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Information technologies for creating spatiotemporal modems multiposition active-passive radar systems

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Abstract. The methods of synthesis of the directional diagram of active transmitting antenna arrays when receiving signals reflected from radar targets are considered. It is shown that when using multifrequency orthogonal coherent signals in the elements and addressable access at their reception it is possible to provide a small level of the side lobes of the spatial uncertainty function in a given sector of observation by selecting the type of intrapulse modulation of partial signals. Orthogonalization of antenna basis of transmitting and receiving antennas allows digital spectral-correlation processing of samples of aggregate signal from each target to solve the technological problem of multidimensional observation space in multiposition systems of coherent radiolocation when detecting, resolving, estimating coordinates and motion parameters of targets. The results of simulation modeling of spatio-temporal radar modems implemented according to the stated principles are given.

1. Introduction

45 years ago the book by Y.S. Shifrin "Questions of statistical theory of antennas" was published [1]. Since then, the scientific provisions outlined in it are actively used for analysis and synthesis of not only

a variety of physical designs of antennas in the mastered wavebands, but also in spatially separated transmitting and receiving antenna systems, implementing a variety of methods of multiposition active-passive radiolocation. Multidimensionality of measurement space of vector of target position in such systems leads to ambiguity of estimates, which stipulates the need to take into account statistical characteristics of a set of multichannel active transmitting and receiving antennas, propagation paths and properties of radar objects. Provision of address accessibility to each of radiators of multielement transmitting antenna at reception of aggregate signals reflected from any target in MIMO-radars (MIMO-radar concept is presented in figures 1) is achieved by application of orthogonal partial signals of transmitting system, their coordinated filtering in each receiving channel [2].

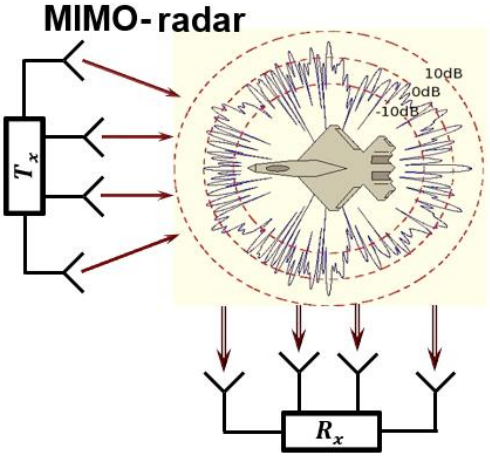


Figure 1. MIMO-radar concept.

Here in the receiver must also be synthesized the directional diagrams of the transmitting system to each target (many inputs - M). In addition, throughout the observation space the receiving beams (many outputs - N) must be formed by means of an antenna array with an appropriate number of controls for the amplitude-phase distribution in the opening. Thus, in the receiving system it is necessary to perform coordinated spatial and temporal processing at the output of an equivalent "virtual" antenna array with the number of spatial channels M×N (figures 2) [3].

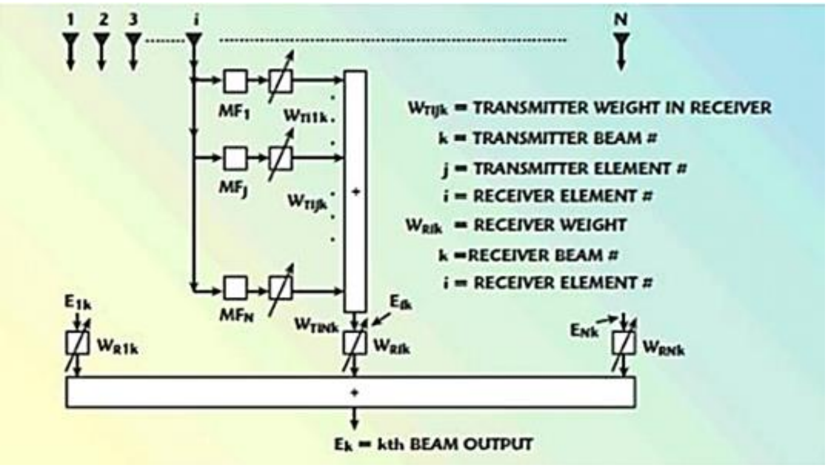


Figure 2. Formation of the directional diagram in the MIMO radar for a single target.

