation is the random process with Gaussian distribution and zero mean. Therefore, only the analytic expression is not enough for complete task of model. It is necessary to investigate the statistical characteristics of these models.

In the article, we develop the analytical models of stochastic radiothermal signals and investigate their statistical characteristics. Herewith the models must be applied to all radiometric complexes, systems and devices [5-10].

1. DEVELOPMENT OF ANALYTICAL MODELS OF STOCHASTIC RADIOTHERMAL SIGNALS FOR RADIOMETRIC MULTI-ANTENNA COMPLEXES

The models of radiometric signals at the outputs of antenna systems with the directional or omnidirectional antennas are considered.

THE GENERAL ANALYTICAL MODEL OF STOCHASTIC RADIOTHERMAL SIGNALS FOR DIRECTIONAL ANTENNAS IN THE ARRAY

Radiometric signals are ultra wideband (UWB) random processes whose spectra substantially continuous all over radio frequency band. We will form a model of radiometric signal, which own emissivity of each element (within the limits range of angels $d\vec{\vartheta}$ and frequency df) is characterized by function [5]

$$\dot{A}(f,\vec{\vartheta})\exp\left[j2\pi ft\right]dfd\vec{\vartheta}, \quad (1)$$

where $\dot{A}(f,\vec{\vartheta})$ is the spectral-angular density of the complex amplitude, df is the infinitesimal frequency band, $d\vec{\vartheta}$ is the infinitesimal range of vector of direction cosines. The real and imaginary parts of spectral density $\dot{A}(f,\vec{\vartheta})$ at the fixed frequency is often seen in technical applications as the real and imaginary coherent image of observation object.

It is assumed that there is the multi-antenna radiometric complex (RMC) (Fig. 1) with directional antennas in array. The antenna A_i ($i=1..M$) is limited by area D_i' and is connected to the i^{th} predetection section of the receiver, frequency characteristic $\dot{K}(j2\pi f)$ of which satisfies the conditions of UWB. Predetection section limits bandwidth of frequency signal $s_{Ai}(t)$ (see Fig. 1) at the i^{th} antenna output and adds noise $n_i(t)$ in the observation. Position of the i^{th} antenna phase center is characterized by vector $\vec{a}_i$, within initial point with coordinates $(0,0)$. Radius vector $\vec{r}_i' \in D_i'$ characterizes the position of an arbitrary elementary area within the region D_i'.

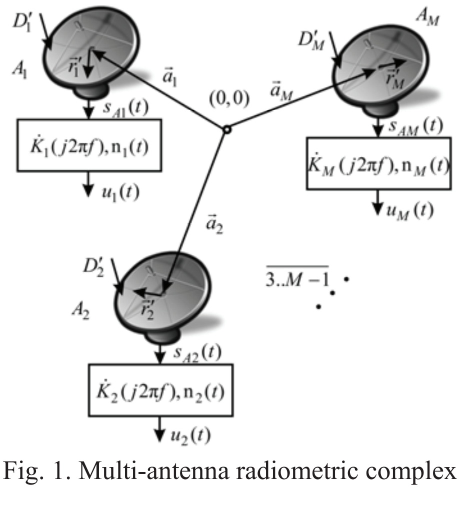

Fig. 1. Multi-antenna radiometric complex

Radiometric signals $s_i(t) = s(t - t_{delay}(\vec{a}_i))$ have common part of the time delay $t_0 = R_0/c$ (R_0 is the distance from radiation point to the phase center of antenna array) and differ only by the time delay of propagation from i^{th} antenna phase center to the phase center of antenna array

$$t_{delay}\left(\vec{a}_i\right) = t_0 + \Delta t_{delay}\left(\vec{a}_i\right) = R_0/c + \vec{\vartheta}\vec{a}_i/c .$$

The distance R_0 is usually unknown and the radiation sources are located in the Fraunhofer region. Therefore, they can be excluded from consideration, leaving only the time $\Delta t_{delay}(\vec{a}_i) = \vec{\vartheta}\vec{a}_i/c$, and we will write signals in the form

$$s_i\left(t\right) = s_i\left[t - \Delta t_{delay}\left(\vec{a}_i\right)\right] = s_i\left[t - \vec{\vartheta}\vec{a}_i/c\right].$$

