Short Range Radar with MIMO Antenna System and Multifrequency Sounding Signal

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Abstract— Algorithms of slow moving objects allocation on a background of motionless local objects reflections in MIMO radar with radiation of orthogonal signals by transmitting elements of the multielement antenna system are offered. Results of laboratory experiments with created breadboard model of MIMO small range radar with eight-elements transmitting and receiving linear antenna arrays at radiation of sounding signals with step frequency modulation are given.

1. INTRODUCTION

The radar of MIMO (Multiple Input-Multiple Output) type [1] assumes the use of transmitting and receiving antenna systems (AS) consisting of spatially distributed elements, radiating mutually orthogonal sounding signals (SS). One of the first radars of the given class is French long range system RIAS [2]. Similar radars are studied also in Russia and China [3–5]. Application of MIMO radar principles is perspective also at creation of short range radars for detection of people behind radiotransparent obstacles since allows to apply energetically more favorable continuous multifrequency SS. At continuous radiation and the greater number of MIMO AS elements the greater signal accumulation takes place. The low level of side lobe of system signal function (SSF) on spatial coordinates is reached also. Such approach does not demand the application of a complex antenna element phase control system and allows to make the space surveillance in digital vector signals processing system fed from outputs of simple receiving elements of AS.

In the given work, some questions of the spatial resolution theory of MIMO radars are considered and breadboard model of small range MIMO radar with AS consisting of eight-element transmitting and eight-element receiving linear antenna arrays at radiation of step-frequency SS in frequency range from 1.45 GHz up to 1.75 GHz is created. Simple methods of allocation of slow moving objects on the background of motionless local objects (LO) without speed resolution are offered and checked up. Operational processing algorithms of receiving signals are developed in view of systematic errors in the microwave signal path and in MIMO AS. Results of laboratory experiments with detection of slowly moving object as a metal plate on a background of reflections from indoor LO and a penetrating signal of the transmitter are received.

2. FUNDAMENTALS OF MIMO RADAR RESOLUTION THEORY

Let AS consists of $N_t + 1$ transmitting and $N_r + 1$ receiving elements. At consecutive radiation and reception of step-frequency modulated (step-FM) SS each n_t element of transmitting antenna array radiates, and each n_r element of receiving antenna array accepts a signal consisting from $M + 1$ frequency components from the general frequency grid with uniform step $\Delta\omega = 2\pi\Delta f$,

$$\omega_m = \omega_0 + m \cdot \Delta\omega, \quad m = 0, \ldots, M. \tag{1}$$

The duration of everyone frequency step is equal to $\tau_\omega = T_\omega - \tau_{\max}$, where T_ω is the time interval of reference signal existence on the same frequency in the receiver device, and $\tau_{\max} = 2R_{\max}/c$, where $R_{\max}$ is equal to the maximum (unique) radar range, c is the velocity of light.

Element pairs "n_t-n_r" work in a time division mode, and a full time working interval of the entire AS will make size

$$T_\Sigma = (N_t + 1)(N_r + 1)(M + 1)\, T_\omega. \tag{2}$$

The value of T_Σ was accepted equal to the radiation time period (or the information updating period), $T_r = T_\Sigma$. If all step-FM bursts of SS are not overlapped in time, the value $N_\Sigma = (N_t + 1)(N_r + 1)(M + 1)$ is equal to the total amount of orthogonal signals in the system. The average level of side lobes of the generalized ambiguity function (GAF) on spatial coordinates of MIMO radar system is estimated by value $1/\sqrt{N_\Sigma}$, but the width of GAF main lobe assesses resolution cell on spatial coordinates.

For a configuration and parameters choice of MIMO AS quantitative analysis of GAF in a horizontal coordinate's plane (x, y) at an arrangement of AS elements in a vertical plane was carried out. Formula received for GAF in [6] was used:

$$\Psi(\vec{r}_R, \vec{r}_M) = \frac{1}{(N_t+1)(N_r+1)(M+1)} \left| \sum_{n_t=0}^{N_t} \sum_{n_r=0}^{N_r} \frac{\sin[\pi\Delta f(M+1)\cdot\Delta\tau(\vec{r}_M, \vec{r}_R; n_t, n_r)]}{\sin[\pi\Delta f\cdot\Delta\tau(\vec{r}_M, \vec{r}_R; n_t, n_r)]} \right.$$
$$\left. \times \exp\{j2\pi[f_0 + \Delta f M/2]\Delta\tau(\vec{r}_M, \vec{r}_R; n_t, n_r)\} \right|, \quad (3)$$

