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IMAGE RESTORATION METHOD, INVARIANT TO SIGNAL CORRELATION IN THE INFORMATION SYSTEM WITH ADAPTIVE ANTENNA ARRAY

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ИНВАРІАНТНИЙ ДО КОРЕЛЯЦІЇ СИГНАЛІВ МЕТОД ВІДНОВЛЕННЯ ЗОБРАЖЕНЬ В ІНФОРМАЦІЙНІЙ СИСТЕМІ З АДАПТИВНОЮ АНТЕННОЮ РЕШІТКОЮ

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ИНВАРИАНТНЫЙ К КОРРЕЛЯЦИИ СИГНАЛОВ МЕТОД ВОССТАНОВЛЕНИЯ ИЗОБРАЖЕНИЙ В ИНФОРМАЦИОННОЙ СИСТЕМЕ С АДАПТИВНОЙ АНТЕННОЙ РЕШЕТКОЙ

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Abstract. The problem of image signal processing in the information system with adaptive antenna array based on the inversion of sample estimates of correlation matrix of observations is considered. The example of the maximum signal-to-noise ratio criterion shows the problem, inherent in classical methods of finding the optimal weight vector under a priori uncertainty conditions when detecting correlated image signals. It has been concluded that the dependence of these methods on the inverse of estimation of the correlation matrix of observations leads to the impossibility of separating correlated image signals. As a consequence, the use of classical methods of finding the optimal weight vector in the information system with adaptive antenna array is effective only in the case of image restoration from a single signal source, with the signal received on the set of independent jamming background. A novel method, invariant to the correlation of image signals, has been developed for finding the optimal weight vector without the usage of correlation matrix of observations. An image restoration algorithm invariant to correlation of image signals in the information system with adaptive antenna array is proposed. Statistical models have been constructed for the classical method based on the criterion of maximum signal-to-noise ratio and invariant to correlation method of image restoration in following cases: a single source against the jamming background of two independent sources; two independent sources against the jamming background. Simulation results in the information system with adaptive antenna array are presented, showing to visually assess efficiency of proposed methods of image signal restoration using optimal weight vector. Detailed analysis of the results obtained is carried out.

Key words: information system, adaptive array antenna, correlation matrix estimate, weight vector, phase shifts, spatial spectrum, focusing, correlation of image signals, invariance

Анотація. Розглянута задача обробки сигналів зображень в інформаційній системі з адаптивною антенною решіткою на підставі інверсії вибіркових оцінок кореляційної матриці спостережень. На прикладі критерію максимального відношення сигнал/шум показана проблема, притаманна класичним методам знаходження оптимального вагового вектору в умовах апріорної невизначеності при виявленні корельованих сигналів зображень. Зроблено висновок, що залежність цих методів від інверсії оцінки кореляційної матриці спостережень приводить до неможливості відокремлення корельованих між собою сигналів зображень. Як наслідок, застосування класичних методів знаходження оптимального вагового вектора в інформаційній системі з адаптивною антенною решіткою ефективно лише у випадку відновлення зображення від одного джерела сигналу, що приймається на фоні сукупності незалежних шумових перешкод. Розроблено метод знаходження оптимального вагового вектора без використання кореляційної матриці спостережень та, як наслідок, інваріантний до кореляції сигналів зображень. Синтезовано алгоритм інваріантного до кореляції сигналів зображень метода їх відновлення в інформаційній системі з адаптивною антенною решіткою. Побудовані статистичні моделі для класичного метода, заснованого на критерії максимального відношення сигнал/шум та інваріантного до кореляції сигналів зображень метода у випадку відновлення зображення від одного джерела на фоні зовнішніх перешкод від двох незалежних джерел та відновлення зображень від двох незалежних джерел на фоні зовнішньої перешкоди. Проілюстровані результати моделювання в інформаційній системі з адаптивною антенною решіткою, які дозволяють візуально оцінити ефективність розглянутих методів відновлення сигналів зображень за допомогою оптимального вагового вектора, та проведено аналіз отриманих результатів.

Ключові слова: інформаційна система, адаптивна антенна решітка, оцінка кореляційної матриці, ваговий вектор, фазові зсуви, просторовий спектр, фокусування, кореляція сигналів зображень, інваріантність.

Аннотация. Рассмотрена задача обработки сигналов изображений в информационной системе с адаптивной антенной решеткой на основе инверсии выборочных оценок корреляционной матрицы наблюдений. На примере критерия максимального отношения сигнал/шум показана проблема, свойственная классическим методам нахождения оптимального весового вектора в условиях априорной неопределенности при обнаружении коррелированных сигналов изображений. Сделан вывод, что зависимость этих методов от инверсии оценки корреляционной матрицы наблюдений приводит к невозможности разделения коррелированных между собой сигналов изображений. Как следствие, применение классических методов нахождения оптимального весового вектора в информационной системе с адаптивной антенной решеткой эффективно лишь в случае восстановления изображения от одного источника сигнала, который принимается на фоне совокупности независимых шумовых помех. Разработан метод нахождения оптимального весового вектора без использования корреляционной матрицы наблюдений и, как следствие, инвариантный к корреляции сигналов изображений. Синтезирован алгоритм инвариантного к корреляции сигналов изображений метода их восстановления в информационной системе с адаптивной антенной решеткой. Построены статистические модели для классического метода, основанного на критерии максимального отношения сигнал/шум и инвариантного к корреляции сигналов изображений метода в случае восстановления изображения от одного источника на фоне внешних помех от двух независимых источников и восстановления изображений от двух независимых источников на фоне внешней помехи. Проиллюстрированы результаты моделирования в информационной системе с адаптивной антенной решеткой, позволяющие визуально оценить эффективность рассмотренных методов восстановления сигналов изображений с помощью оптимального весового вектора, и проведен анализ полученных результатов.