Then the signal at the output of predetection section can be written as follows:

$$s_i\left(t\right) = s_i\left[t - \Delta t_{delay}\left(\vec{a}_i\right)\right] =$$

$$= \frac{1}{\sqrt{2}} \int\limits_{D'} \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} C_f \dot{I}_i(f, \vec{r}' - \vec{a}_i) \dot{K}(j2\pi f) \dot{A}(f, \vec{\vartheta}) \times$$

$$\times \exp\left\{-j2\pi f\left[t - (\vec{\vartheta} - \vec{\vartheta}_0)\vec{r}' c^{-1}\right]\right\} d\vec{\vartheta} df d\vec{r}' = \begin{vmatrix} \vec{r}' - \vec{a}_i = \vec{r}_i', \\ \vec{r}' = \vec{r}_i' + \vec{a}_i \\ d\vec{r}' = d\vec{r}_i', \end{vmatrix} =$$

$$= \frac{1}{\sqrt{2}} \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} C_f \dot{K}(j2\pi f) \dot{A}(f, \vec{\vartheta}) \dot{F}_i(f, \vec{\vartheta} - \vec{\vartheta}_0) \times$$

$$\times \exp\left[-j2\pi f(t - (\vec{\vartheta} - \vec{\vartheta}_0)\vec{a}_i c^{-1})\right] d\vec{\vartheta} df, \tag{2}$$

where $\dot{I}_i(f, \vec{r}' - \vec{a}_i)$ is the amplitude-phase distribution (APhD) of the i^{th} antenna,

$$C_f = fc^{-1}\left\{\int \left|\dot{F}\left(f, \vec{\vartheta}\right)\right|^2 d\vec{\vartheta}\right\}^{-1},$$

$$\dot{F}_i(f, \vec{\vartheta} - \vec{\vartheta}_0) = \int\limits_{D_i'} \dot{I}_i(f, \vec{r}_i') \exp(j2\pi f(\vec{\vartheta} - \vec{\vartheta}_0)\vec{r}_i' c^{-1}) d\vec{r}_i'$$

is the i^{th} antenna pattern.

Any models on the right side of (2) can be used to solve synthesis problems and analysis of the RMC.

SIMPLIFICATION WITH USING OF OMNIDIRECTIONAL ANTENNAS IN THE ARRAY

Omnidirectional antenna [11] is a class of antenna which radiates radio wave power uniformly in all directions in one plane, with the radiated power decreasing with elevation angle above or below the plane, dropping to zero on the antenna's axis.

While using omnidirectional antennas, we assume that

$$\dot{I}_i(f, \vec{r}_i') \to \dot{I}_0(f)\delta(\vec{r}_i'),$$

where $\delta(\vec{r}_i')$ is the Dirac delta function.

Then received signal (2) at the output of receiver predetection section of each omnidirectional antenna takes the form:

$$s_i\left(t\right) = \frac{1}{\sqrt{2}} \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} C_f \dot{K}(j2\pi f) \dot{A}(f, \vec{\vartheta}) \dot{I}_0(f) \times$$
$$\times \exp\left[-j2\pi f(t - (\vec{\vartheta} - \vec{\vartheta}_0)\vec{a}_i c^{-1})\right] d\vec{\vartheta} df. \tag{3}$$

SIMPLIFICATION WITH USING OF AN ANTENNA

Now, let us consider the case of using only one antenna (directional or omnidirectional antenna). In this case, the phase center of the RMC coincides with the phase center of the antenna, that means $\vec{a}_i \to 0$.

Put $\vec{a}_i \to 0$ in the expressions (2), we obtain the received signal while using a directional antenna

$$s\left(t\right) = \frac{1}{\sqrt{2}} \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} C_f \dot{K}(j2\pi f) \dot{A}(f, \vec{\vartheta}) \dot{F}(f, \vec{\vartheta} - \vec{\vartheta}_0) d\vec{\vartheta} df \tag{4}$$

and the received signal while using an omnidirectional antenna

$$s\left(t\right) = \frac{1}{\sqrt{2}} \int\limits_{-\infty}^{\infty} \int\limits_{-\infty}^{\infty} C_f \dot{K}(j2\pi f) \dot{A}(f, \vec{\vartheta}) \dot{I}_0(f) d\vec{\vartheta} df. \tag{5}$$

The expressions (2)–(5) describe the analytical models of radiometric signals which can be used for analysis and synthesis of radiometric devices, systems and complexes for various purposes. Probabilistic characteristics give full description of these processes. They will be discussed in the following paragraph.

