ISSN 0020-4412, Instruments and Experimental Techniques, 2020, Vol. 63, No. 6, pp. 822–829. © Pleiades Publishing, Ltd., 2020.
Russian Text © The Author(s), 2020, published in Pribory i Tekhnika Eksperimenta, 2020, No. 6, pp. 32–39.

ELECTRONICS AND RADIO ENGINEERING

A Method for Determining the Bearing and Roll Angles of an Aircraft by an Orthogonally Linearly Polarized Beacon Signal

V. L. Gulko[a] and A. A. Mescheryakov[a,*]
[a] *Tomsk State University of Control Systems and Radio Electronics, Tomsk, 634050 Russia*
**e-mail: msch@rts.tusur.ru*

Received May 18, 2020; revised May 28, 2020; accepted May 30, 2020

Abstract—Orthogonally linearly polarized radio-beacon signals are emitted simultaneously from two spatially separated points in the horizontal plane to determine the bearing and roll angles. The resulting vector signals from the radio beacon are received by a receiving antenna on board an aircraft. The antenna irradiator is equipped with a polarizing modulator in the form of a ferrite rotator of the polarization plane. The bearing and roll angles are estimated at the receiver output at a frequency that is a multiple of the polarization-modulation frequency of the received beacon signals. The layout of the apparatus that performs this method is described. The results of measuring the navigation elements are presented. The mean square errors of the bearing and roll angle measurements were 0.48° and 0.35°, respectively.

DOI: 10.1134/S0020441220060068

INTRODUCTION

One of the promising ways to expand the functionality of onboard and ground-based radio-navigation equipment is the practical use of the vector nature of radio signals as a carrier of navigation information.

The existing methods for determining the angular position of an aircraft in radio-beacon navigation systems (RBSs) are based on the use of the amplitude, frequency, phase, or time characteristics of radio-beacon (RB) signals [1]. To measure the navigation elements such as the roll and pitch, expensive and technically complex inertial navigation tools are used [2]. However, the polarization characteristics of RB signals are virtually not used [3].

In [4–6], the possibility of using orthogonally linearly polarized RB signals was investigated for estimating the bearing [4, 5] and roll [6] of a mobile object using the polarization-modulation method. The essence of this method is that signals with vertical and horizontal polarizations and equal amplitudes, wavelengths λ, and known initial phases were emitted synchronously from two points spatially separated by a distance d in the horizontal plane.

The resulting RB vector signals were received by a receiving antenna on board an aircraft; the single-channel microwave path of this antenna includes a polarization modulator in the form of a mechanically rotating (at the frequency Ω) section of a circular waveguide with a half-wave $\lambda/2$ [4, 6] or quarter-wave $\lambda/4$ [5] phase plate, which is placed inside it. The phase plate is rotated by a stepper motor that is mechanically connected to a circular-waveguide section. The bearing α was defined as the angle between the normal to the middle of the base d and the direction to the movable object using the formula [4–6]

$$\alpha = \pm \arcsin\left(\frac{\lambda}{2\pi d}\Delta\varphi\right) \pm n\pi, \quad (1)$$

where $n = 0, 1, 2...$; $\Delta\varphi$ is the high-frequency phase difference between orthogonally linearly polarized signals at the reception point on board a moving object.

The phase difference $\Delta\varphi$ included in (1) was proposed to indirectly estimate the receiver output by the amplitude of the spectral component at the frequency 2Ω when using a quarter-wave phase plate [5] and at the frequency 4Ω when using a half-wave phase plate [4, 6]; the roll γ was estimated by the phase of the spectral component [6]:

$$\gamma, \text{rad} = \pm\frac{\varphi_{4\Omega}}{2}. \quad (2)$$

Experimental estimates of bearing measurements were obtained in [7] from orthogonally linearly polarized RB signals using a polarization modulator in the form of a rotating half-wave phase plate. The standard error of the bearing-angle measurement was 0.38°.

The disadvantage of the methods from [4–7] is that the polarization modulation of the received RB signals requires mechanical rotation of a circular-waveguide section, which in turn is limited by the technical capabilities of a stepper motor. This results in limiting the speed of measurements of the navigation elements and complications in the design of the polarization modulator itself.