Ключевые слова: информационная система, адаптивная антенная решетка, оценка корреляционной матрица, весовой вектор, фазовые сдвиги, пространственный спектр, фокусировка, корреляция сигналов изображений, инвариантность.

Introducing

Signal reception by multi-element antenna arrays is one of the main methods of solving signal detection problems and evaluation of parameters of received signals. At the same time, a space-time signal processing in information systems with adaptive antenna arrays can be considered as a task of optimal multichannel filtering, the main purpose of which is to improve reception or detection of the signal against a background noise. Since the statistical characteristics of signals and noises are not known in advance, this task belongs to a class of statistical tasks with a priori uncertainty. All algorithms for solving such problems are based on the construction of the maximum likelihood estimate of space-time samples correlation matrix of the process at the antenna array input. This estimate defines the main statistical characteristics of the observed process and displays the interference situation in the information system [1].

Images from several independent sources are generally somewhat correlated. As a result, the signals corresponding to these images, with the same modulation function and no code separation, retain cross-correlation. Therefore, their correlation matrix is different from diagonal, which leads to the problem of dividing the set of images. In this case, classical image restoration methods prove ineffective, and the problem of developing and synthesizing the image restoration algorithm, invariant to the degree of signals correlation, becomes urgent. Therefore, the application of invariant methods becomes a promising approach to image restoration in the situation described above. The essence of invariant methods lies in a finding of an unambiguous linear operator, which transforms the observed process without changing its components of sufficient statistics [2].

The aim of this work is to develop and synthesize the image restoration method invariant to the signals correlation in the information system with adaptive antenna array.

1. Mathematical model of signal processing in information system with adaptive antenna array

Let us consider the *N*-element adaptive array with the spacing *d* between its elements. By $s_m(t)$ we denote the signal, corresponding to the rectangular raster $L_m(x, y)$ of some image. Jamming $n_k(t)$ is a stationary Gaussian ergodic process. Directions of signal reception θ_m and jamming θ_k don't coincide with each other. If the antenna array elements are identical, the output signals of each element differ only by phase shifts relative to the signal at the first element output [3]. Then, the column vector of the signal and the jamming, respectively, at the *N*-dimensional antenna array input can be represented as

$$\mathbf{s}_m(t) = \mathrm{s}_m(t) \cdot \mathbf{v}(\theta_m) \text{ and } \mathbf{n}_k(t) = \mathrm{n}_k(t) \cdot \mathbf{v}(\theta_k),$$

where $\mathbf{v}(\theta_m)$ and $\mathbf{v}(\theta_m)$ are the column vectors of amplitude-phase distribution of the signal $s_m(t)$ and jamming $n_k(t)$ by *N*-dimensional array opening

$$\mathbf{v}(\theta_m) = \left\{e^{-j(n-1)\cdot\varphi(\theta_m)}\right\}; \quad \mathbf{v}(\theta_k) = \left\{e^{-j(n-1)\cdot\varphi(\theta_k)}\right\}; \quad n = \overline{1, N}.$$

Here $\varphi(\theta_m)$ and $\varphi(\theta_m)$ are phase shifts resulting from the diversity of the antenna phase centers by a distance *d* and equal to θ for an arbitrary argument $\varphi(\theta) = 2\pi\frac{d}{\lambda}\sin\theta,$ where λ is the length of electromagnetic wave.

Then, in general, with *M*-sources of useful information $s_m(t); m = \overline{1, M}$ and *K*-sources of jamming $n_k(t); k = \overline{M+1, M+K}$, the input vector process at the antenna array can be represented as the sum of

$$\mathbf{y}(t) = \sum_{m=1}^{M} \mathbf{s}_m(t) + \sum_{k=M+1}^{M+K} \mathbf{n}_k(t) + \mathbf{n}_0(t), \tag{1}$$

where $\mathbf{n}_0(t) = \{n_{n1}(t)\}; n = \overline{1, N}$ is the column vector of internal noises of the reception channels antenna array. The expression (1) is a mathematical model of a narrowband signal generated at the antenna array input in a space-time sense.

Further, regardless of selected spectral methods and efficiency criteria [1,4], a correlation matrix $\mathbf{R}$ of observation vector (1) is used to solve optimization problems. In practice, even in the absence of jamming, the internal element noises are always present in the antenna array, so the correlation matrix $\mathbf{R}$ is positive-definite, except the rare cases of linearly-dependent signals $\mathrm{s}_m(t)$ [5]. The correlation matrix $\mathbf{R}$ of the observation vector is the sum of the three types of correlation matrices

$$\mathbf{R} = \mathbf{R}_s + \mathbf{R}_j + \mathbf{R}_n,$$

where $\mathbf{R}_s$, $\mathbf{R}_j$ and $\mathbf{R}_n$ are the correlation matrices of signals, jammings and noises, respectively.

In the case of narrowband signals these matrices have the form [1]

$$\mathbf{R}_s = \mathrm{M}\left[\sum_{m=1}^{M}\mathbf{s}_m(t)\cdot\sum_{m=1}^{M}\mathbf{s}_m^H(t)\right] = \mathbf{V}_s\,\mathbf{P}_s\,\mathbf{V}_s^H;$$

$$\mathbf{R}_j = \mathrm{M}\left[\sum_{k=M+1}^{M+K}\mathbf{n}_k(t)\cdot\sum_{k=M+1}^{M+K}\mathbf{n}_k^H(t)\right] = \mathbf{V}_j\,\mathbf{P}_j\,\mathbf{V}_j^H;$$

$$\mathbf{R}_n = \mathrm{M}[\mathbf{n}(t)\cdot\mathbf{n}^H(t)] = P_0\cdot\mathbf{I};$$

where $\mathrm{M}[\cdot]$ denotes the static averaging operator; $[\cdot]^{\mathrm{H}}$ denotes the sign of the Hermitian conjugate; P_0 is the thermal noise power of the antenna array receiving channels; $\mathbf{I}$ is the *N*-order unit matrix.

