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RESEARCH ARTICLE

On the equivalence of characteristics and specularity in the construction of traditional and MIMO radars with a parallel view of space based on antenna arrays

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Abstract
Objectives. In recent years, more and more attention has been paid in radar theory and practice to the development of multiple-input and multiple-output (MIMO) radar, which offers a number of advantages over traditional radar based on phased antenna arrays (PAAs). These include the possibility to flexibly view space and adapt to a changing signal-interference environment, etc. MIMO technology used in radar requires the emission of a probe signal in the form of a coherent system of orthogonal signals, each of which triggers its own emitter in the transmitting antenna array (AA). As a result, the specified target search area is simultaneously illuminated. Specific spatiotemporal processing (SSP) is used to collect signals from all directions in the irradiated zone at the receiver output. In this regard, the task of finding an SSP structure in MIMO radar that is optimal compared to the traditional approach becomes urgent. The study set out to synthesize the structure of SSP with single–channel reception in MIMO radar and compare the obtained structure and characteristics with those similar in traditional parallel-view radars based on multipath receiving radar.
Methods. The study is based on methods and principles of the theory of multibeam synthesized aperture antennas and methods for the synthesis of optimal Neiman–Pearson detectors based on the likelihood ratio.
Results. For a MIMO radar with AA for transmission and reception provided by a single weakly directional antenna, a split SSP was synthesized to form optimal pre-threshold statistics (PTS) of the detector against a background of white Gaussian noise. The obtained PTS is compared with a similar PTS in a traditional parallel space survey radar with a mirror structure.
Conclusions. It is shown that the detection quality indicators of the compared radars in the mirror construction are equivalent in the mode of parallel target search in the same spatial sectors.

Keywords: MIMO radar, parallel space survey, space-time processing, FFT algorithm, multipath antenna array, pre-threshold statistics

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НАУЧНАЯ СТАТЬЯ

Об эквивалентности характеристик и «зеркальности» построения традиционных и MIMO радиолокационных станций при параллельном обзоре пространства на основе антенных решеток

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Резюме

Цели. В последние годы в теории и практике радиолокации все больше внимания уделяется вопросам создания MIMO (англ., «много входов – много выходов») радиолокационных станций (РЛС), обладающих рядом достоинств перед традиционными РЛС с фазированными антенными решетками. К этим достоинствам следует отнести возможности гибкого обзора пространства, адаптации к меняющейся сигнально-помеховой обстановке и т.д. Технология MIMO в радиолокации требует излучения зондирующих сигналов в виде когерентной системы ортогональных сигналов, каждый из которых возбуждает собственный излучатель передающей антенной решетки (АР). Вследствие этого одновременно «освещается» заданная зона поиска цели. Пространственно-временная обработка (ПВО) «собирает» сигналы со всех направлений в облученной зоне на выходе приемника. В связи с этим актуальной является задача поиска оптимальной структуры ПВО в MIMO РЛС по сравнению с традиционным подходом. Цель работы – синтез структуры ПВО при одноканальном приеме в MIMO РЛС и сравнение полученного построения и характеристик с аналогичными в традиционных РЛС параллельного обзора на основе многолучевой приемной АР.

Методы. Использованы методы и принципы теории многолучевых антенн с синтезированной апертурой и методы синтеза оптимальных по критерию Неймана – Пирсона обнаружителей на основе отношения правдоподобия.

Результаты. Для MIMO РЛС с АР на передачу и одиночной слабонаправленной антенной на прием синтезирована разделяющаяся ПВО, формирующая оптимальную предпороговую статистику (ППС) обнаружителя на фоне белого гауссова шума. Проведено сравнение полученной ППС с аналогичной ППС в традиционной РЛС параллельного обзора пространства, имеющей «зеркальное» построение.

Выводы. Доказано, что в режиме параллельного поиска цели в одинаковых пространственных секторах показатели качества обнаружения у сравниваемых РЛС при «зеркальном» построении эквивалентны.

Ключевые слова: MIMO РЛС, параллельный обзор пространства, пространственно-временная обработка, алгоритм БПФ, многолучевая антенная решетка, предпороговая статистика

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INTRODUCTION

In recent years, research into Multiple-Input, Multiple-Output (MIMO) radars has claimed an important position within the theory and practice of radiolocation. Interest in MIMO radars has arisen in connection with the emerging possibilities of overcoming the limitations of traditional phased antenna array (PAA) radars in observing targets. MIMO technology is anticipated to be as revolutionary as the electronic scanning that replaced mechanical scanning in antenna technology to provide new radar characteristics and functionality [1, 2].

The idea of MIMO radar was originally based on the well-known property of radars in survey mode: the signal-to-noise ratio (SNR) at the receiver input and consequent detection quality index is practically independent of the transmit beamwidth $\Delta\theta_{0.5\mathrm{tr}}$ for a given survey sector $\Delta\theta_{\mathrm{svy}}$ and time t_{svy}. This statement, which is based on the fact that a decrease of the antenna directivity on transmission and concomitant decrease in the signal level on the target in the radar can be compensated by increasing the observation time, can be clarified as follows.

