Organization of a local navigation system with the use of adaptive low-element antenna array

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Abstract: *The operation principles of local navigation system with the use of adaptive low-element antenna array are considered in this paper. The system will allow determining the coordinates of the vessel with high accuracy. For the eliminating the ambiguity of phase measurements of distances, the necessity of the formation of microwave signals with a small frequency shift was justified. The method of microwave signal forming is discussed. It is shown that the use of adaptive low-element antenna arrays improves system performance without a significant increase in the cost of the system. Adaptive antenna arrays minimize the effect of multipath propagation, which inevitably occurs while microwave propagation over the water surface.*

Keywords: *navigation, atmospheric channel, phase measurement, homodyne frequency transform, antenna array, multipath propagation.*

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Организация локальной навигационной системы с использованием адаптивных малоэлементных антенных решеток

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Аннотация: В данной статье рассматривается принцип работы локальной навигационной системы с использованием адаптивной малоэлементной антенной решетки. Система позволят определять координаты судна с высокой точностью. Для устранения неоднозначности фазовых измерений расстояний обоснована необходимость формирования микроволновых сигналов с малым частотным сдвигом. Обсуждается метод формирования микроволнового сигнала. Показано, что использование адаптивных малоэлементных антенных решеток повышает производительность системы без значительного удорожания системы. Адаптивные антенные решетки позволяют минимизировать влияние многолучевого распространения, неизбежно возникающего при микроволновом распространении над водной поверхностью.

Ключевые слова: навигация, атмосферный канал, измерение фазы, гомодинное преобразование частоты, антенная решетка, многолучевое распространение.

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1. Introduction

The creation of adaptive antenna arrays in the microwave band is an urgent task both in communication technology and in measurement technology for positioning systems design. In this case, there are often conflicting requirements for the array dimension, namely, the simultaneous provision of a large scanning angle and small mass-dimensional parameters. One of the applications of such arrays is their use in local navigation systems for moving objects tracking. One way of the determining the coordinate of an object is the measurement of fluctuations of the phase progression and/or the angle of arrival at microwave propagation [1, 2].

While solving the problem of constructing of local navigation system for accurate positioning of the vessel, the main source of errors in determining the coordinates is the vessel's pitching, which leads not only to a spread of coordinates as a result of antenna movement, but also to a fading of measured microwave signals.

This paper presents the results of modeling the effect of the number of elements of an adaptive antenna array on the signal-to-noise ratio at the receiver input of a local navigation system.

2. The principle of creating a local navigation system

Let's consider the operation of the meter of fluctuations of amplitude, phase progression and angle of arrival of the microwave signal. A generalized structural scheme of the meter is shown in Fig. 1 [3].

In fig. 1 the following notations are used: MWO is the microwave oscillator; C1, C2 and C3 are the microwave Y-circulators; A1, A2 and A3 are the microwave antennas; M1 and M2 are the microwave mixers; AD1 and AD2 are the amplitude detectors; PD1 and PD2 are the phase detectors; RO is the high-frequency high-quality quartz reference oscillator; CO is high-frequency high-quality voltage controlled oscillator; MWA and K are the microwave amplifiers; CPS and φ are the controlled microwave phase shifters.

In each i-th measuring channel the microwave oscillator of the microwave band of 10 GHz forms the signal