The structural scheme, by analogy with communication systems, corresponds to the MIMO radar modem with one output, addressed to the spatial-temporal position of a particular target. To solve the problem of radar observation at ranges of energy availability in all angular directions of the receiving antenna, it is necessary to have the appropriate number of copies of the structure of figures 3.

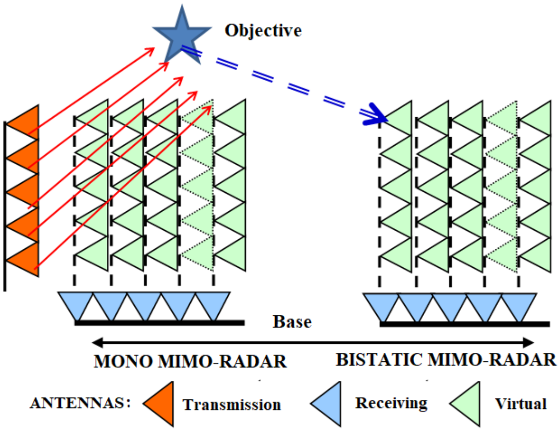


Figure 3. Structure of MIMO radar transmitters at orthogonal scan planes.

When trying to solve the problem directly, it is necessary to provide control of M×N2 weight coefficients, the calculation of which requires the circulation of matrices with M×N dimension [3 - 6]. The complex task of controlling the parameters of the matched filters for signal separation of the virtual channels of the transmitting lattice [3] at reception, as well as the choice of amplitude-phase distribution in the opening, which provides focusing of the radiation energy in the direction of the target, can be solved using multi-frequency (MF) dynamic transmitting AR with ultra-fast scanning [7, 8]. The common property of MF AR is the formation of spatio-temporal fields of impulse form. Due to the effect of "compression" of the partial signals of MF AR transmitters in space, energy is concentrated under the envelope of pulses of the form sin(x)/x. The duration of pulses and the scanning time of the MF AR are inversely proportional: the width of the spectrum of the partial signals and the difference in average frequency spectra of the partial signals of the transmitters T=Δf-1 respectively [8]. Technical feasibility of such MF AR is now possible due to the creation of methods for direct synthesis of signals by vector modulators at ultra-high frequencies (UHF) and solid-state power amplifiers with stable characteristics, as well as the mastered high-speed digital microelement base with stable clock frequencies up to 1 ... 3 GHz and the possibility of synchronization from atomic frequency standards with an accuracy of 1 ... 3 ns [9 - 11].

It allows to unify signal processors on the basis of spectral correlators, using algorithms of discrete Fourier transform of short samples of total echo signal in a range strobe (figures 4). Thus the problem of multidimensionality is solved when synthesizing (restoring) DN MF AR in the direction of the target, for subsequent determination of the angular coordinate in the scanning plane. However, dynamic control of weight coefficients in the spectral region, in order to reduce the level of side lobes DN throughout the observation sector, is significantly dependent on the type of angular intra-pulse and interchannel modulation of the partial coherent signals of MF AR [12].

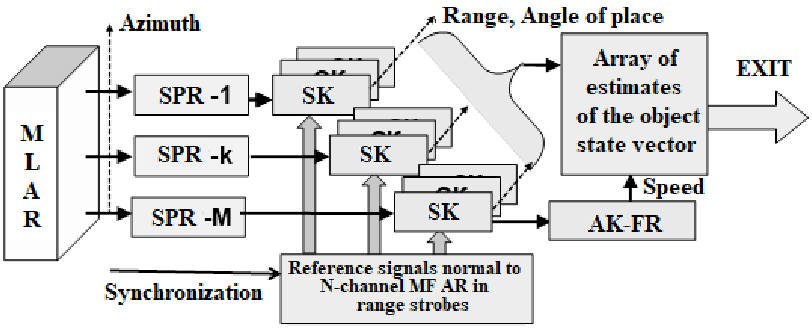


Figure 4. The structural diagram of the receiving system of MIMO radar with dynamic N- element AR.

Figure 4 shows: MLAR - multi-beam antenna array (antenna), M - channels, SPR - broadband receiver, SK - spectral-correlation processor, AK-FR - autocorrelation phase difference meter Doppler frequency shift.