2. RESEACH OF STATISTICAL CHARACTERISTIC OF SIGNALS

We will consider statistical characteristics of radiometric signals (models are given earlier).

It is known [5] that radiometric signal is the random zero mean Gaussian process $\left\langle s_i\left(t\right)\right\rangle = 0$, where $\left\langle \cdot \right\rangle$ is the sign of statistical average. According to this, the full description of random process contains its correlation function.

We will write signals at the output of M antenna array as a vector (look at (2))

$$\vec{s}\left(t\right) = \left\{s_i\left(t\right)\right\}_{i=1}^{M}. \tag{6}$$

The matrix of correlation functions of signals (6) can be written in the form

$$\underline{R}_s\left(t_1 - t_2, B(f, \vec{\vartheta})\right) = \left\langle \vec{s}\left(t_1\right) \vec{s}^T\left(t_2\right)\right\rangle =$$
$$= \begin{Vmatrix} R_{s11} & R_{s12} & \dots & R_{s1M} \\ R_{s21} & R_{s22} & \dots & R_{s2M} \\ \vdots & \vdots & \ddots & \vdots \\ R_{sM1} & R_{sM2} & \dots & R_{sMM} \end{Vmatrix}, \tag{7}$$

where R_{sij} ($i, j = 1..M$) is the cross-correlation function between signals on the outputs of channels i and j,

$$R_{sij}(t_1-t_2,B(f,\vec{\vartheta}))=\left\langle s_i(t_1)s_j(t_2)\right\rangle=$$
$$=\frac{1}{2}\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty}A_{eff}(f,\vec{\vartheta}-\vec{\vartheta}_0)\left|\dot{K}(j2\pi f)\right|^2 B(f,\vec{\vartheta})\times \quad (8)$$
$$\times\exp\{j2\pi f(\vec{\vartheta}-\vec{\vartheta}_0)\vec{a}_{ij}c^{-1}\}d\vec{\vartheta}\exp\{-j2\pi f(t_1-t_2)\}df.$$

Here $A_{eff}\left(f,\vec{\vartheta}-\vec{\vartheta}_0\right)=C_f^2\left|\dot{F}\left(f,\vec{\vartheta}-\vec{\vartheta}_0\right)\right|^2$ is the effective area of antenna, $B(f,\vec{\vartheta})$ is the spectral-angular power density (is the radiometric image).

For models of signals (3)–(5), correlation function (8) takes the following forms:

$$R_{sij}(t_1-t_2,B(f,\vec{\vartheta}))=$$
$$=\frac{1}{2}\int\limits_{-\infty}^{\infty}C_f^2\left|\dot{I}_0(f)\right|^2\left|\dot{K}(j2\pi f)\right|^2\int\limits_{-\infty}^{\infty}B(f,\vec{\vartheta})\times \quad (9)$$
$$\times\exp\{j2\pi f(\vec{\vartheta}-\vec{\vartheta}_0)\vec{a}_{ij}c^{-1}\}d\vec{\vartheta}\exp\{-j2\pi f(t_1-t_2)\}df,$$

$$R_s(t_1-t_2,B(f,\vec{\vartheta}))=$$
$$=\frac{1}{2}\int\limits_{-\infty}^{\infty}\left|\dot{K}(j2\pi f)\right|^2\int\limits_{-\infty}^{\infty}A_{eff}(f,\vec{\vartheta}-\vec{\vartheta}_0)B(f,\vec{\vartheta})d\vec{\vartheta}\times \quad (10)$$
$$\times\exp\{-j2\pi f(t_1-t_2)\}df,$$

$$R_s(t_1-t_2,B(f,\vec{\vartheta}))=\frac{1}{2}\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty}B(f,\vec{\vartheta})d\vec{\vartheta}\times$$
$$\times C_f^2\left|\dot{I}_0(f)\right|^2\left|\dot{K}(j2\pi f)\right|^2\exp\{-j2\pi f(t_1-t_2)\}df. \quad (11)$$