$$u_{MWi}(t) = U_{MWi}\cos(2\pi f_{MW}t + \phi_{MWi}) \qquad (2)$$

with initial amplitude U_{MWi}, initial frequency f_{MWi}, and initial phase ϕ_{MWi}.
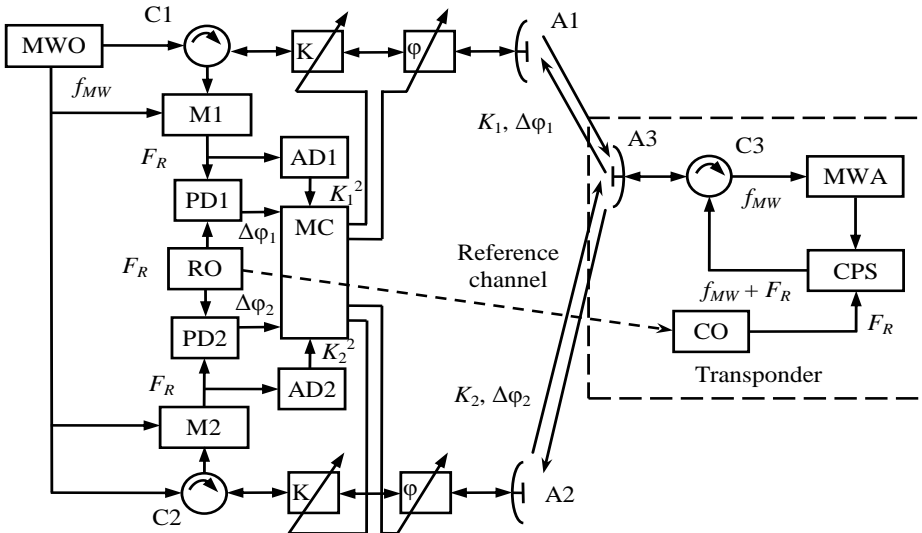
Fig. 1. Structural diagram of the amplitude fluctuation meter, phase progression fluctuations
meter, and determining the angle-of-arrival of microwaves.

Рис. 1. Структурная схема измерителя флуктуаций амплитуды,
набега фазы и угла прихода микроволнового сигнала

Then microwave oscillations through the microwave Y-circulators C1
and C2 feed the inputs of the microwave antennas A1 and A2. Further the mi-
crowave oscillations are radiated in the direction of the transponder. After pass-
ing through the measuring channel the microwave signal obtains the phase pro-
gression proportional to the length of the path

$$\Delta\phi_i = k_i d_i \,, \tag{3}$$

where k_{MWi} is the propagation constant; d_i is the length of the i-th path. Then
the microwave oscillations are received by the antenna A3 and through the mi-
crowave Y-circulator C3 they are transmitted to the microwave amplifier. The
amplified oscillations are fed to the signal input of the controlled microwave
phase shifter, which realizes the signal frequency shift by an amount equal to
the frequency of the phase shifter control signal F_R [4, 5].

The microwave oscillations, which are shifted in frequency, are emitted
by antenna A3. The oscillations that pass through the measuring microwave
channel and received by microwave antennas again obtain the phase shift $\Delta\phi_i$.

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The received microwave oscillations are multiplied in the microwave mixers with the original microwave oscillations, as a result of which low-frequency oscillations are obtained at the mixers outputs. As a result of the homodyne transformation in the mixer, the initial frequency and initial phase of the microwave oscillations of the original and information signals are respectively subtracted. The amplitudes of detected in amplitude detectors signals are proportional to the attenuation K_i of microwave signals. The phases of received signals are equal to the phase shift $2\Delta\phi_i$ of microwave signals in the corresponding channel. In phase detectors these phases are transformed in corresponding signals at its outputs.

The microcontroller adaptively adjusts the radiation pattern of the microwave antenna array to the maximum signal-to-noise ratio by the changing the amplitude-phase distribution of the microwave signal in the antenna array aperture, which consists of antennas A1 and A2, microwave amplifiers K, and phase shifters φ.

Changes in the propagation constants of microwave signals in the measuring channels also affect the measurement error of the distance measurement by the phase method. These changes are due to the changes in the physical parameters of the communication channel, such as temperature, pressure, humidity, etc.

For the compensation of the changes in the propagation constants k_i of microwave signals in the measuring channels, it is necessary to periodically calibrate the homodyne meter using the transponder, which is located at the known distance. For this, one of the transponders of the positioning system is located on the mobile object itself. Thus, by comparing the measured and true distances, the positioning system is calibrated.

For eliminating the ambiguity of determining the distance by the phase method, it is necessary to carry out the multi-frequency measurements. For this purpose the microwave oscillator with a small frequency step is used as a reference one [6]. Thus, from one highly stable reference oscillator with a frequency of 100 MHz is proposed to form a grid of frequencies

$$f_{ref\,i} = 100\,\text{MHz} + \Delta f_i \,, \tag{4}$$

where Δf_i is the frequency changes of the reference signal from 1 kHz to 10 kHz [6]. This change of the frequency of reference signal results in changes of microwave signals in a frequency band in 10 GHz $\pm$ (0.1-1.0 MHz) [6].