Therefore, the problem of selecting the type of coherent signal modulation for the formation of spatial and temporal mismatch function in MIMO radars is relevant and little studied.

This determines the urgency of the first problem of the article, which consists in the justification of using MF AR, in the orthogonalization of the antenna base of the transmitting and receiving antennas, which allows for digital spectral-correlation processing of samples of the aggregate signal from each target, to replace the channel described in [3], broadband and solve the technological problem of accounting for the multidimensional observation space in multi-position systems of coherent radar.

In view of variety of types and parameters of pulse signals with angle modulation and analytical complexities of solution of multidimensional problems, estimation of influence of type of intrapulse modulation on parameters of spatial and temporal mismatch function, determining resolution and accuracy of joint estimation of coordinates and parameters of motion of MIMO radar targets, is performed by methods of statistical simulation modeling.

2. Main part

The complex envelope of the spatial-temporal signal (PVS) in the free space and the far AR zone of the transmitting position on its main polarization, without taking into account the effects of interaction of transmitters, with accuracy to the constant, will be proportional:

$$\dot{E}\left(\tilde{\vec{R}}^{TR}, t\right) = \sum_n^N F_n^{TR}\left(\vec{\rho}_n \cdot \tilde{\vec{R}}_0^{TR}\right) \cdot T\left(t - \frac{\left|\tilde{\vec{R}}^{TR}\right|}{c}\right) \times \exp\left\{j \frac{\omega_0}{c}\left(\overleftarrow{\rho}_n \cdot \tilde{\vec{R}}^{TR}\right)\right\} \qquad (1)$$

where: $\tilde{\vec{R}}^{TR}$, $\tilde{\vec{R}}_0^{TR} = \tilde{\vec{R}}_0^{TR} \cdot \tilde{\vec{R}}_0^{TR^{-1}}$ and $\tilde{\vec{R}}^{TR} = \left|\tilde{\vec{R}}^{TR^{-1}}\right|$- the radius-vectors of direction and range of the target observation point in the coordinate system relative to the center of the transmitting MF AR, respectively; $F_n^{TR}\left(\vec{\rho}_n \cdot \tilde{\vec{R}}_0^{TR}\right)$ - directivity diagram of a single transmitter transmitting MF AR; $\left(\vec{a} \cdot \vec{b}\right)$ - scalar product of vectors.

The PVS spectrum has a look:

$$\dot{E}^{\omega}\left(\tilde{\vec{R}}^{TR}, \omega\right) = \exp\left\{-j \frac{\omega}{c} \tilde{R}^{TR}\right\} \cdot \sum_n^N F_n^{TR}\left(\vec{\rho}_n \cdot \tilde{\vec{R}}_0^{TR}\right) \times \exp\left\{j \frac{\omega_0}{c}\left(\overleftarrow{\rho}_n \cdot \tilde{\vec{R}}^{TR}\right)\right\} \cdot \dot{S}_n(\omega) \qquad (2)$$

where: $\dot{S}_n(\omega) = \int_{-\infty}^{\infty} \dot{T}_n(t) \exp\{j\omega t\} dt$ - the complex value of the signal spectrum in the n-emitter.

As can be seen from (1) and (2), changes in the amplitude-phase distribution of currents (fields) in the transmission position grid take into account complex multipliers $\dot{T}_n(t)$ and $\dot{S}_n(\omega)$. Consequently, parameters of the input signals influence both spatial and temporal structure of the emitted signal.

As is known, a narrowband signal in the spatial and temporal sense implies the fulfillment of the condition [13, 14]:

$$\frac{2\pi f_0}{c} \cdot \max\left(\frac{\Delta F \cdot |\vec{\rho}|}{f}\right) \ll 1, \forall \vec{\rho} \in s, f \in \Delta F \qquad (3)$$

where: $\max\left(\frac{\Delta F \cdot |\vec{\rho}|}{f}\right)$ - a function that determines the extreme frequencies of the signal spectrum and the maximum (characteristic) antenna size, respectively.