During the target location time in the beam width $\Delta\theta_{0.5}$, the size of the accumulated packet of reflected signals with period T_0 is $Q = (t_{\mathrm{svy}}\Delta\theta_{0.5})/(T_0\Delta\theta_{\mathrm{svy}})$. Therefore, as the observation rate increases, the value of Q decreases in proportion to the decrease in t_{svy}, which can only be increased at $T_0 = \mathrm{const}$ by widening the beam by $\Delta\theta_{0.5}$. If the beam width is matched to the survey sector $\Delta\theta_{0.5} = \Delta\theta_{\mathrm{svy}}$, the echo signals from all targets having a priori unknown angular coordinates within the coverage area can be collected using a receiving multibeam AA (MBAA). When this parallel type of view is applied, the number of coherently accumulated pulses Q is limited only by the correlation time interval of the target itself $t_{\mathrm{TRG\ corr}}$ [3, 4]. In practice, traditional radars with parallel-view PAA have the following well-known disadvantages [5, 6]:

1. A wide directivity pattern (DP) for transmission equal to $\Delta\theta_{\mathrm{svy}}$ is usually achieved by a weakly directional antenna (WDA). It must therefore have increased electrical strength for a given radiated power.
2. If the orthogonality condition is satisfied, the number of MBAA beams formed cannot exceed the number of radiators, and the step d between them is limited to overlap the area. These two factors determine the angular resolution of the radar.
3. Like any PAA, the MBAA has dispersive properties that limit the bandwidth of the probe signals (PS) used [4].

Some studies [7–9] have demonstrated the possibility to compensate or completely eliminate these disadvantages and limitations using the MIMO radar technology. The essence of this technology is as follows. A transmitting M-element AA radiates an M-component system of mutually orthogonal coherent PS. The width of partial DPs of this AA $\Delta\theta_{\mathrm{el}}$ should be equal to $\Delta\theta_{\mathrm{svy}}$. In turn, the PS orthogonality supports the assumption that the superposition of the received echo signals, after reflection from the target, can be divided into M independent channels with uncorrelated noise $\overline{n_i n_j} = \begin{cases} \sigma^2_{\mathrm{noise0}} & \text{at } i = j, \\ 0 & \text{at } i \neq j, \end{cases}$ $i, j \in M$, where $\sigma^2_{\mathrm{noise0}}$ is the noise variance, assumed to be equal in all channels for simplicity, and the line above is the averaging symbol.

MIMO radars are limited to parallel space survey because there is virtually no PS interference on the target. In search mode, the radar is assumed to have a multi-beam pattern at the receiver, as in a traditional radar. We consider the implementation of parallel view in MIMO radars combined with spatiotemporal processing (SSP), which forms the optimal pre-threshold statistics (PTS) according to the Neyman–Pearson criterion [10].

This integrated approach allows MIMO radars to be compared with traditional radars at the PTS level in terms of providing equivalent detection quality index when searching for targets. Once this problem is solved, the design conditions and principles of MIMO radar can be determined to offer advantages over traditional radars despite possible practical difficulties.

The present work sets out to synthesize the SSP structure in a MIMO radar and compare it with similar processing in a traditional parallel-view radar assuming similar detection quality performance.

PARALLEL SURVEY AND TARGET DETECTION IN TRADITIONAL RADARS WITH MBAA

We consider the design principles of traditional radars with MBAA for parallel survey of a given angular sector $\Delta\theta_{svy}$. The most common is to use WDA for transmission and MBAA for reception, as shown in Fig. 1. Without loss of generality, it is assumed that the WDA DP width $\Delta\theta_{WDA} = \Delta\theta_{svy}$ and the number of independent beams of the linear MBAA is equal to the number of emitters N, arranged in equidistant steps $d_r \le \dfrac{\lambda_0}{1+\left|\sin\left(\Delta\theta_{svy}/2\right)\right|}$, where λ_0 is the operating wavelength. In addition, the narrow-bandwidth condition of the excitation signal $u(t)$ with a bandwidth Δf_s [2, 8] is imposed on the receiving MBAA:

$$T_a = (N-1)d_r \sin\left(\frac{\Delta\theta_{svy}}{2}\right) \ll \frac{1}{\Delta f_s}, \quad (1)$$

where T_a is the time of filling the MBAA aperture with a pulse of equivalent duration $\tau_{p.e.} = 1/\Delta f_s$.

We define the PS complex envelope $\dot{U}_{ref}(t)$ following reflection from a point target with a three-component vector of information parameters $\boldsymbol{\kappa} = \{R_{TRG}, V_{rTRG}, \theta_{TRG},\}$, where R_{TRG}, V_{rTRG}, and θ_{TRG} are range, radial velocity, and angular coordinate of the target, respectively. At the MBAA output, it has the following form:

$$\dot{U}_{ref}(t,\boldsymbol{\kappa}) = \\ = F_{tr}(\theta_{TRG})\dot{U}_{tr}(\gamma_{TRG}t-\tau_{TRG})e^{j2\pi f_0\gamma_{TRG}t} = \\ = U_{tr}(t'-\tau_{TRG})e^{j2\pi f_0 t'}, \quad (2)$$

where $F_{tr}(\theta_{TRG})$ is the WDA DP level in the θ_{TRG} direction; $\tau_{TRG} = 2R_{TRG}/c$ is signal delay time; c is the speed of light; $\gamma_{TRG} = 1 \pm 2V_r/c$ is a Doppler time scale change coefficient for which $F_D = 2V_r/\lambda_0$ is a Doppler frequency, $t' = \gamma_{TRG}t$.