3. The algorithm of the antenna array control

The control algorithm of the antenna array pattern works as follows. In a state until that time when there is no useful signal, the antenna has an initial amplitude-phase distribution, characterized by the presence of the only one main lobe of the radiation pattern. Since there is a priori information about the direction of arrival of the signal, the main lobe of the radiation pattern is tuned exactly to this direction. Further, the amplitude-phase distribution of the antenna array is adjusted to the maximum of the useful signal. Thus, the constant adjustment of the maximum radiation pattern in the direction of the transponder compensates for the reduction in signal level caused by noise and the vessel's pitching.

In the case of interference affecting the side lobes of the radiation pattern the microcontroller detects a decreasing in the signal-to-noise ratio at the output of the amplitude detector and includes an adaptation algorithm. The purpose of the adaptation algorithm is to form "zeros" of the radiation pattern in the direction of the noise effect while maintaining the direction of the main lobe to the source of the useful signal. Since the objective function corresponds to the only one global maximum [7], the gradient method is used for its finding.

4. Selection of antenna array parameters

Let's consider a linear equidistant antenna array. Let the radiation pattern of primary emitters be described in a spherical coordinate system by a function $f_1(r, \theta, \varphi)$ (r is the distance to the observation point, θ and φ are the angular coordinates of the observation point). For further analysis it is sufficient to consider the placement of the observation point in the far zone (in the radiation zone) of the antenna, i.e. for the case of a plane phase front of an electromagnetic wave generated by the antenna in the direction of the observation point.

A simplified model of the linear array of radiators is shown in Fig. 2
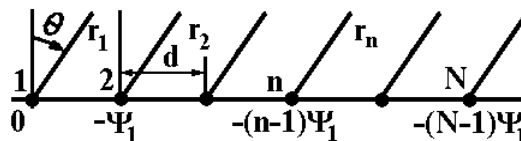

Fig. 2. The model of linear phase antenna array.

Рис. 2. Модель решетки с линейным набегом фазы

Let the amplitudes of the currents fed the inputs of the emitters be the same, and the initial phase of the current in the i-th antenna element differs from the phase of the i-th current of the antenna element by the same amount $\psi_1 = \psi_i - \psi_{i-1}$, while the phase distribution of the phased antenna array exciting the primary emitters is linear. Let's take the initial phase of the current in the first radiating element for zero, then the initial phase in the n-th radiator will be $(n-1)\psi_1$, and the radiation field generated by this radiator in the far zone is determined by the expression

$$E_n = A f_1(\theta, \varphi)\cos(\omega t - k r_n + (n-1)\psi_1), \tag{5}$$

where A is the constant (amplitude) factor, independent of angles θ and φ; r_n is the distance from the n-th antenna element to the observation point; $k = 2\pi/\lambda$ is the propagation constant.

It can be shown, the $r_n = r_1 - (n-1)d\sin\theta$. In this case, the expression (5) can be written in the following form

$$E_n = A f_1(\theta, \varphi)\cos(\omega t - k r_1 + (n-1)(kd\sin\theta + \psi_1)).$$

The field of the entire antenna array is determined by summing the fields of the individual radiators and is written in the following form:

$$E = \sum_{n=1}^{N} E_n = A f_1(\theta, \varphi)\frac{\sin\left(\dfrac{N}{2}(nd\sin\theta + \psi_1)\right)}{\sin\left(\dfrac{1}{2}(kd\sin\theta + \psi_1)\right)}\cos(\omega t - k r_0) =$$

$$= A f_1(\theta, \varphi)\frac{\sin\dfrac{N\psi}{2}}{\sin\dfrac{\psi}{2}}\cos(\omega t - k r_0), \tag{6}$$

where $\psi = kd\sin\theta + \psi_1$ is the phase shift between the fields of adjacent emitters at the point of observation; ψ_1 is the electrical phase shift, which is formed by phase shifters in the diagram forming device; r_0 is the distance from the phase center of the antenna array to the observation point; N is the number of emitters in the linear array.