When performed (3), in an expression for envelope PVS (2), it is possible to neglect the time delay in the antenna $\dot{T}(\vec{\rho}, t)$ emitted by different points. In this case, the expression for complex envelope PVS takes into account only the phase difference due to signal propagation to the observation point calculated at the average (carrier) frequency ω^0[14].

$$\dot{\vec{E}}\left(\vec{R}_0, t'\right) = \vec{F}_0\left(\vec{R}_0\right) \times \int_S \dot{T}(\vec{\rho}, t') \exp\left\{j \frac{\omega_0}{c} \cdot \left(\vec{\rho} \cdot \vec{R}_0\right)\right\} ds \qquad (4)$$

In particular, this simplification takes place if the product of the maximum width of the spectrum of complex envelope signals by the difference in the travel of waves from the extreme points of MF AR is much less than one, which is typical for a point target. For example, when the range resolution element of the MIMO radar δr is much larger than the characteristic size of the transmitting antenna. From (4) it follows that taking into account the lag, in general, this expression is a transformation of the Fourier instantaneous distribution of currents (fields) in the antenna, ie define the shape of DN MF AR in the direction of the target.

As can be seen, the functions of temporal - $\dot{T}(\vec{\rho}, t)$ and spatial modulation - $\vec{F}_0(\vec{R}_0)$ as well as the interference multiplier at the carrier frequency harmonic are included in the expressions for envelope PVS as a work of. The time (spectral) composition of PVS (fields) is related to the spatial coordinate of the observation point - $\vec{R}_0$ and is the result of the superposition of complex envelope partial currents (fields) supplied to the antenna aperture, taking into account the relative lag on the aperture - $t' + \frac{\vec{\rho}\cdot\vec{R}_0}{c}$.

In the considered case, addressing of angular directions is provided when the temporal (frequency) structure of PVS is unequivocally connected with the target spatial position. It is known [15, 16] that the used signal set in the transmitting antenna aperture meets the orthogonality condition on the accumulation time interval of the

$$\dot{K}_{\vec{\rho},\vec{\rho}'}(\tau) = \frac{1}{\sqrt{E_{\vec{\rho}}E_{\vec{\rho}'}}}\int_{t'}^{t'+\tau_{acc}} \dot{T}(\vec{\rho}, t)\cdot\dot{T}(\vec{\rho}', t-\tau)dt \approx\approx \begin{cases} \dot{K}_{\vec{\rho}(\tau),} & \vec{\rho}=\vec{\rho}' \\ 0, & \vec{\rho}\neq\vec{\rho}' \end{cases} \tag{5}$$

where: $\dot{K}_{\vec{\rho},\vec{\rho}'}(\tau)$ - mutual correlation function (MCF) of signals with energy $E_{\vec{\rho}}$ and $E_{\vec{\rho}'}$ at the points of the transmitting antenna with the coordinates $\vec{\rho}$ and $\vec{\rho}'$ respectively; $\dot{K}_{\vec{\rho}(\tau)}$ - autocorrelation function signal (ACF).

On the basis of the above relations the field structure has the form shown in figure 5 [17].