It can be further assumed that $F_{tr}(\theta_{TRG}) \approx$ const and that the complex envelope of the received signal is decomposed by condition (1) into a scalar time function and an N-dimensional vector $\boldsymbol{\beta}(\theta_{TRG})$ of spatial phases in the single-target situation:

$$U_r(t'-\theta_{TRG}) = U_{tr}(t'-\tau_{TRG})\boldsymbol{\beta}(\theta_{TRG}), \\ \boldsymbol{\beta}(\theta_{TRG}) = \exp\left\{ j\frac{2\pi d_r}{\lambda_0}(n-1)\sin\theta_{TRG} \right\}_{n=1}^{N}. \quad (3)$$

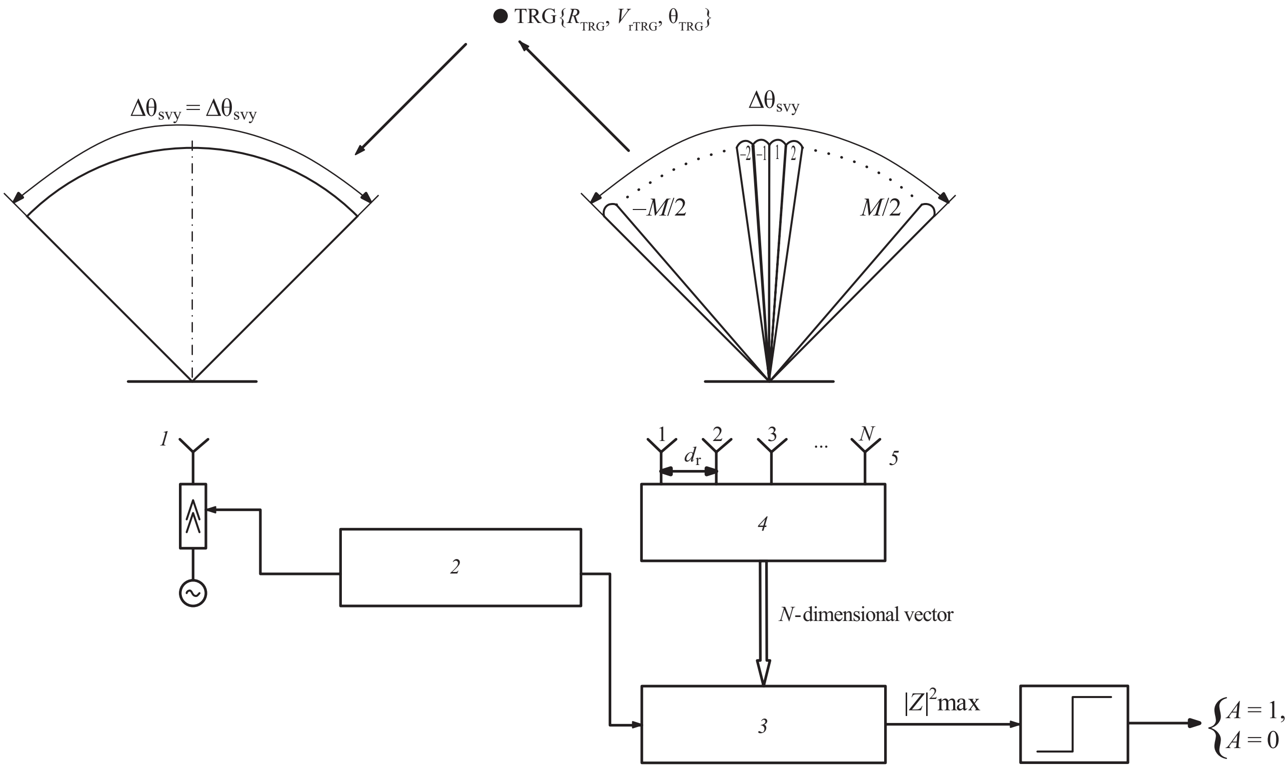

Fig. 1. Traditional radar with parallel space survey: (*1*) WDA; (*2*) PS shaper; (*3*) temporal processing (PS shaping); (*4*) spatial processing (diagram-forming scheme); (*5*) MBAA. TRG{R_{TRG}, V_{rTRG}, θ_{TRG}} is target; *A* is the threshold at which a decision is made about the presence or absence of a signal

We consider the multichannel target detection problem in the classical mixture reception formulation, $y(t) = A\dot{U}_{\text{r}}(t) + n(t)$, where $A = \{1, 0\}$ depending on the presence/absence of the valid signal, and $n(t)$ is white Gaussian noise. In the absence of correlating external interference with the same white Gaussian noise intensity in the MBAA channel, $\sigma_i^2 = \sigma_j^2 = \sigma_0^2(\overline{i, j} \in M)$, while the $(N \times N)$ dimensional correlation matrix function of the interference is represented by the following equation:

$$\mathbf{\Phi}(t - s') = N_0 \mathbf{I} \delta(t - s), \tag{4}$$

where $\mathbf{I}$ is the unit diagonal matrix; N_0 is the noise power spectral density; δ is the Dirac delta function.

Under these conditions, the optimal SSP by Neyman–Pearson criterion can be reduced to calculating the PTS in the form of the squared modulus of the weight integral:

$$\xi = |Z|^2 = \frac{1}{N_0} \left| \int \dot{Y}_\Sigma(t') \dot{U}^*_{\text{rec}}(t') dt' \right|^2, \tag{5.1}$$

$$\dot{Y}_\Sigma(t') = \mathbf{Y}^{\text{T}}(t', \theta_{\text{TRG}}) \boldsymbol{\beta}^*(\theta_{\text{TRG}i}), \tag{5.2}$$

where $\mathbf{Y}$ is the input vector.