Rectangular matrices $\mathbf{V}_s$ and $\mathbf{V}_j$ with dimensions $N\times M$ and $N\times K$, respectively, unites *M* and *K* column vectors $\mathbf{v}(\theta_m); m=\overline{1,M}$ and $\mathbf{v}(\theta_k); k=\overline{M+1,M+K}$

$$\mathbf{V}_s = \left(\mathbf{v}(\theta_1)\quad \mathbf{v}(\theta_2)\quad \ldots\quad \mathbf{v}(\theta_M)\right),$$
$$\mathbf{V}_j = \left(\mathbf{v}(\theta_{M+1})\quad \mathbf{v}(\theta_{M+2})\quad \ldots\quad \mathbf{v}(\theta_{M+K})\right). \tag{2}$$

Due to absence of correlation between jammings $n_k(t); k=\overline{M+1,M+K}$, sources of which are spaced in space, matrix $\mathbf{P}_j$ has the diagonal form [6]

$$\mathbf{P}_j = \begin{pmatrix} \sigma^2(n_{M+1}) & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & \sigma^2(n_{M+K}) \end{pmatrix}.$$

The *M*-order matrix $\mathbf{P}_s$ is not diagonal and is

$$\mathbf{P}_s = \{P_{ij}\} = \begin{cases} \mathrm{M}[\mathrm{s}_\mathrm{i}^2(\mathrm{t})]; i=j \\ \mathrm{M}[\mathrm{s}_\mathrm{i}(\mathrm{t})\cdot \mathrm{s}_\mathrm{j}(\mathrm{t})]; i\neq j \end{cases};\quad i,j=\overline{1,M}\quad .$$

In addition, since images coming from different sources are usually correlated with each other, this results in an approximate relationship between its columns and, as a result, in ill-conditionality of the matrix $\mathbf{P}_s$ [6]. These properties of the matrix $\mathbf{P}_s$ determine the feature of adaptive image signals processing, received from several sources against the jammings background.

The vector process $\mathbf{y}(t)$ formed by the antenna array elements undergoes linear processing in the form

$$\mathbf{w}^H(t)\cdot\mathbf{y}(t) = u(t), \tag{3}$$

where $\mathbf{w}(t)$ is the parametric vector of complex weight coefficients; $u(t)$ is the output scalar signal at the information system with adaptive antenna array.

Considering (1), the signal processing (3) can be written as

$$\sum_{m=1}^{M}\mathbf{v}^H(\theta_m)\cdot\mathbf{w}_m(t)\cdot s_m(t) + \sum_{k=M+1}^{M+K}\mathbf{v}^H(\theta_k)\cdot\mathbf{w}_k(t)\cdot n_k(t) + \mathbf{w}^H(t)\cdot\mathbf{n}(t) = \mathbf{u}(t).$$

Similar to (2), denoting by $\mathbf{W}_s$ and $\mathbf{W}_j$ some rectangular matrices of dimensions $N\times M$ and $N\times K$, respectively

$$\mathbf{W}_s = \left(\mathbf{w}_1(t)\quad \mathbf{w}_2(t)\quad \ldots\quad \mathbf{w}_M(t)\right);\quad \mathbf{W}_j = \left(\mathbf{w}_{M+1}(t)\quad \mathbf{w}_{M+2}(t)\quad \ldots\quad \mathbf{w}_{M+K}(t)\right),$$

we introduce block matrices $\mathbf{V}^H_{(M+K)\times N}$ and $\mathbf{W}_{N\times(M+K)}$ of the form

$$\mathbf{V}^H_{(M+K)\times N} = \begin{bmatrix} \mathbf{V}_s^H \\ \mathbf{V}_j^H \end{bmatrix}; \quad \mathbf{W}_{N\times(M+K)} = \begin{bmatrix} \mathbf{W}_s & \mathbf{W}_j \end{bmatrix}.$$

Then, the input signals processing in the *i*-th information channel of the antenna array can be written as

$$\mathbf{w}_i^H \cdot \mathbf{y} = \mathbf{u}_i; \quad i = \overline{1, M+K}, \tag{4}$$

where $\mathbf{w}_i$ is the *i*-th column of the weight vector matrix $\mathbf{W}_{N\times(M+K)}$; $\mathbf{u}_i$ is the output signal at the *i*-th information channel, respectively.

2. Determination of the optimal weight vector using maximum signal-to-noise ratio criterion

Efficiency criteria such as mean-square error, signal-to-noise ratio, maximum likelihood, noise dispersion are used to find the optimal vector of weight coefficients. But since all of them differ only by a scalar multiplier, which provides the same output signal-to-noise ratio of the information system, the selection of a specific efficiency criterion is usually not of great importance [1].

If the adaptive antenna array receives signals from $(M+K)$ independent sources, then the optimal, based on the criterion of the maximum signal-to-noise ratio, parametric weight vector of the *i*-th information channel can be written as

$$\mathbf{w}_i = \frac{\mathbf{R}^{-1}\cdot \mathbf{v}_i}{\mathbf{v}_i^H \cdot \mathbf{R}^{-1} \cdot \mathbf{v}_i}; \quad i = \overline{1, M+K}, \tag{5}$$

where $\mathbf{v}_i$ is the *i*-th column of the phase shift matrix $\mathbf{V}_{N\times(M+K)}$.