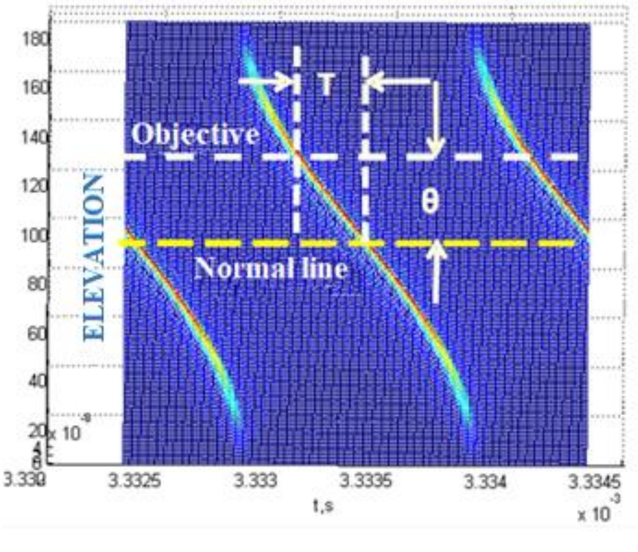
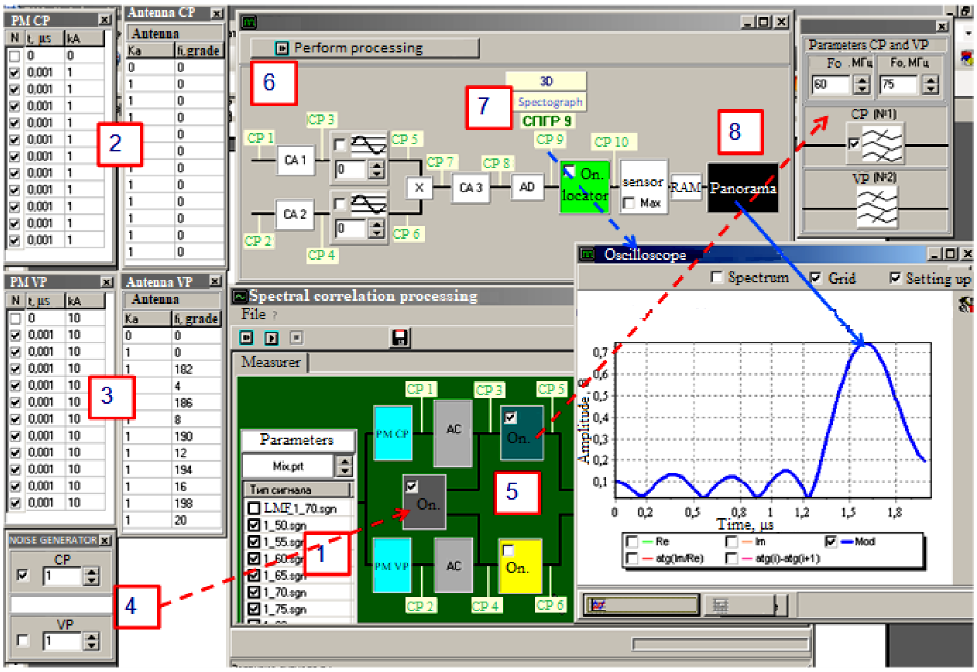


Figure 5. Structure of the MF AR field in the object distance strobe.

This structure indicates a linear relationship between the lag time τ and the target angular coordinate offset θ with respect to the normal of the MIMO radar transmitting array, which allows in the scheme of figure 4 makes it possible to measure by the time position of the maximum of the main lobe of the mutually correlated function (synthesized DN) using a spectral correlator with respect to the spectrum of the reference signal corresponding to the normal of the transmitting MF AR.

Simulation of processes in the spatial-temporal MIMO radar modem with MF AR. To assess the influence of the type of intrapulse modulation on the parameters of the spatial-temporal mismatch function, a comprehensive interactive simulation model of the MIMO radar modem (figure 6), which provides all the necessary algorithms for the formation and spectral-correlation processing of spatiotemporal signals in the structure of figure 4.



PM CP

N	t, µs	kA
☐	0	0
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1
☑	0,001	1

Antenna CP

Ka	fi, grade
0	0
1	0
1	0
1	0
	0
	0
	0
1	0
1	0
1	0
1	0
1	0

PM VP

N	t, µs	kA
☐	0	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10
☑	0,001	10

Antenna VP

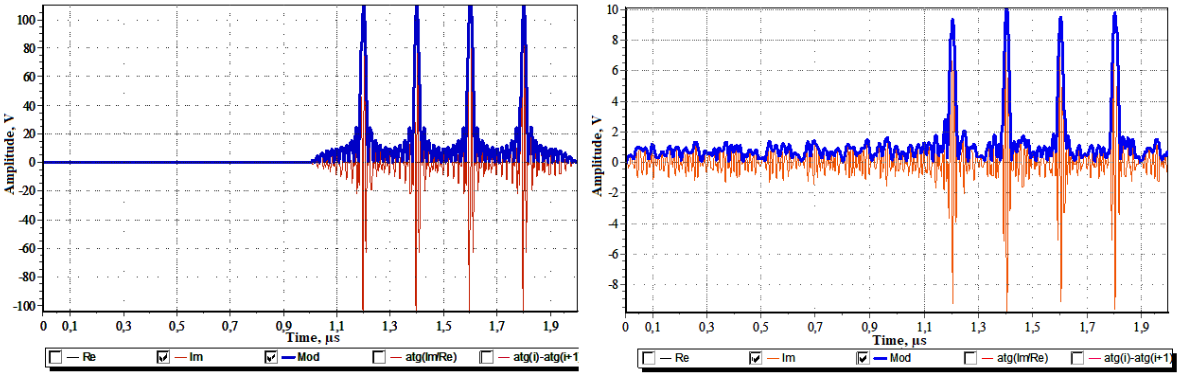
Ka	fi, grade
0	0
1	0
1	182
	4
	186
	8
1	190
1	12
1	194
1	16
1	198
1	20

NOISE GENERATOR: CP ☑ 1; VP ☐ 1

Parameters CP and VP: Fo, MГц 60; Fo, MГц 75

Figure 6. Interactive simulation model of the MIMO radar modem and target position angle measurements from the maximum of synthesized AF MF AR.