In Eqs. (5.1) and (5.2), the symbols (*) and ($^{\text{T}}$) stand for complex conjugation and transposition, respectively. Equation (5.2) defines the complex amplitude at the output of the ith secondary MBAA channel phased in the expected direction $\theta_{\text{TRG}i}$ ($i \in \overline{1, N}$). As mentioned above, the N rays formed by MBAA should cover the entire given survey sector $\Delta\theta_{\text{svy}}$. In practice, the lossless formation of orthogonal rays can be conveniently implemented based on the fast Fourier transform (FFT) algorithm when $N = 2^q$, where q is an integer (the Butler matrix in analogue form [1]). The FFT algorithm converts the counts of the N-dimensional vector of the input signal (3) (primary MBAA channels) into a vector of N orthogonal rays (secondary channels (DP)) using the $(N \times N)$ transformation matrix $\mathbf{W}(\theta) = \{w\}_{n,i}^{N,N}$, where $w_{ni} = \exp\left(j2\pi n/N\right)$; n, i are the numbers of the primary and secondary MBAA channels, respectively.

After implementing the FFT, Eq. (5.1) can be considered as expressing the PTS in each of the N secondary channels if we assume: $\dot{Y}_\Sigma(t') = \mathbf{Y}^{\text{T}}(t', \theta_{\text{TRG}}) \mathbf{W}^*(\theta_{\text{TRG}i})$, where $\theta_{\text{TRG}i} = \arcsin\left[(i - 1/2)\lambda_0 / (N - 1)d_{\text{r}}\right]$ (see Fig. 1).

The principles of the parallel survey described above are common to the traditional radar systems with MBAA. They have some features that are more important for comparison with MIMO radars. These include:

1. The target is simultaneously irradiated by a single coherent PS $\dot{U}_{\text{tr}}(t)$ at the carrier frequency f_0 with a given average power.
2. Increasing the number of elements in the WDA, e.g., in the form of a small AA, is often impossible in principle. This is because it is accompanied by a narrowing of $\Delta\theta_{\text{WDA}}$, which does not effectively illuminate the search area $\Delta\theta_{\text{svy}}$.
3. The resolving power of MBAA beams is determined by the geometric size of their aperture $L_{\text{multiAA}} = (N - 1)d_{\text{r}}$. In this case, according to point 2, the number of orthogonal beams is limited by the number of primary channels N, and the increase in step d_{r} is limited by the width of the specified survey sector $\Delta\theta_{\text{svy}}$. These factors do not allow the MBAA beams to be narrowed or their number to be increased.
4. The design of a traditional parallel space survey radar (Fig. 1) implements a factorized representation of the PTS (3). This allows the sequential SSP to be divided into spatial (DP) and spatiotemporal processing (Woodworth function) in this order.

It should be noted here that the reverse order is impractical as it would require the same temporal accumulation to be performed in each primary MBAA channel prior to the spatial accumulation, which conveniently performed only once.

The above features and limitations are rare. They are mostly removed in MIMO radars due to the increased dimensionality of the problem. Instead of a single PS, N orthogonal but coherent signals are transmitted simultaneously, providing additional freedom for radar surveillance.

Assuming equivalent PTS and detection performance, we now turn to the analysis of the differences between MIMO radars and traditional radars.

PARALLEL SURVEY AND TARGET DETECTION IN MIMO RADARS

We start with the main characteristic of MIMO radars, which is the illumination of the coverage area by a system of orthogonal arrays that excite the AA with step d_{r}, shown in the left part of Fig. 2. The array generally emits a vector signal with a complex envelope $\dot{\mathbf{U}}_{\text{tr}}(t) = \{\dot{U}_{\text{tr}\,m}\}_{m=1}^{M}$. The orthogonality condition of these components should be satisfied for all directions θ within the sector $\Delta\theta_{\text{svy}}$. Then the normalized correlation coefficient between the pth and qth components can be described by the following equation:

$$\rho_{pq} = \frac{\int \dot{U}_{p\text{tr}}\left[t + (p-1)\frac{d_{\text{tr}}}{\text{c}}\sin\theta\right] dt \int \dot{U}^*_{q\text{tr}}\left[t + (q-1)\frac{d_{\text{tr}}}{\text{c}}\sin\theta\right] dt}{\left[\int |\dot{U}_{p\text{tr}}(t)|^2\, dt \int |\dot{U}_{q\text{tr}}(t)|^2\, dt\right]^{1/2}}. \tag{6}$$

The complex envelope of the total signal reaching the target has the following form:

$$\dot{\mathbf{U}}_{\text{tr}}(t,\theta_{\text{TRG}}) = \\ = \sum_{m=1}^{M} \dot{U}_{m\text{tr}} \left[t + (m-1)\frac{d_{\text{tr}}}{\text{c}} \right] \exp\left[j\frac{2\pi d_{\text{tr}}}{\lambda_0}(m-1)\sin\theta_{\text{TRG}} \right]. \quad (7)$$

As in the previous case, it is assumed to be narrowband. This satisfies condition (1). Note that for MIMO radars, by operating on orthogonal signals, e.g., separated by Δf_0 carrier frequencies [11, 12], the traditional limitations of the AA bandwidth are practically eliminated. When received, they can be band-separated and thus their interference can be neglected. For the correctness of the comparison, it is assumed that the signal bandwidth transmitted by the MIMO radar AA is the same as that of a traditional radar and is equal to $\Delta f_s = (N-1)\Delta f_0$ under the condition $\Delta f_s \ll \Delta f_0$.