From the analysis of correlation functions (8) – (11) follows that the information about the radiometric image $B(\cdot,\vec{\vartheta})$ can be identified using directional and omnidirectional antenna system, as well as when using a single directional antenna. While using the single omnidirectional antenna, the information about angular radio brightness is excluded by averaging over all of angular coordinates, i.e. $\int\limits_{-\infty}^{\infty}B(f,\vec{\vartheta})d\vec{\vartheta}$.

Signals (2)–(5) and their statistical characteristics (7)–(11) can be used for analysis of existing devices, systems and complexes and for calculating perspective algorithms of signal processing.

3. CONSTRUCTION OF LIKELIHOOD FUNCTION

Statistical theory of synthesis of radiometric systems is used while developing the optimal algorithm of signal processing. To do this, it is usually necessary to concretize the Likelihood function. We will construct several types of Likelihood function, which are needed to solve problems of statistical synthesis of radiometric complexes and devices [5–9].

We shall restrict our consideration to the additive model of observation

$$\vec{u}(t)=\{u_i(t)\}_{i=1}^{M}=\{s_i(t)+n_i(t)\}_{i=1}^{M}, \quad (12)$$

where $n_i(t)$ is the internal noise of the i^{th} channel of receiver.

Depending upon the restrictions imposed on the signals and internal noises in (12), we will consider several types of Likelihood function. Below, the estimate parameters will be denoted as the vector $\vec{\lambda}$. In the particular case λ can be the radiometric imaging $B(f,\vec{\vartheta})$ or $\int B(f,\vec{\vartheta})df$.

Initially, we write the Likelihood function for M channels of RMC in general form [5]

$$p\left[\vec{u}(t)\,|\,\vec{\lambda}\right]=$$
$$=k(\vec{\lambda})\exp\left[-\frac{1}{2}\int\limits_0^T\int\limits_0^T\vec{u}^T(t_1)\underline{W}(t_1,t_2,\vec{\lambda})\vec{u}(t_2)dt_1dt_2\right], \quad (13)$$

where $W(t_1,t_2,\vec{\lambda})$ is the inverse correlation matrix, which is determined by equation

$$\int\limits_0^T\underline{R}(t_1,t_2,\vec{\lambda})\underline{W}(t_2,t_3,\vec{\lambda})dt_2=\underline{I}\delta(t_1-t_3), \quad (14)$$

$$\underline{R}(t_1,t_2,\vec{\lambda})=\underline{R}_s(t_1,t_2,\vec{\lambda})+\underline{R}_n(t_1,t_2), \quad (15)$$

$k(\vec{\lambda})$ is the coefficient, which depends on the parameter $\vec{\lambda}$ in the case of evaluation of energy parameters.

Depending upon the type of correlation matrix (15) we distinguish the following characteristic cases.

NOISES ARE CORRELATED BETWEEN CHANNELS ALSO IN TIME

The expression (15) will have the form

$$\underline{R}(t_1,t_2,\vec{\lambda})=\underline{R}_s\left(t_1,t_2,\vec{\lambda}\right)+\underline{R}_n\left(t_1,t_2\right)=$$
$$=\begin{Vmatrix}R_{s11} & R_{s12} & \dots & R_{s1M}\\ R_{s21} & R_{s22} & \dots & R_{s2M}\\ \vdots & \vdots & \ddots & \vdots\\ R_{sM1} & R_{sM2} & \dots & R_{sMM}\end{Vmatrix}+ \quad (16)$$
$$+\begin{Vmatrix}\sigma_{11} & \rho\sigma_1\sigma_2 & \cdots & \rho\sigma_1\sigma_M\\ \rho\sigma_2\sigma_1 & \sigma_{22} & \cdots & \rho\sigma_2\sigma_M\\ \vdots & \vdots & \ddots & \vdots\\ \rho\sigma_M\sigma_1 & \rho\sigma_M\sigma_2 & \cdots & \sigma_{MM}\end{Vmatrix},$$

where $\rho=\dfrac{\left\langle n(t_1)n(t_2)\right\rangle}{\sigma_1\sigma_2}$ is the correlation coefficient of noises between $n_i(t)$ and $n_j(t)$, $\sigma_i=\sqrt{\left\langle n_i^2(t)\right\rangle}$.