The model consists of interactive functional blocks: 1. Constructor of any number of radar signals with specified types of modulation; 2. Spatial-temporal modulator based on N-channel MF AR, which forms also the reference signal corresponding to the normal direction (figure 7, a); 3. Shaper of spatial-temporal signal reflected from the target at an angle θ (figure 7, b); 4. Noises of the receiving channels; 5. A bandpass filter of the ensemble of MF signals; 6. Processor of spectral-correlation processing of MF signals based on Fourier transforms of echo signal samples in range strobe; 7 Synthesized DN of the MF AR; 8 Unit of detection and estimation of the target bearing by the maximum DN.



a) b)

Figure 7. Structure of spatiotemporal signals: a) in the direction of the normal of the transmitting antenna array (reference signal), b) echo signal and noise at the input of the virtual receiving antenna of the MIMO radar.

The properties of a radar modem MIMO with 11-channel active transmitting AR, when excited by coherent signals of constant duration of 1.4 μs, with the following types of modulation were studied:

- unmodulated rectangular pulses (IM) with the center frequencies of the spectra standing at the base frequency Δf = 5 MHz;
- phase-code-manipulated (FCM) pulses with a 7-element Barker code and a duration of one 0.2 μs (BA) discrete;
- discrete-frequency-coded (FCC) seven elemental Costas (CO) signal, with the same discrete duration;
- FCC Costas signal, additionally modulated in phase by the 7-element Barker Code (COBA);
- linear frequency modulation (LFM) signal with 5 MHz frequency deviation, with different tilt sign relative to the frequency change in the MF AR elements.

The influence of the type of intrapulse angle modulation on the parameters of the synthesized DN of the MF AR is illustrated in figure 8.

Modeling has shown that when the object is in the direction of normal MF AR (figure 8), the width of the main rays synthesized by DN depends only on the maximum AR frequency diversity.

$$\Delta\tau_{DN} = (\Delta f \cdot N)^{-1} \tag{6}$$

At the same time, the side lobe (SL) reduction rate has the advantage of signals with frequency-phase angular modulation LFM and FCC, additionally modulated in phase in matching samples by the Barker code. These signals also have an advantage in cases where DN synthesis occurs when the objective is angularly deflected from the normal direction (figure 9).

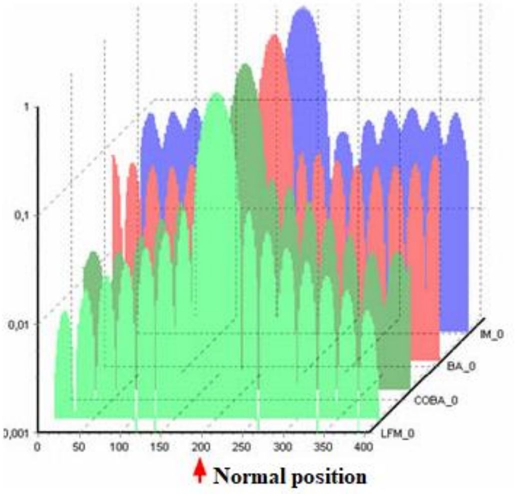


Figure 8. Synthesized DN MF transmitting AR (11 elements) at the object position in the normal direction.