The average power of the vector signal (7) reaching the target can be represented by quadratic Hermite:

$$P_{\text{tr}} = \sum_{p=1}^{M}\sum_{q=1}^{M} \overline{\dot{U}_p \dot{U}_q} \exp\left[j\frac{2\pi d_{\text{tr}}}{\lambda_0}(p-q)\sin\theta_{\text{TRG}} \right] = \\ = \alpha^{\text{T}}(\theta_{\text{TRG}})\mathbf{I}\alpha^*(\theta_{\text{TRG}}). \quad (8)$$

We assume that the power (8) is the same as in the previous case, i.e., $P_{\text{tr}} = P_{\text{t.p.}} G_{\text{WDA}}$, where $P_{\text{t.p.}}$ is the transmitter power at the WDA input of the traditional radar and G_{WDA} is the directional coefficient of the WDA.

For a point target with a vector of information parameters $\boldsymbol{\kappa} = \{t', V_{\text{r TRG}}, \theta_{\text{TRG}}\}$, the complex amplitude of the reflected signal is as follows:

$$\dot{\mathbf{U}}_{\text{ref}}(t',\tau_{\text{TRG}},\theta_{\text{TRG}}) = F_{\text{tr}}(\theta_{\text{TRG}}) \sum_{m=1}^{M} \dot{U}_{m\text{tr}}(t'-\tau_{\text{TRG}}) \times \\ \times \exp\left[j\frac{2\pi d_{\text{tr}}}{\lambda_0}(m-1)\sin\theta_{\text{TRG}} \right]. \quad (9)$$

We assume that all radiators of the transmitting AA have the same weakly directional DP adapted to the coverage area, i.e., $F_{\text{tr}}(\theta_{\text{TRG}}) = \text{const}$ for all $\theta_{\text{TRG}} \in \Delta\theta_{\text{svy}}$. Then, Eq. (9) can be viewed as the M-dimensional vector $\dot{\mathbf{U}}_{\text{ref}}(t) = \left\{ \dot{U}_{m\text{tr}}(t,\tau'_{\text{TRG}}) \text{e}^{j\alpha_m(\theta_{\text{TRG}})} \right\}_{m=1}^{M}$, which coincides with the vector exciting the single receiving WDA in the right part of Fig. 2, where $\alpha_m(\theta_{\text{TRG}})$ is the phase run-up of the mth partial signal.

We proceed with the synthesis of the SSP at the output of this WDA, given that the received signal $\dot{U}_{\text{rec}}(t) = \dot{U}_{\text{ref}}(t)$ is factorized into M temporal and spatial multipliers. We therefore divide it into M independent channels, as shown in Fig. 3:

$$\dot{\mathbf{U}}_{\text{rec}}(t',\tau_{\text{TRG}},\theta_{\text{TRG}}) = \mathbf{E}^{\text{T}} \otimes \dot{\mathbf{U}}_{\text{ref}}(t',\tau_{\text{TRG}},\theta_{\text{TRG}}) = \\ = \left\{ \dot{U}_{m\text{tr}}(t'-\tau_{\text{TRG}}) \text{e}^{j\alpha_m(\theta_{\text{TRG}})} \right\}_{m=1}^{M}, \quad (10)$$

where $\mathbf{E} = \{1\}_{m=1}^{M}$ is the M-dimensional unit vector and $\otimes$ is the Kronecker product symbol.