Relative delays $\Delta\tau(\cdot)$ are calculated here as a difference of arrival times of the received signals reflected from the target with a vector of coordinates $\vec{r}_R$ and reference signals in processing system, adequate to virtual target with a vector of coordinates $\vec{r}_M$, at working of "transmitter-receiver" elements with numbers (n_t, n_r):

$$\Delta\tau(\vec{r}_M, \vec{r}_R; n_t, n_r) = \tau(\vec{r}_M; n_t, n_r) - \tau(\vec{r}_R; n_t, n_r), \quad \text{where} \quad \tau(\vec{r}; n_t, n_r) = \tau_{tn_t}(\vec{r}) + \tau_{rn_r}(\vec{r}), \quad (4)$$

$$\text{and} \quad \tau_{tn_t}(\vec{r}) = \frac{1}{c}|\vec{r} - \vec{r}_{tn_t}|, \quad \tau_{rn_r}(\vec{r}) = \frac{1}{c}|\vec{r} - \vec{r}_{rn_r}| \quad (5)$$

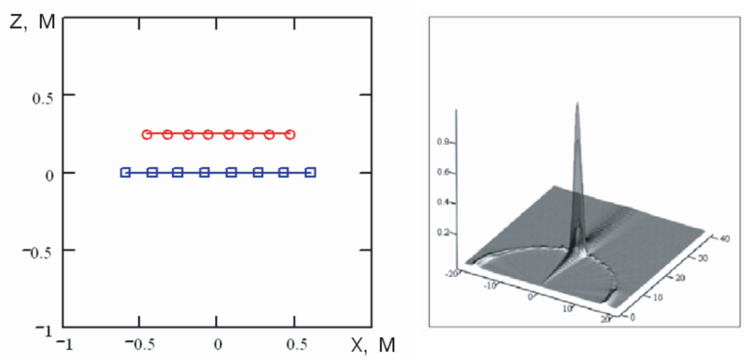
are accordingly propagation delays for a way from transmitting element number n_t and coordinate vector $\vec{r}_{tn_t}$ up to a point of space with coordinate vector $\vec{r}$ and for a way from this point up to receiving element with number n_r and coordinate vector $\vec{r}_{rn_r}$.

For 2D radar objects detection and coordinate measurement in a horizontal plane (x, y), it is sufficient the arrangement of transmitting and receiving elements linearly in a plane (x, z) with constant interelement distances. Transmitting and receiving antenna arrays are parallel and vertically divided in this plane (Fig. 1). Interelement distances were different in transmitting and in receiving arrays. Optimization of transmitting and receiving arrays length was carried out at a constant number of elements $N_t+1 = N_r+1 = 8$ by the criterion of a minimum level of the diffraction lobes remains of GAF. GAF calculations were carried out at initial frequency and frequency bandwidth of step-FM equal accordingly to $f_0 = 1.45\,\text{GHz}$, $\Delta F = 300\,\text{KHz}$, and $M+1 = 64$. The optimum sizes of transmitting and receiving antenna arrays have turned out equal $L_t = 0.918\,\text{m}$ and $L_r = 1.2\,\text{m}$, at interelement distances in them equal to $d_t = 0.131\,\text{m}$ and $d_r = 0.171\,\text{m}$. It is more then a half of average radiation wavelength, $\lambda_{av}/2 = 0.094\,\text{m}$.

A configuration of the AS and a view of GAF are given on Figs. 1(a) and 1(b). The view of an ambiguity body testifies to low levels of lateral and diffraction lobes remains in an azimuths interval (−90°, 90°). It is explained by a choice of various and not multiple steps of elements in transmitting and receiving antenna arrays.