This paper describes a method for measuring the bearing and roll angles of an aircraft using an electronic polarization modulator in the form of a ferrite rotator of the polarization plane and provides experimental estimates of the accuracy of the measurements of navigation elements.

DESCRIPTION OF THE METHOD

Let a radio beacon that consists of two points, which are spatially separated in the horizontal plane by a distance d, simultaneously emits orthogonally linearly polarized signals with vertical and horizontal polarizations with equal amplitudes, initial phases, and wavelengths λ. The resulting signal in the direction α can then be represented in a linear polarization basis in the vector form [4–6]:

$$\mathbf{E}_{\mathrm{P}} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ e^{j\Delta\varphi} \end{bmatrix}, \quad (3)$$

where $\Delta\varphi = \frac{2\pi d}{\lambda}\sin\alpha$ is the phase shift between the orthogonally linearly polarized signals at the reception point on board the aircraft.

The factor $1/\sqrt{2}$ in expression (3) is present due to the unit intensity of the resulting signal, which is assumed for convenience.

It was noted in [4] that the resulting signal (3) at the reception point on board the aircraft generally has an elliptical polarization. In this case, the orientation angle β of the polarization ellipse can take two fixed values: the first one is $\beta_1 = \pi/4$ and the second is $\beta_2 = 3\pi/4$. When passing through the circular polarization state of the resulting signal, a jump in the orientation angle of the polarization ellipse from the value $\beta_1 = \pi/4$ to $\beta_2 = 3\pi/4$ occurs and vice versa.

To describe the interaction of the resulting signal (3) with the microwave elements of the receiving antenna with an installed polarization modulator in the form of a ferrite (Faraday) rotator of the polarization plane, we use the Jones operator [8].

The ferrite rotator of the polarization plane is a segment of a circular waveguide, in whose central part a ferrite rod is placed. The rod is located along the axis of the longitudinal magnetic field with a current that flows in a coil, which is wound on the outside of the waveguide [8]. A harmonic change in the bias current in this modulator leads (as a result of the Faraday effect) to rotation of the polarization plane of the wave propagating in the circular waveguide, without changing the parameters of the wave ellipticity. The frequency of rotation of the output-wave polarization plane is set by the frequency of the harmonic change in the bias current in the modulator. The angle of rotation of the polarization plane is determined by the value of the current that flows through the coil and the length of the ferrite rod (or rods placed one after another) [8].

Let us assume that in a general case, the aircraft has a roll angle γ defined as the angle between the right (relative to the center of mass) transverse semiaxis of the aircraft and the horizontal plane [6, 9]. The Jones vector of the signal at the linear-polarizer output, which is a transition from a round waveguide to a rectangular one, can then be written in a linear polarization basis as the result of the transformation:

$$\mathbf{E}_{\mathrm{out}}(\theta) = C\frac{1}{\sqrt{2}}[\Pi][\mathrm{M}][R(\pm\gamma)]\mathbf{E}_{\mathrm{P}}, \quad (4)$$

where $\mathbf{E}_{\mathrm{P}}$ is the Jones vector of the resulting signal (3), which is defined in a linear polarization basis; $[R(\pm\gamma)] = \begin{bmatrix} \cos\gamma & \mp\sin\gamma \\ \pm\sin\gamma & \cos\gamma \end{bmatrix}$ is the operator of rotation by the roll angle $\pm\gamma$; $+\gamma$ is the positive roll angle when the right transverse semiaxis (or the right wing of the aircraft) is below the horizontal plane; $-\gamma$ is the negative roll angle when the right transverse semiaxis (or the right wing of the aircraft) is above the horizontal plane [9]; $[\mathrm{M}] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$ is the Jones operator of the polarization modulator in the form of a ferrite rotator of the wave polarization plane by an angle $\theta = \Omega t$, which is a harmonic function of the magnetic-field strength H and is set in the linear polarization basis [8]; $[\Pi] = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ is the Jones operator of the linear polarizer (the transition from the circular waveguide to the rectangular one) with a horizontal eigenpolarization that coincides with the right transverse axis of the aircraft, which is specified in the linear polarization basis; and C is a constant that takes the performance of the RB and the distance from it to the aircraft into account.