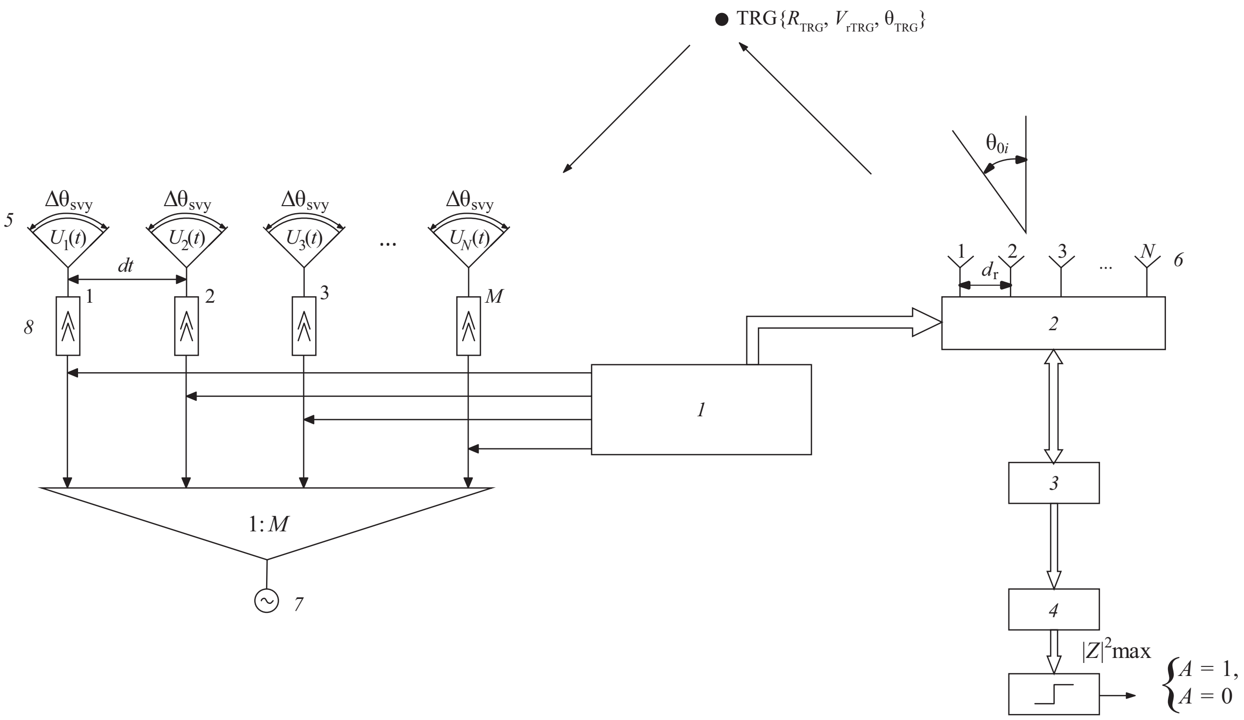

Fig. 2. MIMO radar with parallel space survey: (*1*) orthogonal PS generator; (*2*) temporal processing; (*3*) spatial processing; (*4*) PTS generator; (*5*) transmitting AA; (*6*) receiving AA; (*7*) driving generator; (*8*) power amplifier

With respect to the noise properties, these channels are independent and their correlation matrix function is described by Eq. (4), which applies here as well. In the white Gaussian noise background, optimal temporal processing is implemented by a set of matched filters (MFs) for each partial signal $U_m(t)$ in the receive channel. However, in contrast to (5), in the one-target situation for the expected direction $\theta_{\mathrm{TRG}i}$ in the expression for PTS, the time multiplier of the signal is a vector rather than a scalar and is of the following form:

$$\xi = |Z|^2 = \mathbf{Y}^{\mathrm{T}}(t', \theta_{\mathrm{TRG}})\mathbf{U}^*(t', \theta_i) =$$
$$= \frac{1}{N_0}\left|\sum_{m=1}^{M} \dot{Y}_m(t', \theta_{\mathrm{TRG}})\dot{U}^*_{0m}(t')\mathrm{e}^{-j\frac{2\pi d_{\mathrm{tr}}}{\lambda_0}(\sin\theta_{\mathrm{TRG}} - \sin\theta_i)}\right|^2 =$$
$$= \frac{1}{N_0}\left|\sum_{m=1}^{M} Y_{m\,\mathrm{mf}}(0)\mathrm{e}^{-j\frac{2\pi n d_{\mathrm{tr}}}{\lambda_0}(m-1)(\sin\theta_{\mathrm{TRG}} - \sin\theta_i)}\right|^2, \quad (11)$$

where $\dot{U}_{0m}(t')$ is the complex envelope of the expected signal in the mth partial channel, $Y_{m\,\mathrm{mf}}(0)$ is the result of temporal accumulation of the signal, which corresponds to the maximum amplitude at $t' = 0$ at the MF output in the mth channel.

An important feature of the scheme in Fig. 3 is that temporal accumulation precedes spatial accumulation, indicating an inverse order relative to traditional SSP.

Using $t' \neq 0$ in (11), the output signal $\dot{Y}_{m\,\mathrm{mf}}(t')$ can be considered as a frequency-temporal mismatch in range and velocity, and the formula generally as a multidimensional mismatch function in the range-velocity-angle coordinates, similar to [13].

An additional interpretation of Eq. (11) can be provided. It corresponds to the traditional AA multiplier formula, where the vector $\dot{\mathbf{Y}}_{\mathrm{mf}}(t')$ has the form of a time-dependent amplitude distribution of M-element equidistant AA with step d_{tr}. If $Y_{\mathrm{mf}}(0)$ = const in all channels, then this equivalent distribution is uniform at the time corresponding to the signal maximum. In antenna theory, this transformation of a single receive radiator into an AA identical to the transmit one (Fig. 4) corresponds to the concept of the synthesized aperture. However, most papers dealing with MIMO radars use the term virtual sublattice/lattice [7, 14, 15].