Function $\underline{W}(t_2,t_3,\vec{\lambda})$ is solved by solving (14) and substituting into it (16).

NOISE ARE CORRELATED BETWEEN CHANNELS BUT NOT IN TIME

In this case $\rho=\dfrac{N_{0n}}{2}\dfrac{\delta(t_1-t_2)}{\sigma_1\sigma_2}$ the equation (16) takes the form

$$\underline{R}(t_1,t_2,\vec{\lambda})=\underline{R}_s\left(t_1,t_2,\vec{\lambda}\right)+\underline{R}_n\left(t_1,t_2\right)=$$
$$=\begin{Vmatrix}R_{s11} & R_{s12} & \dots & R_{s1M}\\ R_{s21} & R_{s22} & \dots & R_{s2M}\\ \vdots & \vdots & \ddots & \vdots\\ R_{sM1} & R_{sM2} & \dots & R_{sMM}\end{Vmatrix}+\frac{N_{0n}}{2}\begin{Vmatrix}1 & 1 & \cdots & 1\\ 1 & 1 & \cdots & 1\\ \vdots & \vdots & \ddots & \vdots\\ 1 & 1 & \cdots & 1\end{Vmatrix}\delta(t_1-t_2). \quad (17)$$

NOISES ARE NOT CORRELATED BETWEEN CHANNELS ALSO IN TIME

In this case

$$\left\langle n_i(t_1)n_j(t_2)\right\rangle = 0\,,\ \left\langle n_i(t_1)n_i(t_2)\right\rangle = 0{,}5N_{0n}\delta(\mathrm{t}_1-\mathrm{t}_2)\,,$$

then

$$\underline{R}(t_1,t_2,\vec{\lambda}) = \underline{R}_s\left(t_1,t_2,\vec{\lambda}\right)+\underline{R}_n\left(t_1,t_2\right)= \\ =\begin{Vmatrix} R_{s11} & R_{s12} & \cdots & R_{s1M} \\ R_{s21} & R_{s22} & \cdots & R_{s2M} \\ \vdots & \vdots & \ddots & \vdots \\ R_{sM1} & R_{sM2} & \cdots & R_{sMM} \end{Vmatrix}+ \\ +0{,}5N_{0n}\begin{Vmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{Vmatrix}\delta(\mathrm{t}_1-\mathrm{t}_2). \quad (18)$$

USING A SINGLE ANTENNA

While using a single antenna, Likelihood function (13) takes the form

$$p\left[u(t)\,|\,\vec{\lambda}\right] = k(\vec{\lambda})\exp\left[-\left(N_{0s}(\vec{\lambda})+\mathrm{N}_{0n}\right)^{-1}\int_0^T u^2(t)dt\right]. \quad (19)$$

USING SPECIAL CONTINUAL REGISTERING MEDIUM

It is evident that the continual processing in the majority of the existing antenna radio-band (if we not use the special continual registering medium) is practically impossible. The exception is the holographic processing of radiations in the optical range, where it is possible to create continual registering medium and processing medium as the photographic films, lenses, crystals, special fluids and others.

In the future we will use continual aperture, which is the presupposing possibility of registering and processing fields at each point. Also this is the presupposing possibility of the transition to the final stage of synthesis algorithms to real discrete aperture of antenna array.

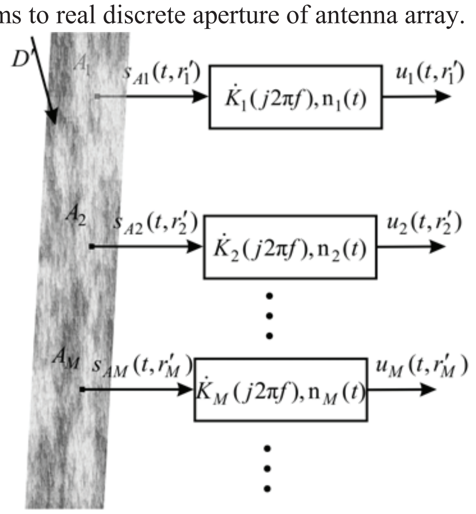

Fig. 2. The geometry of problem

The simplest observation equation in this case has the form:

$$u\left(t,r'\right) = s\left(t,r'\right)+n\left(t,r'\right), \\ r'\in D',\ t\in(0,T), \quad (20)$$

where $r'=(x',y',z')$ is the coordinate of the point in the registering medium.