After performing the necessary transformations in (4), we obtain the Jones vector of the output signal of the linear polarizer in the form

$$\mathbf{E}_{\mathrm{out}}(\theta) = \frac{1}{\sqrt{2}}C\begin{bmatrix} \cos(\theta\pm\gamma) + \sin(\theta\pm\gamma)e^{j\Delta\varphi} \\ 0 \end{bmatrix}. \quad (5)$$

In view of (5), the signal at the receiver input as a function of the angular position θ has the form

$$\dot{E}_{\mathrm{in}}(\theta) = \frac{1}{\sqrt{2}}C\{\cos(\theta\pm\gamma) + \sin(\theta\pm\gamma)e^{j\Delta\varphi}\}. \quad (6)$$

The signal amplitude at the output of a receiver with a logarithmic amplitude characteristic and a linear detector is

$$A(\theta) = \log\frac{1}{\sqrt{2}}C + \log|\cos(\theta\pm\gamma) + \sin(\theta\pm\gamma)e^{j\Delta\varphi}|. \quad (7)$$

After transformations (7) and in view of the fact that the signal level for a logarithmic receiver is commonly measured in decibels, we obtain for $\theta = \Omega t$:

$$A(\Omega t),\ \text{dB} = 20\log\frac{1}{\sqrt{2}}C + 10\log\{1 + \cos\Delta\varphi\sin(2\Omega t \pm 2\gamma)\}. \quad (8)$$

As is seen from (8), the signal amplitude at the output of a receiver with a logarithmic amplitude characteristic is modulated by a doubled frequency of rotation 2Ω of the signal polarization plane. The modulation depth depends on the phase difference $\Delta\varphi$ and determines the polarization state of the resulting signal (3) at the reception point on board the aircraft. Therefore, the spectral component at the frequency 2Ω will be present in the envelope spectrum of the receiver output signal. Moreover, its amplitude $A_{2\Omega}$ is determined by the cosine of the phase difference $\Delta\varphi$ and, taking (1) into account, is related to the estimate of the angular coordinate α^* by the ratio

$$\alpha^* = \pm\arcsin\frac{\lambda}{2\pi d}\Delta\varphi^* \pm n\pi, \quad (9)$$

where $\Delta\varphi^*$ is the estimate of the phase difference $\Delta\varphi$ obtained indirectly via a measurement of the amplitude $A_{2\Omega}$ of the spectral component at the frequency 2Ω.

At the same time, its phase $\varphi_{2\Omega}$ with allowance for (8) is determined only by the roll angle γ and is related to it through the relationship

$$\gamma,\ \text{rad} = \pm\frac{\varphi_{2\Omega}}{2}. \quad (10)$$

It should be noted that the phase $\varphi_{2\Omega}$ is read from the phase of the reference signal $\sin 2\Omega t$, which is determined by the master oscillator of the rotation of the signal polarization plane.

In this case, the amplitude $A_{2\Omega}$ and phase $\varphi_{2\Omega}$ do not depend on the RB performance and the distance from it to the aircraft. The energy parameters determine the constant component of the signal at the logarithmic-receiver output.

However, the factor $\cos\Delta\varphi$ that is included in (8) is an even function of the angular coordinate α, which does not allow the determination of the side of the aircraft deviation from the zero direction ($\alpha = 0$), which coincides with the normal to the middle of the base d. To avoid this disadvantage, it is proposed to emit orthogonally linearly polarized signals with equal amplitudes and wavelengths but with an initial phase difference $\Delta\varphi_0 = \pm\pi/2$ in this direction. In this case, the resulting signal (3) at the reception point on board the aircraft in the equisignal direction at $\alpha = 0$ will have left or right circular polarization. Substituting a constant initial phase shift $\Delta\varphi_0$, e.g., $\pi/2$, into (8), we obtain