In this case, the multiplier $kd\sin\theta$ determines the spatial phase shift, which depends on the distance between the radiators in the array.

Thus, the directivity pattern of a phased antenna array is determined by two aggregated factors:

— radiation pattern of the primary antenna element $f_1(\theta, \varphi)$;

— antenna array multiplier $f_n(\theta, \varphi)$.

According to (6) the multiplier of the linear antenna array has the form

$$f_n(\theta, \varphi) = \frac{\sin \dfrac{N\psi}{2}}{\sin \dfrac{\psi}{2}} = \frac{\sin\left(\dfrac{\pi}{\lambda} Nd\left(\sin\theta + \dfrac{\psi_1}{kd}\right)\right)}{\sin\left(\dfrac{\pi}{\lambda} d\left(\sin\theta + \dfrac{\psi_1}{kd}\right)\right)}.$$

This factor depends on the shift of the initial phases ψ_1 of the excitation currents of the neighboring emitters of the linear antenna array.

The maximum radiation in such antenna occurs for those directions in space for which the condition $\psi = 2\pi p$ is satisfied, where $p = 0, \pm 1, \pm 2, \ldots$, i.e., where the phase difference between the fields of the antenna element caused by the difference in the path of the rays is fully compensated by the difference between the initial phases of the excitation currents of the antenna element

$$kd \sin\theta_0 + \psi_1 = kd\left(\sin\theta + \frac{\psi_1}{kd}\right) = 2\pi p,$$

then

$$\sin\theta_0 = -\frac{\psi_1}{kd} + p\frac{\lambda}{d}. \qquad (7)$$

This equation is called the beam swing equation, and p is the number of the beam of maximum radiation.

From equation (7) it follows the movement of the beam in the antenna array in space can be carried out in the following ways:

— by the changing the oscillation frequency of the connected microwave oscillator;

— by the changing in the phase shift ψ_1 between the emitters using the phase shifters and corresponding controlling system;

— by the switching of the radiating elements of the array, the pitch of the radiators or segments of the supply paths.

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The distance between the emitters is selected according to the criterion of the absence of additional diffraction maxima according to the formula

$$\frac{d}{\lambda} \le \frac{1}{1+\sin\theta_0}\ .$$

This expression defines the maximum deviation of the radiation maximum in the absence of additional side maxima in the radiation pattern.

5. Modeling results

For the antenna array creating the microstrip patch antenna was chosen as an array element. The advantages of this type of antenna are: simplicity of design, easy of manufacture, easy of excitation, the ability of creation of arrays of the same type of elements, the possibility of combining antennas, amplifiers and phase shifters in a single printing unit.

The design of a single antenna element is a square patch resonator located on the dielectric substrate and metal ground plane. With a substrate thickness of 1.5 mm and a relative dielectric constant of 4.2, and a central operating frequency in 10 GHz, the size of the antenna array element is 6.4x6.4 mm^2. The feed point is located at a distance of 1.6 mm from the edge of the printing element with an input impedance of 50 Ohms.

The antenna array consists of 2 elements. The elements are displaced in a plane perpendicular to the plane passing through the excitation point of the antenna elements and their centers. This choice of the location of the antenna elements reduces their mutual influence on each other. The distance between the edges of the antenna elements is also 6.4 mm.

The antenna pattern for the case of the in-phase excitation and quadrature antenna elements is shown in Fig. 3

As follows from the Fig. 3, when the difference in the excitation phases of the antenna elements changes from 0 to 90 degrees, the maximum of the directional pattern is rotated by 15 degrees. At the same time, the level of radiated power drops by 20 %.