In practice, signal reception directions $\theta_i; i = \overline{1, M+K}$ are generally unknown. Therefore, methods of spatial spectral analysis such as Bartlett, Capon, thermal noise, adaptive angular characteristic (AAR), linear prediction, maximum entropy, minimum norm, multi-signal classification (MUSIC), eigenvector (EV) [6.7] are used to determine estimates of required focusing directions $\hat{\theta}_i; i = \overline{1, M+K}$ of antenna array.

Furthermore, since the exact correlation matrix $\mathbf{R}$ is known only in model studies, the maximum likelihood estimate $\hat{\mathbf{R}}(L)$ obtained from the vector process sample (1) and dependent on its size *L* is used instead

$$\hat{\mathbf{R}}(L) = \frac{1}{L}\sum_{j=1}^{L} \mathbf{y}(j)\cdot \mathbf{y}^H(j).$$

Considering that, the parametric weight vector of the *i*-th information channel (5) takes on form

$$\mathbf{w}_i = \frac{\hat{\mathbf{R}}^{-1}\cdot \mathbf{v}_i(\hat{\theta}_i)}{\mathbf{v}_i^H(\hat{\theta}_i)\cdot \hat{\mathbf{R}}^{-1}\cdot \mathbf{v}_i(\hat{\theta}_i)}; \quad i = \overline{1, M+K}, \tag{6}$$

where $\hat{\mathbf{R}}^{-1}$ is the inverse correlation matrix of the observations estimate. Then, according to (4) and (6), the output signal at the *i*-th antenna array channel can be represented as

$$\mathbf{u}_i = \mathbf{w}_i^H \cdot \mathbf{y} = K(\hat{\theta}_i)\cdot \mathbf{v}_i^H(\hat{\theta}_i)\cdot \hat{\mathbf{R}}^{-1}\cdot \mathbf{y}; \quad i = \overline{1, M+K}, \tag{7}$$

where the scalar $K(\hat{\theta}_i)$ is equal

$$K(\hat{\theta}_i) = \frac{1}{\mathbf{v}_i^H(\hat{\theta}_i)\cdot \hat{\mathbf{R}}^{-1}\cdot \mathbf{v}_i(\hat{\theta}_i)}.$$

The generalized structure of the multi-channel processor implementing signal processing according to algorithm (7) is shown in Fig. 1. Here $\mathbf{u}_i; i = \overline{1, M}$ are the signals, corresponding to image estimates $\hat{L}_i(x, y)$; $\mathbf{u}_i; i = \overline{M+1, M+K}$ are the signals, corresponding to jammings $n_i(t)$.

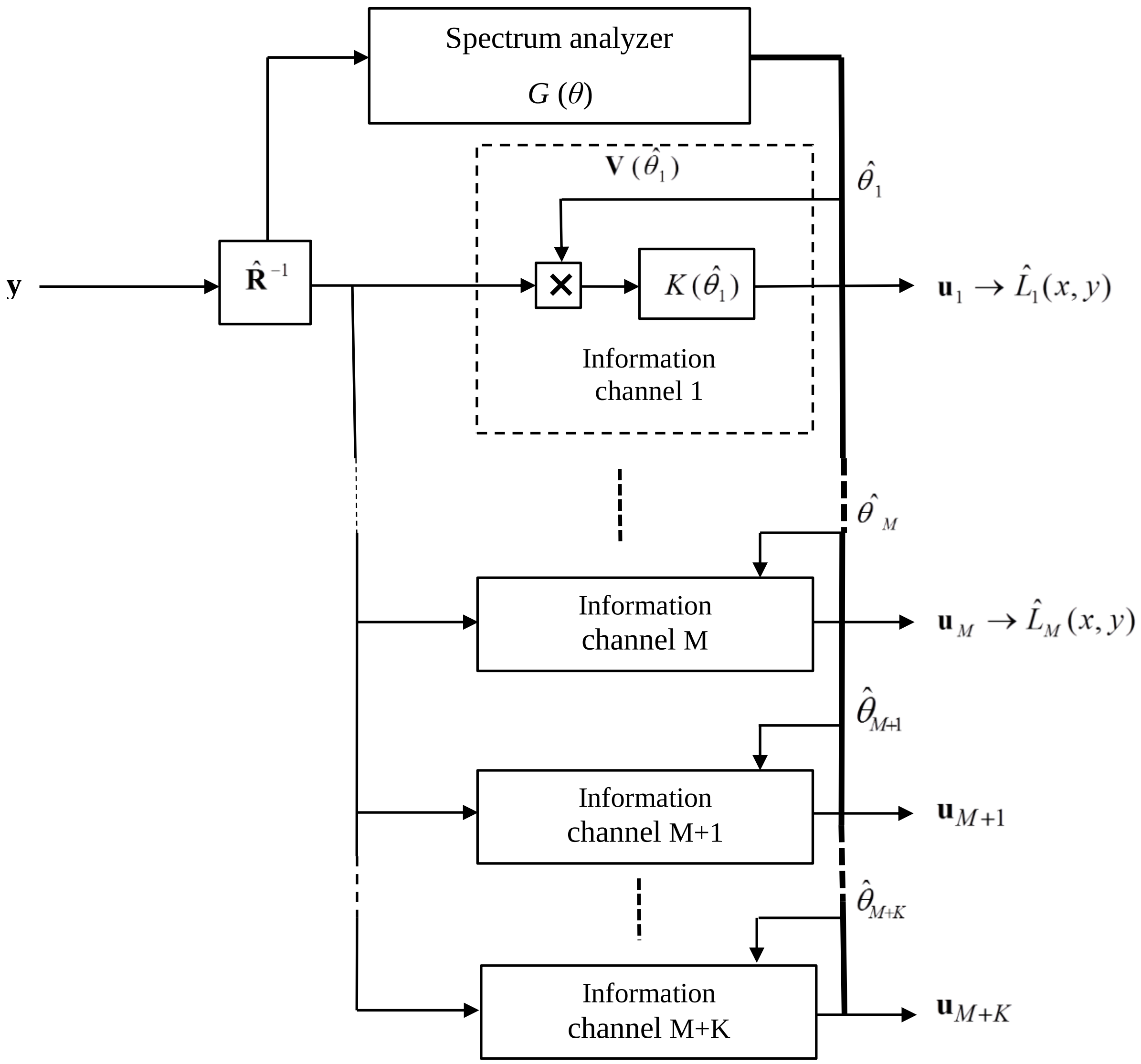


Fig. 1. The structure of *N*-dimensional adaptive antenna array processor, implementing the (*M*+*K*) signal processing in accordance with the algorithm (7)