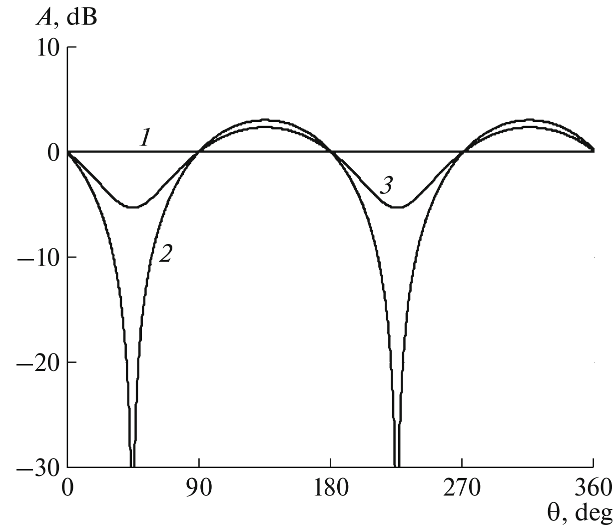

Fig. 1. The dependences of the amplitude of the receiver output signal on the orientation angle of the polarization plane θ for Δφ that is equal to (*1*) 0, (*2*) π/2, and (*3*) π/4.

$$A(\Omega t),\ \text{dB} = 20\log\frac{1}{\sqrt{2}}C + 10\log\{1 - \sin\Delta\varphi\sin(2\Omega t \pm 2\gamma)\}. \quad (11)$$

In this case, the amplitude of the spectral component at the frequency $A_{2\Omega}$ in (11) is determined by the sine of the phase difference $\Delta\varphi$ and is an odd function of the angular coordinate α.

Relationship (11) allows calculation of the amplitude of the logarithmic-receiver output signal as a function of the angular position θ of the plane of polarization of the polarization-modulator signal for different values of $\Delta\varphi$ and γ; the form of these dependences makes it possible to trace the mechanism of the appearance of the spectral component at the frequency 2Ω in the spectrum of the envelope of the receiver output signal.

The calculation results are shown in Figs. 1 and 2. Curves 1–3 in Fig. 1 correspond to the $\Delta\varphi$ values equal to 0, $\pi/2$, and $\pi/4$ for $\gamma = 0$, respectively; the curves in Fig. 2 correspond to the values of the roll angle γ of 0°, 15°, and −15° for $\Delta\varphi = \pi/2$, respectively.

From the analysis of Fig. 1, it follows that for $\Delta\varphi = 0$ (curve *1*), the amplitude of the receiver output signal is constant and does not depend on the angular position θ of the polarization plane of the polarization-modulator output signal. In this case, taking the introduced initial phase shift $\Delta\varphi_0 = \pi/2$ into account, the resulting signal (3) in the zero direction $\alpha = 0$ is polarized circularly, and the amplitude $A_{2\Omega}$ is equal to zero.

If $\Delta\varphi = \pi/2$ (curve *2*), the amplitude modulation of the signal at the receiver output reaches 100% of its depth. During a complete revolution of the polarization plane θ, the signal amplitude becomes modulated by the double rotation frequency 2Ω of the signal

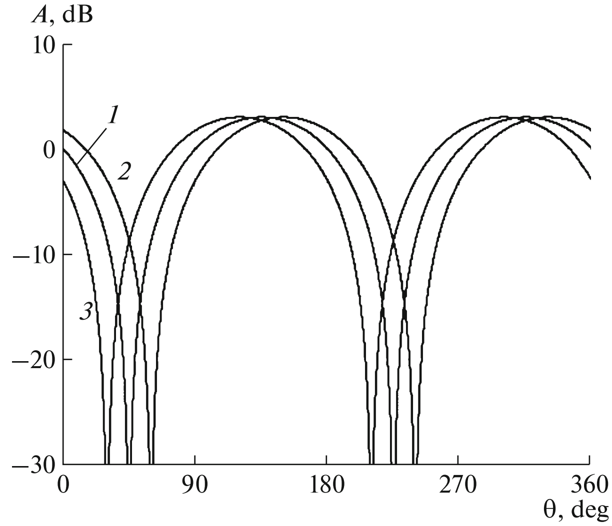

Fig. 2. The dependences of the amplitude of the receiver output signal on the orientation angle of the polarization plane θ at the roll angle γ equal to (*1*) 0°, (*2*) 15°, and (*3*) −15° for $\Delta\varphi = \pi/2$.