The radiation patterns of a three-element antenna array with the in-phase and non-phase excitation of elements is shown in Fig.4. By changing the phases of the excitation of the side elements, relative to the central element, it is possible to significantly change the position of the minima of the radiation pattern, and due to this matter, it is possible to reduce the noise influence on the useful signal.
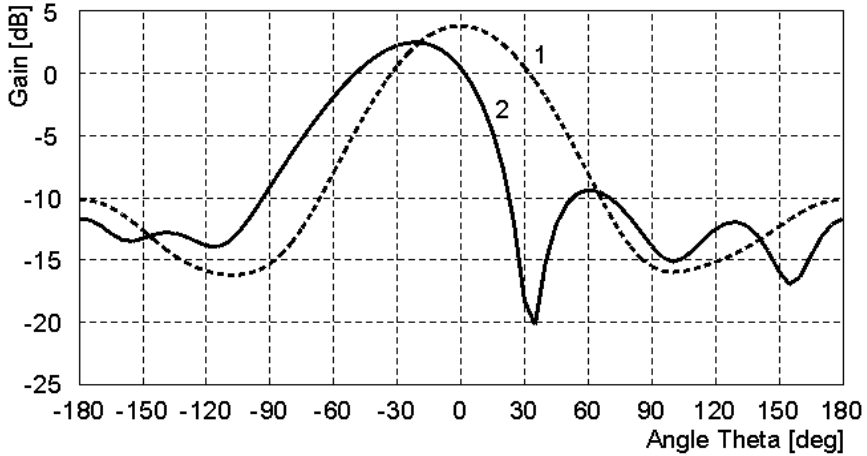
Fig. 3. Antenna pattern of a two-element antenna array.

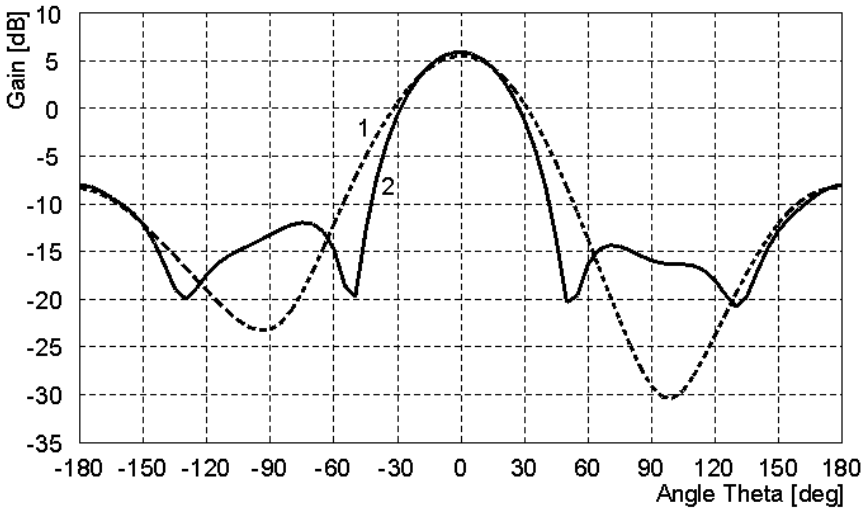Рис. 3. Диаграмма направленности двухэлементной антенной решетки

Fig. 4. Antenna pattern of a three-element antenna array
(curve 1 in-phase excitation, 2 – non-in-phase excitation).

Рис. 4. Диаграмма направленности трехэлементной антенной решетки
(кривая 1 синфазное возбуждение, 2 — несинфазное возбуждение)

Table 1 shows the dependence of the width of the directional pattern and the range of scanning angles vs. the number of elements of the antenna array.

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Table 1. Characteristics of low-element antenna arrays
Табл. 1. Характеристики малоэлементных антенных решеток.

Number of elements Число элементов	Width of radiation pattern, degree Ширина диаграммы направленности, градус	Scanning angle range, degree Диапазон углов сканирования, градус
2	60	±13,5
3	41	±15
4	30	±16

6. Conclusions

The proposed method of measuring the position of the vessel allows the creation of a local navigation system. Providing the determination of the instantaneous coordinates of the vessel with high accuracy, which is sufficient for ensuring the remote control of the mooring. Due to the formation of the discrete-tunable pattern of antenna array, the accuracy and noise immunity of a homodyne measuring system can be significantly improved.

Due to the proposed low-element antenna array, it is possible to significantly reduce the effect of multipath propagation of the measurement signal on the accuracy of determining the location of moving objects. In this case, an antenna array with an odd number of elements is preferred. Thus, the minimum number of elements of the antenna array must be equal to three.

Acknowledgement

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