It is obvious, that the efficiency of the signal processing algorithm (7) depends directly on the accuracy of the obtained focus directions estimates $\hat{\theta}_i; i = \overline{1, M+K}$ of the antenna array on the signal sources, which influence the statistical characteristics of the signals and displayed in the correlation matrix of observations.

3. The invariant to signal correlation method of the optimal weight vector determination

In order for the result of the processing $\mathbf{u}(t)$ to be invariant with respect to the phase shifts of the signals $s_m(t); m = \overline{1, M}$ and jammings $n_k(t); k = \overline{M+1, M+K}$ at a given time *t* [8] and, as a consequence, the correlation of the signals, the fulfillment of the following condition is necessary

$$\mathbf{V}^H_{(M+K)\times N} \cdot \mathbf{W}_{N\times(M+K)} = \mathbf{I}_{(M+K)}, \tag{8}$$

where $\mathbf{I}_{(M+K)}$ is the unit matrix of (*M*+*K*)-order. In practice, the total number of signal and jamming sources is considerably smaller than the number of reception channels of antenna array (*M* + *K* < *N*), so the system (8) is overdetermined [9]. In this case, the system solution will be

$$\mathbf{W}_{N\times(M+K)} = \mathbf{V}^{-}_{N\times(M+K)} \cdot \mathbf{I}_{(M+K)}, \tag{9}$$

where $\mathbf{V}^{-}_{N\times(M+K)}$ is the generalized inverse matrix to the matrix $\mathbf{V}^{H}_{(M+K)\times N}$, equal to

$$\mathbf{V}^{-}_{N\times(M+K)} = \mathbf{V}_{N\times(M+K)} \cdot \left[\mathbf{V}^{H}_{(M+K)\times N} \cdot \mathbf{V}_{N\times(M+K)}\right]^{-1}. \quad (10)$$

If the unit matrix $\mathbf{I}_{(M+K)}$ is represented in the block form

$$\mathbf{I}_{(M+K)} = \left[\mathbf{e}_1 \quad \mathbf{e}_2 \quad \dots \quad \mathbf{e}_{M+K}\right],$$

where $\mathbf{e}_i;\, i=\overline{1, M+K}$ is the single orts-columns, the solution of the system (8), taking into account the formula (10), is

$$\mathbf{W}_{N\times(M+K)} = \mathbf{V}_{N\times(M+K)} \cdot \left[\mathbf{V}^{H}_{(M+K)\times N} \cdot \mathbf{V}_{N\times(M+K)}\right]^{-1} \cdot \left[\mathbf{e}^{T}_1 \quad \mathbf{e}^{T}_2 \quad \dots \quad \mathbf{e}^{T}_{M+K}\right].$$

As a result, the parametric vector of the *i*-th information channel of the antenna array is equal to

$$\mathbf{w}_i = \mathbf{V} \cdot \left[\mathbf{V}^{H} \cdot \mathbf{V}\right]^{-1} \cdot \mathbf{e}_i; \quad i=\overline{1, M+K}. \quad (11)$$

According to (4) and (11), the signal at the output of the *i*-th antenna array channel can be represented as

$$\mathbf{u}_i = \mathbf{e}_i^{T} \cdot \left[\mathbf{V}^{H} \cdot \mathbf{V}\right]^{-1} \cdot \mathbf{V}^{H} \cdot \mathbf{y}; \quad i=\overline{1, M+K}. \quad (12)$$

where $[\,\cdot\,]^{T}$ denotes the transposing operation.

Note that the operation $\left[\mathbf{V}^{H} \cdot \mathbf{V}\right]^{-1} \cdot \mathbf{V}^{H}$ in formula (12) is the same for all antenna array channels.

The generalized structure of the signal processing algorithm (12) is shown in Fig. 2. Here $\mathbf{u}_i;\, i=\overline{1, M}$ are the signals, corresponding to image estimates $\hat{L}_i(x,y)$; $\mathbf{u}_i;\, i=\overline{M+1, M+K}$ are the signals, corresponding to jammings $n_i(t)$.