For the noises which are correlated in time and spatial coordinates r'

$$p\left[u(t,r')\,|\,\vec{\lambda}\right]= \\ =k(\vec{\lambda})\exp\left[-\frac{1}{2}\int_{D'}\int_{D'}\int_0^T\int_0^T u(t_1,\mathrm{r}_1')W(t_1,t_2,\mathrm{r}_1',\mathrm{r}_2',\vec{\lambda})\times \\ \times u(t_2,\mathrm{r}_2')dt_1dt_2dr_1'dr_2'\right]. \quad (21)$$

Here $W(t_1,t_2,\mathrm{r}_1',\mathrm{r}_2',\vec{\lambda})$ is the continual function.

For the limited number of points in the space, the vector equation of observation can be written:

$$\vec{u}\left(t,r'\right)=\left\{u(t,r_i')\right\}_{i=1}^{M}=\left\{s\left(t,r_i'\right)+n\left(t,r_i'\right)\right\}_{i=1}^{M}. \quad (22)$$

The Likelihood function is written as follow:

$$p\left[\vec{u}(t)\,|\,\vec{\lambda}\right]= \\ =k(\vec{\lambda})\exp\left[-\frac{1}{2}\int_0^T\int_0^T \vec{u}^T(t_1)\underline{W}(t_1,t_2,\vec{\lambda})\vec{u}(t_2)dt_1dt_2\right], \quad (23)$$

where inverse matrix $\underline{W}(t_1,t_2,\vec{\lambda})$ can be found from the following equation

$$\int_0^T \underline{R}(t_1,t_2,\vec{\lambda})\underline{W}(t_2,t_3,\vec{\lambda})dt_2=\underline{I}\delta(t_1-t_3). \quad (24)$$

Here

$$\underline{R}(t_1,t_2,\vec{\lambda})=\underline{R}_s(t_1,t_2,\vec{\lambda})+\underline{R}_n(t_1,t_2)= \\ =\begin{Vmatrix} R_{s11} & R_{s12} & \cdots & R_{s1M} \\ R_{s21} & R_{s22} & \cdots & R_{s2M} \\ \vdots & \vdots & \ddots & \vdots \\ R_{sM1} & R_{sM2} & \cdots & R_{sMM} \end{Vmatrix}+ \\ +0{,}5N_{0n}\begin{Vmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{Vmatrix}\delta(t_1-t_2).$$

CONCLUSIONS

The analytical models of stochastic radiothermal signals for directional antennas and omnidirectional antennas are developed. The statistical characteristics of signals are derived.

The observation equations which are given and Likelihood function are constructed. Classification of the possibility of internal noises in all channels have been implemented to facilitate calculations of correlation functions and Likelihood function.

ACKNOWLEDGMENT

The authors thank Prof. V. K. Volosyuk and D.Sc. V. V. Pavlikov for their constructive comments and suggestion.

The work was supported by the Ministry of Education and Science of Ukraine.

References

[1] *A. Perley.* Synthesis Imaging in Radio Astronomy / A. Perley, *F. R.* Schwab and A. H. Bridle // Astronomical Society of the Pacific Conference Series, vol. 6, 1994.

[2] *Lillesand T. M.* Remote sensing and image interpretation (5th ed.) / Lillesand T. M. R. W. Kiefer J. W. // Wiley. ISBN 0-471-15227-7- 2003.

[3] *Ben-David C.* Parametric high resolution techniques for radio astronomical imaging / Ben-David C., Leshem A. // IEEE J. Sel. Topics in Signal Processing 2(5), 670–684 (2008).