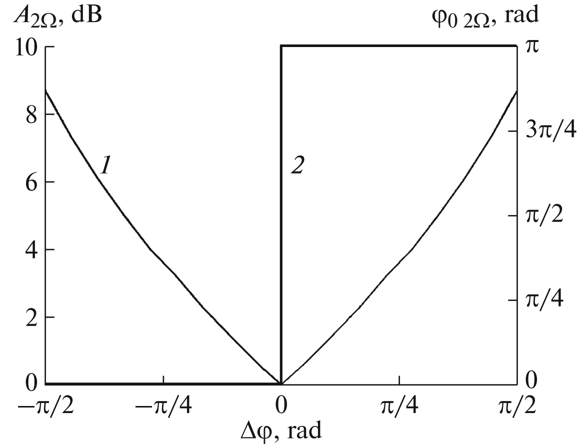

Fig. 3. The dependences of (*1*) the amplitude $A_{2\Omega}$ and (*2*) the initial phase $\varphi_{02\Omega}$ of the spectral component at the frequency 2Ω on the phase difference $\Delta\varphi$ at $\Delta\varphi_0 = \pi/2$.

polarization plane. Therefore, in the spectrum of the receiver output-signal envelope, there will be an informative spectral component at the frequency 2Ω, and its amplitude $A_{2\Omega}$ reaches its maximum. In this case, the resulting signal (3) at the point of reception on board the aircraft will be linearly polarized. In the intermediate case where $\Delta\varphi = \pi/4$ (curve *3*), the resulting signal (3) will have an elliptical polarization, while the amplitude $A_{2\Omega}$ takes intermediate values.

Similar dependences are observed for negative values of Δφ that are equal to $-\pi/2$ and $-\pi/4$ for $\gamma = 0$; the only difference is that these curves are in antiphase in comparison with curves *2* and *3* in Fig. 1, which were obtained for positive values of Δφ equal to π/2 and π/4, respectively. As noted in [4], this is due to the fact that when passing through the circular polarization state of the resulting signal (3), a jump-like change in the spatial orientation angle of the polarization ellipse occurs from a value of π/4 to 3π/4 and vice versa. Taking the introduced constant initial phase shift $\Delta\varphi_0 = \pi/2$ into account, this allows one to determine the side to which the aircraft deviates from the zero direction $\alpha = 0$.

It follows from the analysis of Fig. 2 (curves *1*–*3*), that when, e.g., $\Delta\varphi = \pi/2$, i.e., the resulting signal (3) is linearly polarized at the reception point, then, as noted above, the amplitude modulation of the signal at the output of the logarithmic receiver reaches 100% of its magnitude. At the same time, different values of the roll angle γ do not affect both the form of this dependence and the depth of the signal amplitude modulation, but these only determine the signal phase shift by the doubled roll angle γ of the aircraft. Similar dependences are observed for the values $\Delta\varphi \neq 0$. This confirms the correctness of the obtained formula (8) that characterizes the relationship between the aircraft roll angle and the phase of the spectral component at the frequency 2Ω.

The amplitude $A_{2\Omega}$ at the logarithmic-receiver output can be calculated by applying the Fourier transform to relationship (11):

$$A_{2\Omega},\ \text{dB} = \frac{1}{\pi}\int_0^{2\pi} A(\Omega t)\sin 2\Omega t d\Omega t. \tag{12}$$

The results of the calculation of the dependence of $A_{2\Omega}$ on the phase difference Δφ at $\Delta\varphi_0 = \pi/2$ and the roll angle $\gamma = 0$ are shown in Fig. 3 (curve *1*).

Figure 3 shows that the amplitude reaches its maximum value of 8.69 dB at $\Delta\varphi = \pm\pi/2$, while at $\Delta\varphi = 0$, the amplitude $A_{2\Omega}$ is 0 dB. In the first case, as noted above, the resulting signal (3) at the reception point on the aircraft is linearly polarized; in the second case, signal (3) is circularly polarized.