3. SIGNAL PROCESSING ALGORITHMS IN MIMO RADAR WITH STEP-FM SS

The signal processing algorithm on a single k-th full working cycle (period) of multielement AS with radiation of step-FM signals was received on the basis of generalized covariance signals processing integral in multichannel receiving system [7] in view of all pairs of transmitting and receiving



(a) (b)

Figure 1: (a) The configuration of transmitting (top line) and receiving (bottom line) antenna arrays, (b) volumetric GAF diagram at the target coordinates $x_R = 0\,\text{m}$, $y_R = 15\,\text{m}$.

elements (n_t, n_r):

$$\dot{Q}_k(\vec{r}_M) = \sum_{n_r=0}^{N_r} \sum_{n_t=0}^{N_t} \sum_{m=0}^{M} \exp\left(j\omega_m \tau\left(\vec{r}_M; n_t, n_r\right)\right) \cdot \dot{V}_{m,k}\left(n_t, n_r\right), \tag{6}$$

where $\dot{V}_{m,k}(n_t, n_r)$ are complex process on a quadrature detector output at coherent processing on m-th frequency in k-th sounding period at work of pair elements (n_t, n_r). The reference delay τ in (6) is given by formulas (5) at $\vec{r} = \vec{r}_M$. Expression (6) is an algorithm of multichannel coherent space-time processing on one sounding period in MIMO radar with arbitrary arrangement of $N_t + 1$ transmitting and $N_r + 1$ receiving elements at consecutive radiation by transmitting elements of step-FM bursts. At realization of Algorithm (6) application of FFT on frequency index number m is possible.

Processing algorithm of moving target detection (MTD) with notch filters on each frequency component. As the first case we consider simple *notch* filter (NF) for complex amplitudes $\dot{V}_{m,k}(n_t, n_r)$ on each frequency component ω_m of the received signal. The elementary NF is the first order high-pass filter with a time constant τ_f rejecting steady components of intensive signals from local objects and a penetrating transmitter signal. A discrete equivalent of such NF for each frequency component is the recursive filter of the first order:

$$\dot{U}_{m,k+1} = (1 - T_r/\tau_f) \cdot \dot{U}_{m,\kappa} + \dot{V}_{m,k+1} - \dot{V}_{m,k}, \quad k = 0, 1, \ldots, K; \quad m = 0, 1, \ldots, M, \tag{7}$$

where $\dot{V}_{m,k}$ — are input sequences of complex amplitudes on filter input at frequency ω_m, $\dot{U}_{m,k}$ are output sequences. To exclude a transitive mode at coherent focusing on spatial coordinates readouts of a kind $\dot{U}_{m,k_0}$ at $\kappa_0 > 3\tau_f/T_r$ were used. Output values $\dot{U}_{m,k_0}$ are substituted further in the Algorithm (6) instead of $\dot{V}_{m,k}$.

MTD system on a basis of intersurvey subtraction. At use for MTD the variant of unitary coherent subtraction of the data focused on space at two AS radiation time periods was considered:

$$\Delta\psi(\vec{r}_M) = \left|\dot{Q}_{k+\Delta k}(\vec{r}_M) - \dot{Q}_k(\vec{r}_M)\right|. \tag{8}$$

Here $\dot{Q}_k(\vec{r}_M)$ is calculated on (6), and the value Δk meets to some number of the radiation time periods. Results of modeling for first and second MTD algorithms have shown their practically identical efficiency on a level of lateral lobes and suppression of LO signals. MTD system with subtraction is characterized by a little bigger losses of a useful signal and, probably, additional losses on signal/clutter ratio. Losses in a level of a useful signal are increased with reduction of Δk up to the values answering to time, comparable with time of correlation of movings of the slow moving target.

4. EXPERIMENTAL RESULTS

For reception of experimental results the breadboard model of small range 2-D MIMO radar was created on the basis of the stated theoretical preconditions. The breadboard model worked with step-FM SS in a frequency bandwidth of 300 MHz and in a frequency range from 1450 MHz up to 1750 MHz. In the given frequency bandwidth it was used 16 frequencies with uniform frequency step. AS has the parameters specified in Section 2. The view of a breadboard model is submitted on Fig. 2.

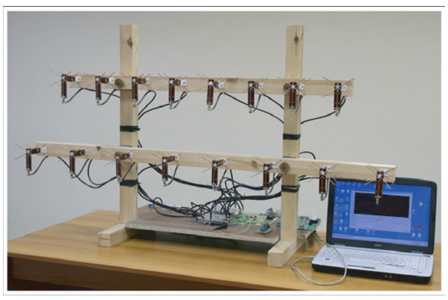


Figure 2: Experimental breadboard model of small range MIMO radar.