[4] *M. Berger [et al.].* Measuring Ocean Salinity with ESA's SMOS Mission / ESA Bulletin. – 2002. – № 111. pp. 113–121.

[5] *Volosyuk V. K.* Statistical theory of radio-engineering systems of remote sensing and radar / Volosyuk V. K., Kravchenko V. F. // Fizmatlit, Moscow 2008 (in Russian).

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

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

[8] *Pavlikov V. V.* 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 / Pavlikov V. V., Kiem Nguyen Van. // proceedings of the XIIIth international conference TCSET'2016, February 23-26, 2016, Lviv-Slavske, Ukraine, pp. 236-239.

[9] *V. V. Pavlikov.* Optimal Structural Synthesis of Multi-Antenna Ultra-Wideband Radiometric Complex / V. V. Pavlikov, Kiem Nguyen Van, O. M. Tymoshchuk // proceedings of the 9th International Kharkiv Symposium on Physics and Engineering of Microwaves, Millimeter and Submillimeter Waves, MSMW'2016, Ukraine.

[10] *Kiem Nguyen Van.* Development and research of mathematical models of stochastic radiothermal signals / Kiem Nguyen Van, K. N. Nezhalskaya, O. M Tymoshchuk // proceedings of the first international scientific and technical conference "RadioElectronic &InfoCommunications", sep. 11-16, 2016, Kyiv, Ukraine. [in the print]

[11] *Johnson R.* Antenna Engineering Handbook / Johnson R. Jasik H. ed. (1984).

Manuscript received June, 06, 2016

Kiem Nguyen Van, PhD student of Department of Design of Radio Engineering Systems of Aircraft, National Aerospace University named after N.E. Zhukovskiy "Kharkiv Aviation Institute", Ukraine.

Kseniya Mykolaivna Nezhalska, Candidate of technical science of Department of Design of Radio Engineering Systems of Aircraft, National Aerospace University named after N.E. Zhukovskiy "Kharkiv Aviation Institute", Ukraine.

Tymoshchuk Olena Mykolaivna, Director of the institute of Water Transport, Kyiv State Maritime Academy named after hetman Petro Konashevych-Sahaydachniy, Kyiv, Ukraine.

УДК 621.396.96

Аналитические модели стохастических радиотепловых сигналов /Нгуен Ван Кием, К. Н. Нежальская, Е. Н. Тимощук // Прикладная радиоэлектроника: науч.-техн. журнал. – 2016. Том 15, № 2. – С. 105 – 109.

Разработаны математические модели сверхширокополосных стохастических радиометрических сигналов, наблюдаемых на выходах многоантенных решеток, составленных из направленных и слабонаправленных антенн. Такие решетки характерны для радиометрических комплексов, обеспечивающих высокую разрешающую способность по угловым координатам. Приведены примеры упрощения многомерных сигналов на случай использования одной антенны (направленной или слабонаправленной). Исследованы статистические характеристики моделей.

Даны примеры конструирования функционалов правдоподобия, необходимые для решения оптимизационных задач синтеза радиометрических комплексов.

Ключевые слова: аналитическая модель сигнала, радиометрический сигнал, пассивный радар.

Ил.: 02. Библиогр.: 11 назв.

УДК 621.396.96

Аналітичні моделі стохастичних радіотеплових сигналів /Нгуєн Ван Кієм, К. М. Нежальская, О. М. Тимощук // Прикладна радіоелектроніка: наук.-техн. журнал. – 2016. – Том 15, № 2. – С. 105 – 109.

Розроблено математичні моделі надширокосмугових стохастичних радіометрічних сигналів, які спостерігаються на виходах багатоантенних решіток із направлених і слабконаправлених антен. Такі решітки характерні для радіометричних комплексів, що забезпечують високу роздільну здатність по кутових координатах. Наводяться приклади спрощення багатовимірних сигналів на випадок використання однієї антени (направленої або слабконаправленої). Досліджено статистичні характеристики моделей.

Наведено приклади конструювання функціоналів правдоподібності, необхідні для вирішення оптимізаційних задач синтезу радіометричних комплексів.

Ключові слова: аналітична модель сигналу, радіометричний сигнал, пасивний радар.

Іл.02.: Бібліогр.: 11 найм.