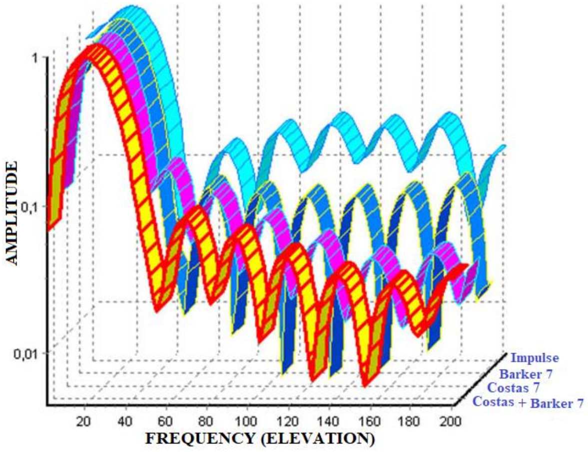
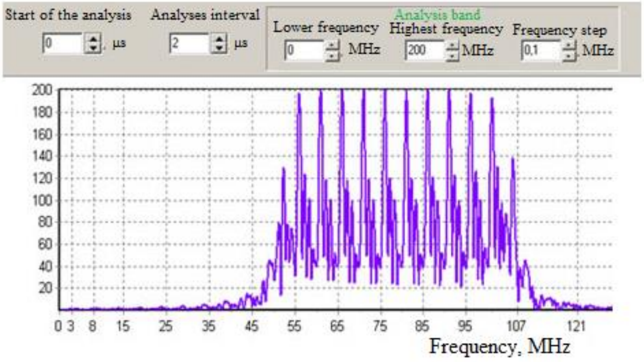


Figure 9. Equivalent DN MF AR (11 elements) when the object deviates from normal.

For signals with frequency-phase angular modulation, the small level of side lobes synthesized DN, due to the shape of the envelope spectrum of the reference signal, which is close to the amplitude distribution of Hemming and is shown in figure 10.



Start of the analysis 0 µs
Analyses interval 2 µs
Analysis band
Lower frequency 0 MHz
Highest frequency 200 MHz
Frequency step 0,1 MHz

Figure 10. Amplitude distribution in MF AR disclosure.

However, increasing the number of MF AR channels may cause narrowband conditions (3), (4) to be violated. In this case, the ACF of the aggregate signal (object in the direction of normal AR) is independent of the deviation sign, although spatially equidistant AR becomes electrically non-equidistant for different frequencies of partial signals. This effect is evident when the object angular position deviates from the normal and is illustrated in figure 11.

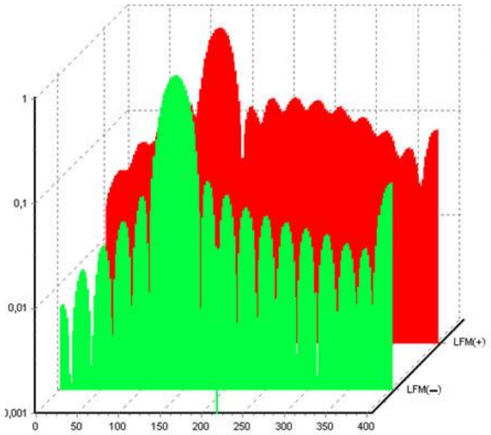


Figure 11. Effect of partial LFM signal deviation sign on SL level change in broadband MF AR.

In this case, the tilt mark of the LFM partial signal opposite the scanning direction (LFM(-)) has a corrective effect on the PHAR of the dynamic MF AR.

It is important to note that the effect of "compression" of the spatial-temporal signal in space, which converts the energy in the pulse volumes of all partial signals into a sequence of several short pulses of large amplitude, allows you to remove the limitation on the maximum peak power of solid-state transmitting modules of the active PHAR and provide single-channel processing of echoes during the synthesis of the DN transmitter PHAR in the direction of the target. The maximum DN corresponds to the angular coordinate of the target in the range strobe, and the width corresponds to the spatial resolution.

3. Conclusion

The presented results show that the use of modern industrial, information and digital technologies open the practical possibility of implementation of single- and multi-position radar systems on the principles of MIMO - modem, address-connected with the spatial-temporal position of each radar target. The key to solve the problem of multichannel in MIMO systems is the use of active transmitting dynamic antenna arrays with multi-frequency signals (spatial-temporal modulation) in combination with correlation processing processors based on digital Fourier transformers, invariant to the type of modulation of partial signals of transmitting AR (spatial-temporal demodulation). The high stability of the frequency standards is capable at present to provide the internal statistics of the spatially separated antenna systems,

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allowing a qualitative synthesis of the DN of the transmitting systems in the directions to the targets at reception.