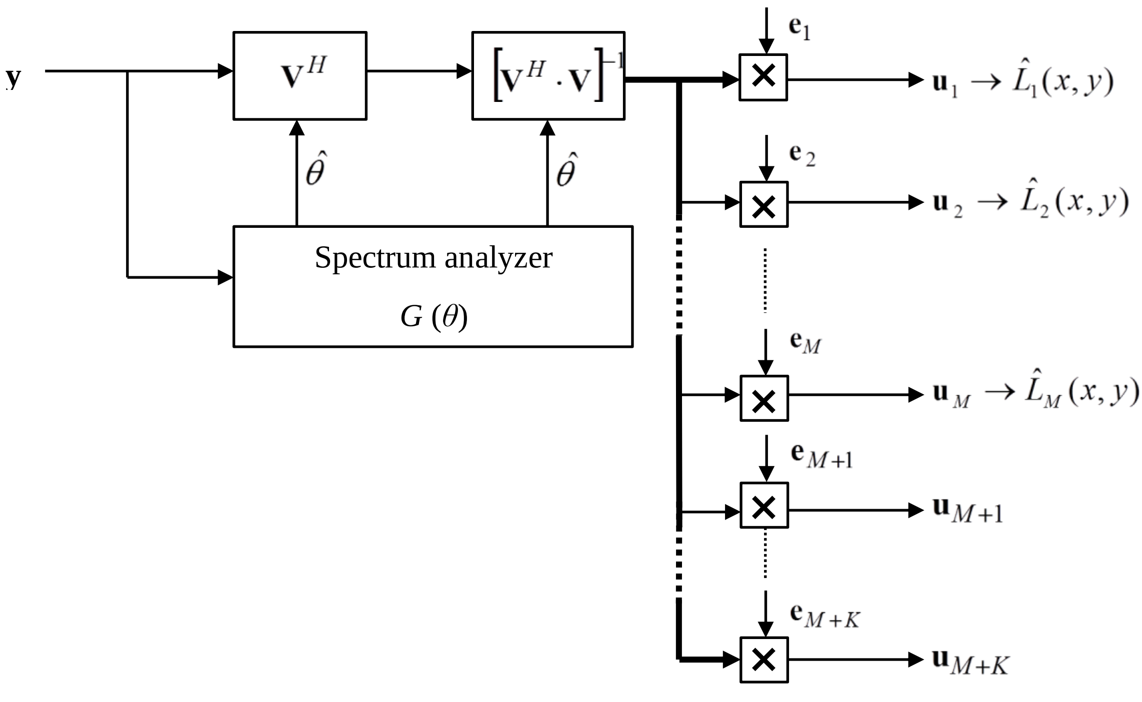


Fig. 2. The structure of *N*-dimensional adaptive antenna array processor, implementing the (*M*+*K*) signal processing in accordance with the algorithm (12)

Note, that unlike the algorithm (7), the signal processing with the algorithm (12) does not require the calculation of inverse correlation matrix and depends only on obtained estimates of antenna array focusing directions $\hat{\theta}_i;\, i=\overline{1, M+K}$ on signal sources.

4. Simulation of image restoration algorithms using the maximum signal-to-noise ratio criterion and the invariant method of the weight vector determination

To analyze the quality of images restored by algorithms (7) and (12), we will build statistical models for the following situations:

– image restoration from a single source against jamming from two independent sources;

– images restoration from two independent sources against jamming from a single source.

As the initial conditions, let us take the following: the dimension of the antenna array $N = 15$ with the distances between antenna phase centers $d/\lambda = 0{,}5$; the radio sources act in directions $\theta_1 = -20^0;\ \theta_2 = 0^0;\ \theta_3 = 15^0$ relative to the normal of the array opening; the image signal power exceeds the jamming level by 10 and 3 dB; the sample size is L=200.

The estimation of signals and jammings reception directions is determined by the method of maximum entropy [7]

$$G(\theta) = \frac{r_{11}^{-1}}{\left|\mathbf{c}^T(\theta)\cdot \mathbf{r}_{n1}^{-1}\right|^2}, \qquad (13)$$

where r_{11}^{-1} and $\mathbf{r}_{n1}^{-1};\ n = \overline{1,N}$ are the first element and the first column of the inverse correlation matrix, respectively; $\mathbf{c}^T(\theta)$ is the scan vector defined as

$$\mathbf{c}^T(\theta) = \{e^{j(n-1)\varphi(\theta)}\};\quad n = \overline{1,N},$$

where $\varphi(\theta) = 2\pi\frac{d}{\lambda}\sin\theta$.

Figure 3 shows the estimation of the spatial spectrum of radio emission power $G(\theta)$ during 30 tests.

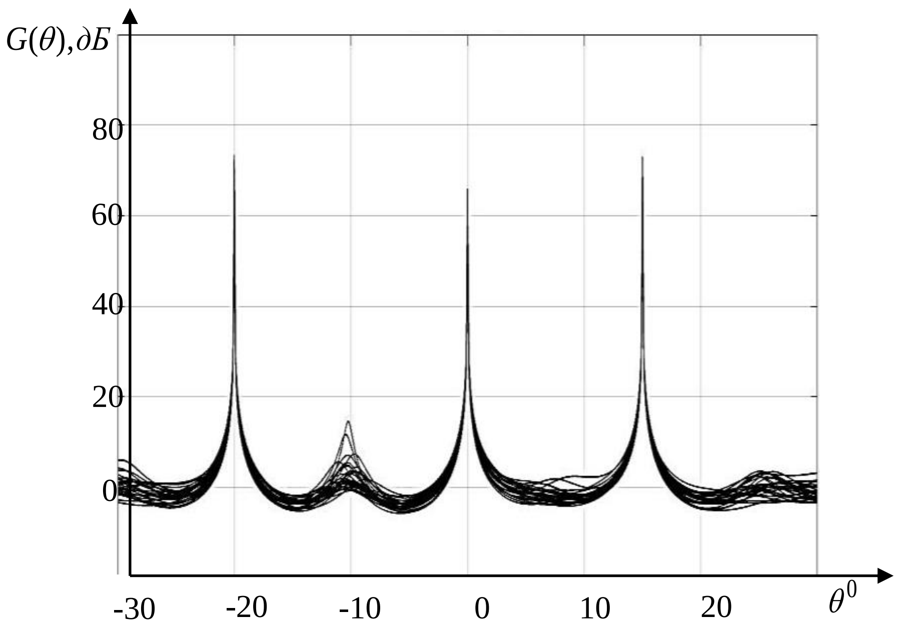


Fig.3 Spatial spectrum of radio emission power sources that act in directions $\theta_1 = -20^0;\ \theta_2 = 0^0;\ \theta_3 = 15^0$.