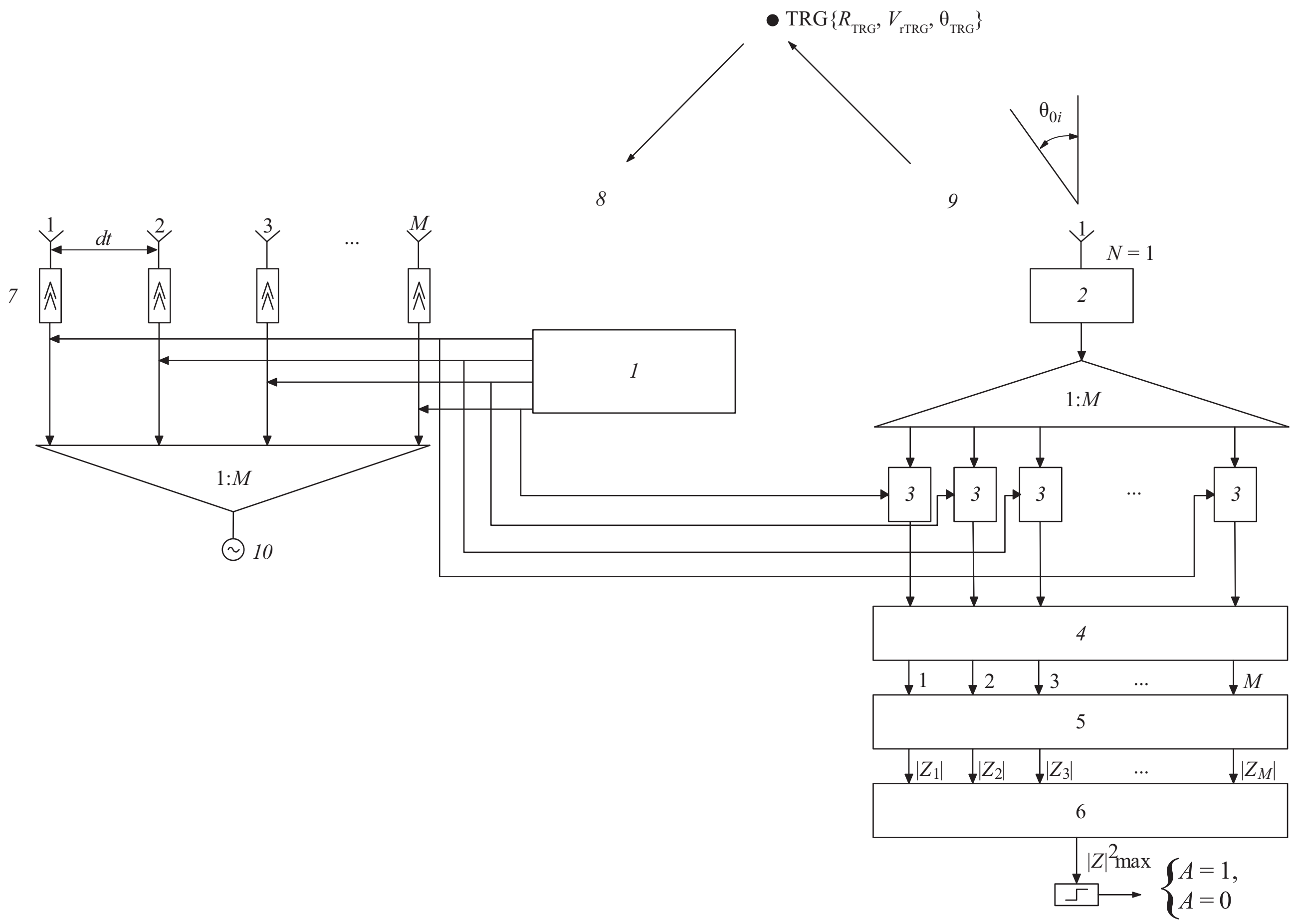

Fig. 3. Sequence of SSP steps in MIMO radars: (*1*) orthogonal PS shaper; (*2*) low-noise amplifier; (*3*) MF; (*4*) diagram-forming scheme (*M*-point FFT); (*5*) PTS shaper; (*6*) maximum sampling; (*7*) power amplifier; (*8*) transmitting AA; (*9*) receiving AA; (*10*) driving generator