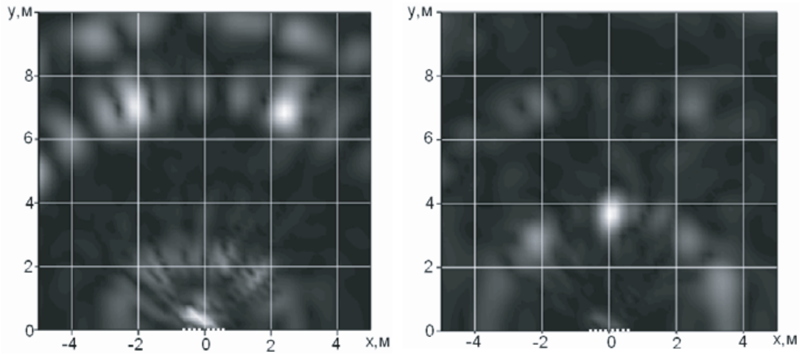


Figure 3: Topographical SSF diagrams at absence (a) and presence (b) of subtraction (experiment).

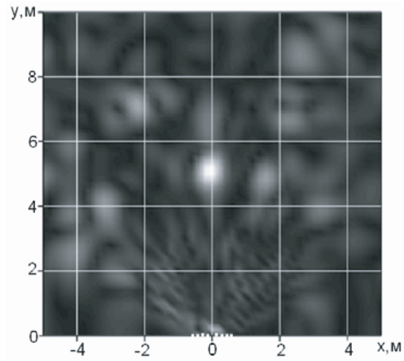


Figure 4: The same, as in Fig. 3, but range up to the target is increased by 1.4 m.

The check of the breadboard model operation was carried out in laboratory experiment at which digital registration of signal quadrature components for all 64 pairs of elements "transmitter-receiver" on each of 16 frequencies of step-FM SS was spend. As slow moving object the metal sheet in the size $25 \times 40\,\text{cm}^2$ was used. Its position changed on 1 cm on range in time interval between two full radiation time periods. During each of the periods the sheet remained motionless. Average distances from radar up to the target were equal 1.6 m and 3.0 m in different experiments. For check of the target selection on a background of motionless LO and a penetrating transmitter signal the data on two radiation time periods were registered. Then these data were focused on plane coordinates in two complex files and *the second variant of processing algorithm* on a basis of unitary coherent subtraction (8) was applied.

By results of processing presence of regular errors on delays of the signals varied with constant step on elements of the antenna arrays was revealed. The given errors were measured at adjustment of breadboard model on a motionless reflector with known angular position and taken into account in digital processing algorithm at focusing on spatial coordinates. There was also a constant additional delay for all antenna elements equivalent to 2 m on distance. Results of processing are submitted as topographical diagrams of system signal function (SSF) on Fig. 3, (a) - at absence of subtraction (Algorithm (6)) and (b) - at presence of subtraction (Algorithm (8)). On Fig. 3 the enough number of the intensive marks caused by reflections from LO and penetrating signals is visible. The target mark on equivalent range 3.6 m on Fig. 3(a) practically is not visible, since it is suppressed by powerful false signals. The result of unitary coherent subtraction (8) submitted on Fig. 3(b) shows presence of a true mark. A nature of false marks is explained by insufficient efficiency of suppression of signals from motionless LO and penetrating signals, and also presence of an interference in a room for signals from the mobile target, including an ambiguous ranges. The Fig. 4 is similar to Fig. 3(b), but corresponds to extending of target range on 1.4 m.

5. CONCLUSION

As a whole the results of the carried out researches open opportunities of the further improvement of hardware and algorithmic construction of spatially and frequency multichannel small range MIMO radars. Directions of such perfection should become the reduction of registration time of spatially multichannel multifrequency signals as due to reduction of duration of one spatial-frequency component, and so, probably, due to reduction of number of spatial channels, for example, on the basis of multiplicate processing algorithms offered in [6]. Such reduction will allow increasing efficiency of subtraction of local objects reflections owing to reduction of absolute instability of frequency grid of a multifrequency signal.

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