The original images of 600x600 pixels are shown in Figure 4.

a) b)

Fig. 4 Original images from independent sources a) $L_1(x,y)$; b) $L_2(x,y)$

At first, we will consider the situation of image restoration from a single source against the background noise from two independent jamming sources. The result of jamming influence on the image is shown in Figure 5.

Fig. 5 The jamming influence on the image quality at the jamming-to-noise ratio equal to 36 dB

The results of focusing in the directions of signal sources on the quality of output images of the adaptive array information system obtained with algorithms (7) and (12) is shown in Figure 6.

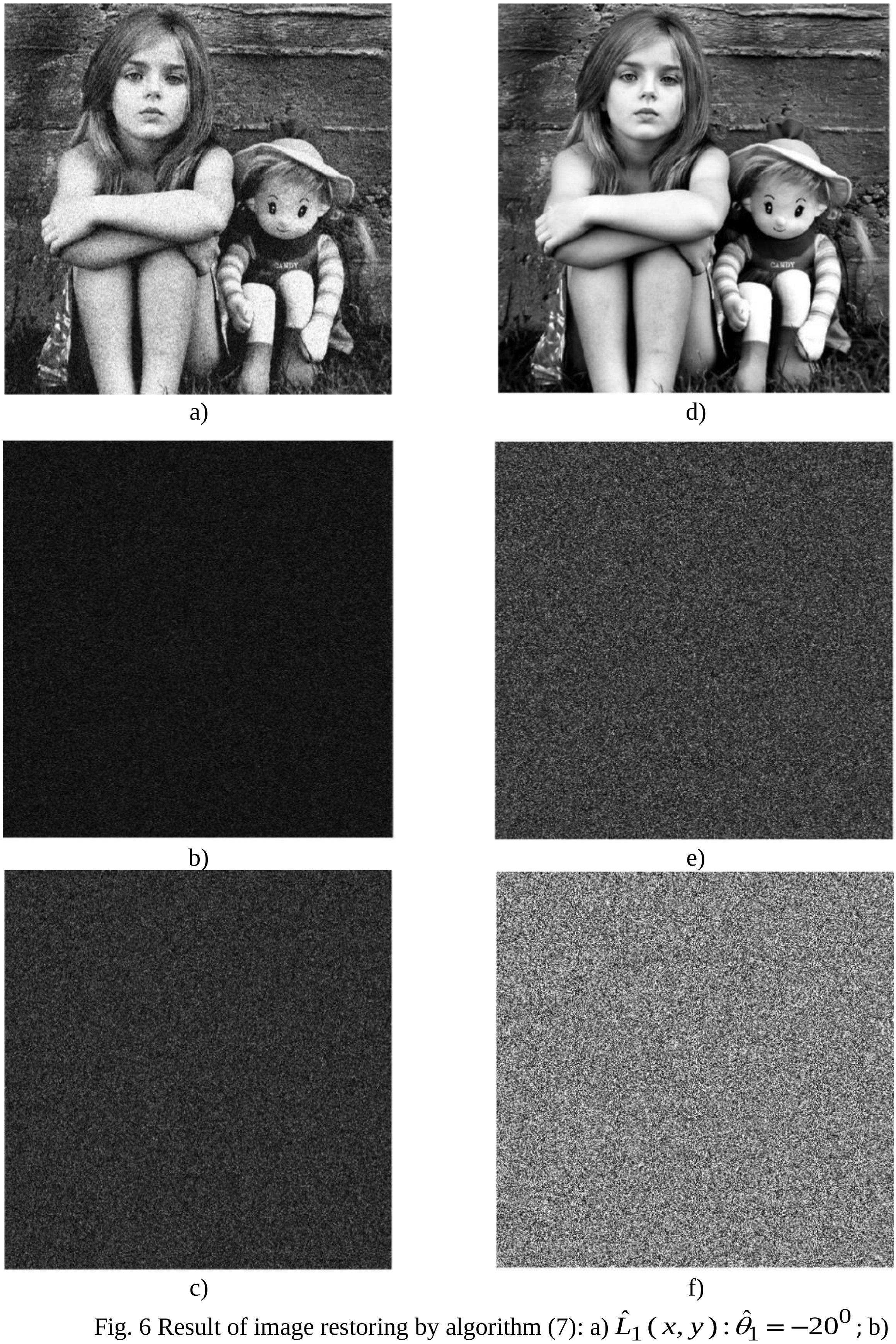


Fig. 6 Result of image restoring by algorithm (7): a) $\hat{L}_1(x,y):\hat{\theta}_1=-20^0$; b) $\hat{\theta}_2=0^0$; c) $\hat{\theta}_3=15^0$ and (12): d) $\hat{L}_1(x,y):\hat{\theta}_1=-20^0$; e) $\hat{\theta}_2=0^0$; f) $\hat{\theta}_3=15^0$

Analysis of the results shown in Figure 6 shows that sources of jammings act in the directions $\theta_2 = 0^0$ and $\theta_3 = 15^0$, and the source of the image signal is oriented in the direction $\theta_1 = -20^0$. This direction corresponds to the image raster restored against the jammings background. The raster of the restored image according to algorithms (7) and (12) are visually different in quality. Obviously, that algorithm (7) requires a larger sample size to obtain the required quality of the reconstructed image in view of the use of the samples correlation matrix inversion.