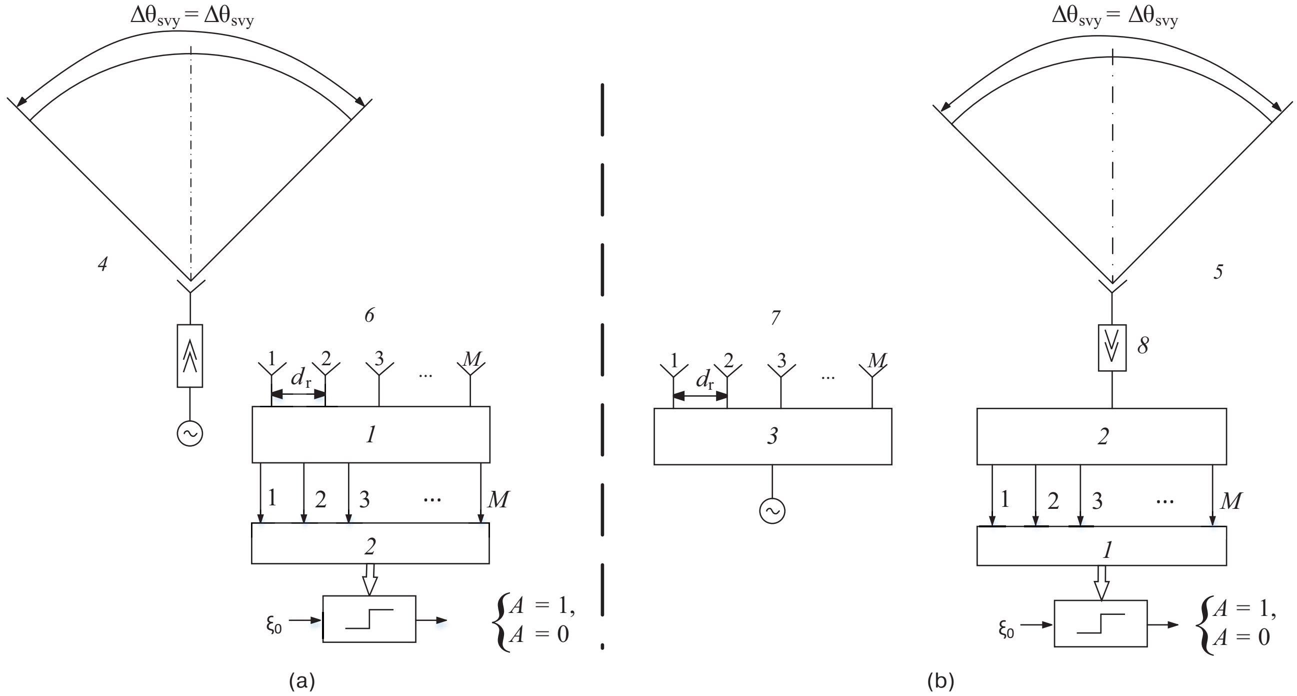

Fig. 4. Mirror construction of traditional (a) and MIMO (b) radars with parallel space survey: (*1*) diagram-forming scheme; (*2*) temporal processing; (*3*) orthogonal PS shaper; (*4*) transmitting WDA; (*5*) receiving WDA; (*6*) receiving MBAA; (*7*) transmitting AA; (*8*) low-noise amplifier

Due to the a priori uncertainty of the angular position of the point target ($\theta_{\mathrm{TRG}i}$) after time accumulation, it is necessary to implement a multi-beam diagram-forming scheme at the virtual sublattice output. As shown above, a digital FFT algorithm can be used to form orthogonal beams and thus to obtain M secondary receive beams:

$$|Z|^2 = \max |\mathbf{Y}_{\mathrm{mf}}^{\mathrm{T}}(0)\mathbf{W}^*(\theta_{0i})|^2,$$
$$\mathbf{W}(\theta_{0i}) = \left\{\exp\left(j\frac{2\pi mi}{M}\right)\right\}_{m,i=-\frac{M}{2}}^{\frac{M}{2}}. \quad (12)$$

From the obtained structure of the MIMO radar, which performs parallel space survey, it is possible to infer its mirror structure compared to the traditional radar, as shown in Fig. 4.

In Fig. 4, the channels for the Doppler processing at the inputs of the threshold devices are not shown in the versions compared. In both cases, the Doppler filtering systems are identical and can be implemented by different methods in the form of inter-cycle compensation or a set of filters tuned to the expected radial velocities $V_{\mathrm{r}0} = \frac{\lambda\Delta\varphi_0}{2\Delta T}$, where $\Delta\varphi_0$ is the phase difference between adjacent packet pulses and ΔT is the repetition interval. This means that the informative parameter *velocity* has no specific characteristics for the narrowband MIMO radar. Under the chosen conditions, PTS equivalence of both versions ensures identity of their statistical detection quality index.

The main characteristics of MIMO radars with transmitting AA and receiving single channel arrangement (WDA) are as follows:

1. The target is simultaneously irradiated by a vector of coherent orthogonal PS $\dot{\mathbf{U}}_{\mathrm{tr}}(t)$ emitted, for example, by AR elements at different carrier frequencies f_{0m}. Increasing the number of AA radiators not only does not lead to a narrowing of the survey sector $\Delta\theta_{\mathrm{svy}}$ but also reduces the requirements on the electrical strength of the path for a fixed radiated power.
2. The angular resolution in this MIMO radar is only determined by the size of the transmitting AA $L_{\mathrm{tr}} = (M - 1)d_{\mathrm{tr}}$ into which the received WDA is transformed by the initial frequency-temporal processing into a virtual sublattice.
3. As in the traditional case of a single WDA for reception, the SSP is factorized into temporal and spatial variants. However, their order is not fundamental and for practical purposes can be reversed compared to the MBAA version.
4. The advantages of MIMO radars mentioned in point 1 are partially offset by certain difficulties in the practical implementation of the transmitting AA. These difficulties include the need to form a set of coherent signals and maintain their coherence when routing ultrahigh frequency signals through the channels of the transmitting AA.

The coherent spatiotemporal processing in the virtual sublattice channels is performed at a lower level of the valid signal compared to the traditional version, where MFs of the secondary channels operate following their coherent spatial accumulation. However, the detection quality is theoretically the same for the same SNR value while maintaining linearity.

CONCLUSIONS

The results obtained in the paper allow the following conclusions:

1. The comparison between the radar of traditional construction and the MIMO radar with a single channel per reception in the parallel target search mode shows the equivalence of their statistical PCOs under the following conditions:

- same resulting SNR and PTS in the detector;
- same bandwidth of coherent PSs and linearity in receive;
- same survey sectors $\Delta\theta_{svy}$;
- the possibility to divide the SSP into frequency-temporal and spatial components.

2. The theoretical equivalence of the versions compared is achieved by mirroring their structural schemes (see Fig. 4).

Traditional version:

- WDA for transmission and *M*-element MBAA for reception;
- spatial accumulation precedes temporal accumulation.

MIMO radar:

- *M*-element AA for transmission and WDA for reception;
- temporal accumulation precedes spatial accumulation.

The total number of SSP channels is equal. When the single WDA for reception is replaced by a multichannel receiving AA, the main advantages of MIMO radars over traditional radars become apparent. This more complex case will be discussed in the next paper.

Authors' contributions

B.M. Vovshin—general statement of the problem, development of principles for constructing MIMO radars, development of a methodology for comparing MIMO radars and traditional parallel-survey radars.

A.A. Pushkov—development of structural design schemes, derivation of analytical ratios, analysis of the results of comparison of radar design options.

E.M. Khalturina—development of structural construction schemes, derivation of analytical ratios, writing text, design of material.

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