The influence of intrapulse angular modulation of partial signals on the amplitude-phase distribution of MF ARs established during modeling opens up the possibility of controlling the parameters of synthesized DNs in a wide sector of the angular position of the targets.

The physical properties of the dynamic RF ARs associated with the "compression" of the field pulses during fast scanning largely remove the limitations in the use of solid-state microwave power amplifiers, which have stable characteristics that meet the requirements for use in dynamic transmitting ARs

Acknowledgements

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References

[1] Shifrin Ya S 1970 *Questions of Statistical Antenna Theory* (Moscow: Sovradio) 384
[2] Li J and Stoica P 2008 *MIMO radar signal processing* (New York: Wiley)
[3] Brookner E 2013 MIMO Radar Demystified *Microwave journal* **56(1)** 18894
[4] Sedyshev Y N and Dudush A S 2013 Evaluation of the impact of the time synchronization accuracy of multistatic radar positions on errors in determining the spatial coordinates of aerial objects *Radioelectron. Commun. Syst.* **56** 178-85
[5] Brookner E 2015 MIMO Radars and their conventional equivalents *IEEE Radar. Conf.* (Arlington VA USA) 918-23
[6] Zamyatin B I, Baturin O V and Tolokneyev E A 2000 Spatial Temporary Modulation of Signals in Ring Antenna Grates Vesnik KHPU **128** 14-9
[7] Kucherov Yu S and Chapursky V V 1994 Superfast beam scanning antenna arrays Radiotekhnika and electronica **10** 1562-9
[8] Vovshin B M and Pakhomov S V 1991 On the principles of operation of an ultra-fast radar beam scanning station *Vapors radio-electronics* **14** 27-38
[9] Sedyshev Y N and Tyutyunnik V A 2015 Information technologies for creating spatio-temporal modems of multiposition active-passive radar systems *Applied Radio Electronics*, **14** 105-10
[10] Kartsan I N, Zhukov A O, Timoshenko A V, Perlov A Y and Ryabchenko D V 2020 Precising the evaluation of radio information system reliability characteristics based on the empirical failure distribution *IOP Conf. Ser.: Mater. Sci. Eng.* **919(5)** 052002
[11] Zhukov A O, Valyaev I N, Kovalenko V P, Turlov Z N, Novikov A S, Kartsan I N and Malanina Y N 2020 Narrow-band correlation processing of signals in a phase direction-finding *Journal of Physics: Conf. Ser.* **1515(2)** 022044
[12] Zhukov A O, Valyaev I N, Kovalenko V P, Turlov Z N, Chebotarev A S, Kartsan I N and Shumakova N A 2020 Adaptation of receiving channels to the spectrum of the received signal *Journal of Physics: Conf. Ser.* **1515(3)** 032070
[13] Allan D W, Ashby N and Hodge C C 1997 *Application Note1289 The science of timekeeping* (Allan USA: Hewlett–Packard Company) 88
[14] Chernyak V S 2010 On the concept of MIMO radars *IEEE Radar. Conf.* (Arlington VA USA) 5494601
[15] Dorey J, Garnier G and G. Auvray 1989 RIAS, synthetic impulse and antenna radar *Colloque International sur le Radar* 556-62
[16] Sedyshev Yu N, Sedyshev P Yu, Tyutyunnik V A and Shevchenko A F 2010 Peculiarities of using space-time multi-frequency signals for fast electronic scanning in radars with active phased antenna array *Radioelectronic and Communication System* **53(4)** 173-84
[17] Zhukov A O, Valyaev I N, Kovalenko V P, Turlov Z N, Minin I V, Zaverzaev A A,

Kartsan I N and Malanina, Y N 2020 Method for phase direction finding of signals with asymmetric spectra *Journal of Physics: Conf. Ser.* **1515(2)** 022051

[18] Vovshin B M and Kulikov K V 2014 Spatial-Multi-Channel reception in MIMO radars of parallel space overview with orthogonal multiple frequency Signals *Successes of modern radio electronics* **7** 35-48

[19] Sedyshev Yu N and Dudush A S 2013 Evaluation of the impact of the time synchronization accuracy of multistatic radar positions on errors in determining the spatial coordinates of aerial objects *Radioelectronics and Communications Systems* **56(4)** 29-38