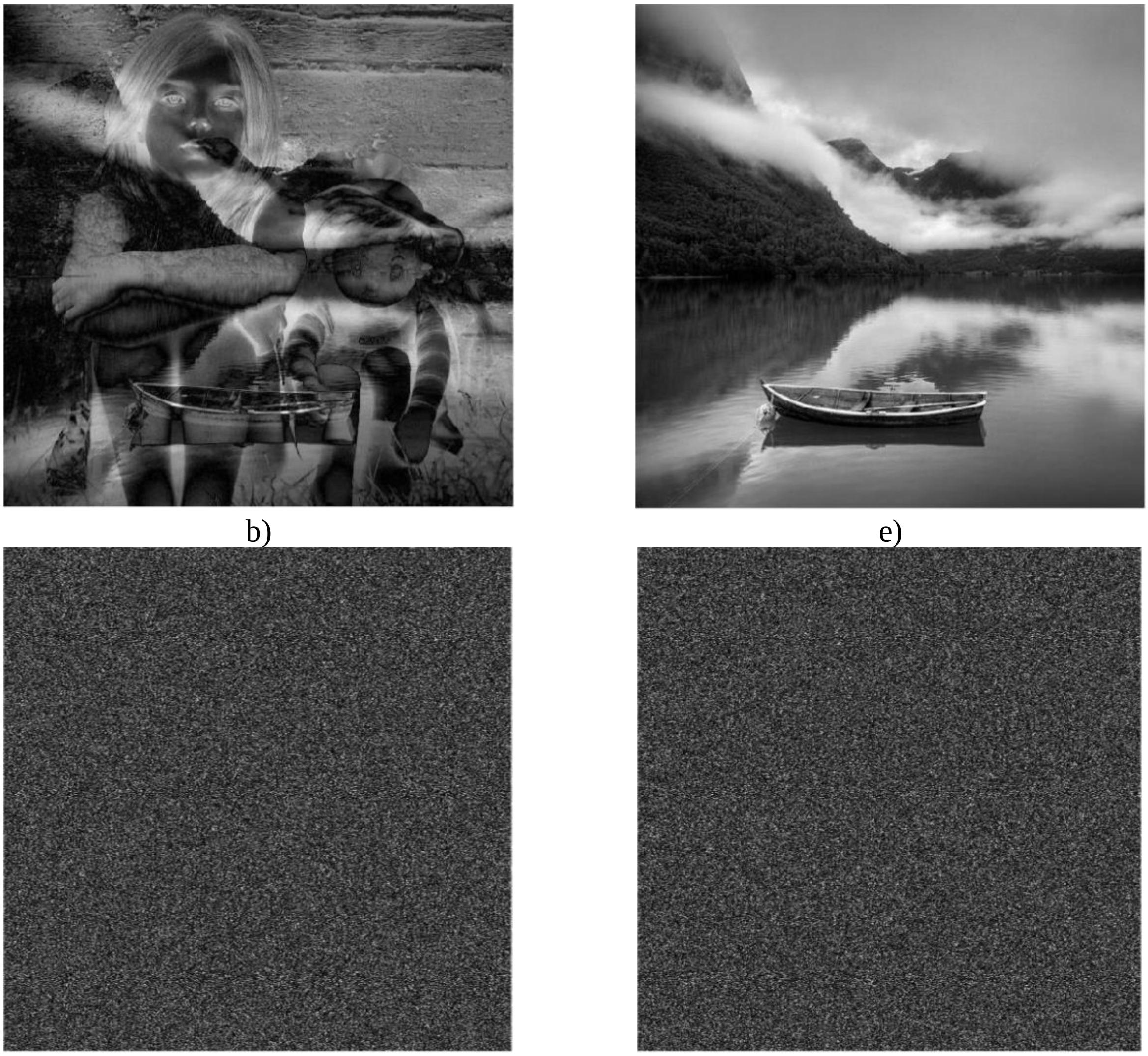
Let's now consider the situation of image restoration for the case of two independent sources against the jamming background from a single source. The result of cross-correlation of images $L_1(x, y)$; $L_2(x, y)$ and the effect of jamming influence on them is illustrated in Figure 7.

Fig. 7 The influence of image cross-correlation and jamming at 28 dB jamming-to-noise ratio

The results of focusing in the signal directions obtained with algorithms (7) and (12) are shown in Figure 8. The analysis of the simulation results presented in Figure 8 shows that the jamming source acts in the direction $\theta_3 = 15^0$ and the sources of image signals are oriented in the direction of $\theta_2 = 0^0$ and $\theta_1 = -20^0$.

a)

d)



b) e)

c) f)

Fig. 8 Result of image restoring by algorithm (7): a) $\hat{L}_1(x,y):\hat{\theta}_1=-20^0$; b) $\hat{L}_2(x,y)$: $\hat{\theta}_1=0^0$; c) $\hat{\theta}_3=15^0$ and (12): d) $\hat{L}_1(x,y):\hat{\theta}_1=-20^0$; e) $\hat{L}_2(x,y):\hat{\theta}_1=0^0$; f) $\hat{\theta}_3=15^0$

Obviously, due to the cross-correlation of images, the algorithm (7) is not effective compared to the algorithm (12), so that the former is not able to separate the images.

Conclusions

Spatial spectral analysis is the main computational operation during the image signals restoration using the information system with adaptive antenna array. The radio emission directions estimation by structure of spatial spectrum of the received radio wave power is a necessary step for optimal focusing on sources of electromagnetic radiation.

The adaptive algorithm (7) depends on estimation of correlation matrix of observations and belongs to the class of optimal only in particular cases when there is no correlation between harmonics of spatial spectrum of radio emissions power. This limits the efficiency of the algorithm (7) in the case of the set of correlated image signals. As a consequence, the algorithm (7) can be applied only in the case of image restoration from a single signal source, received against the set of independent jamming background. The algorithm (12) is invariant to correlation of image signals and does not require the inverse of sample estimates correlation matrix of observations. Therefore, the calculation of the weight vectors with this algorithm does not change the statistical characteristics of the signals received. As a result, the algorithm (12) allows splitting the set of correlated image signals and is more efficient than the algorithm (7) in all of the considered situations.

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