Figure 3 (curve *2*) shows the dependence of the initial phase $\varphi_{02\Omega}$ of the spectral component at the frequency 2Ω on the phase difference Δφ. In the range of change $-\pi/2 \leq \Delta\varphi < 0$, its initial phase coincides with the phase of the reference signal $\sin 2\Omega t$ and changes abruptly by π, being in antiphase with it at $0 < \Delta\varphi \leq \pi/2$. The latter allows determination of the side (sign) of the aircraft deviation from the zero direction $\alpha = 0$ and expansion of the range of unambiguous measurements of the amplitude $A_{2\Omega}$ to $-\pi/2 < \Delta\varphi \leq \pi/2$. Since the range of a unique Δφ measurement is π in this case, in view of (9), the sector of a unique measurement of the angle α for $n = 0$ is defined as

$$\Delta\alpha = \pm\arcsin\left(\frac{\lambda}{2d}\right). \tag{13}$$

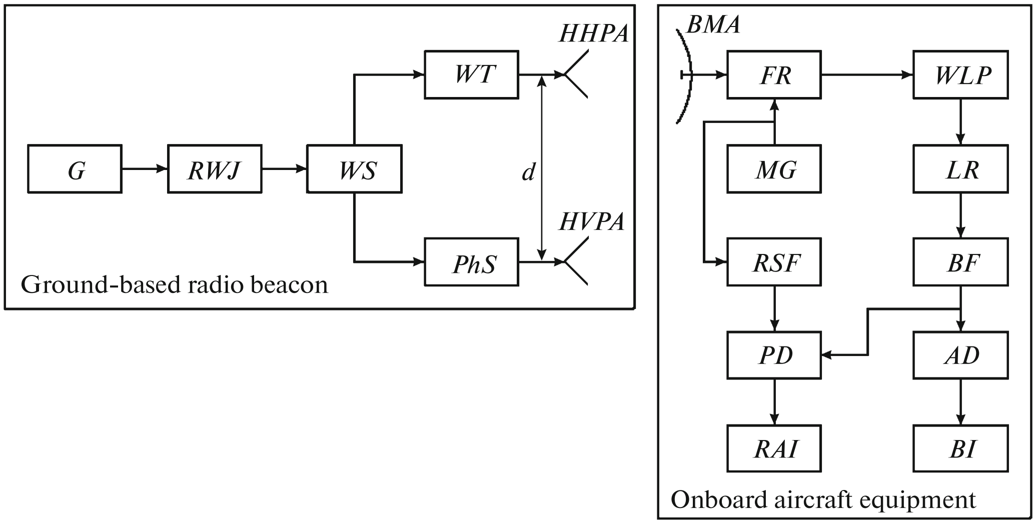

Fig. 4. The functional diagram of the goniometric polarization-modulation radio-beacon system for measuring the aircraft bearing α and roll γ angles: (*G*) high-frequency generator; (*RWJ*) rotating waveguide joint; (*WS*) double T-like waveguide splitter; (*WT*) 90° waveguide twist; (*HHPA*) horn horizontal-polarization antenna; (*PhS*) phase shifter by $\pi/2$; (*HVPA*) horn vertical-polarization antenna; (*BMA*) onboard mirror antenna; (*FR*) ferrite rotator of the polarization plane; (*WLP*) waveguide linear polarizer; (*MG*) low-frequency master generator of the reference signal $\sin\Omega t$; (*LR*) logarithmic receiver; (*RSF*) former of the reference signal $\sin 2\Omega t$; (*BF*) band-pass filter at the frequency 2Ω; (*PD*) phase detector; (*AD*) amplitude detector; (*RAI*) roll-angle γ indicator; and (*BI*) bearing α indicator.

Thus, the dependence of the amplitude $A_{2\Omega}$ on the phase difference $\Delta\varphi$ is essentially the direction-finding characteristic of the angular RBS and the estimate of the angular coordinate α is determined by expression (9).

Moreover, the slope of the direction-finding characteristic and, therefore, the potential accuracy of measuring the aircraft bearing are determined by the spatial separation d of radiating points but not by the directional properties of the receiving onboard antenna, where the dimensions and weight are of paramount importance.

THE EXPERIMENTAL INSTALLATION OF A GONIOMETRIC POLARIZATION-MODULATION RBS

A prototype of a goniometric polarization-modulation RBS was created in order to verify the results of theoretical research and obtain experimental estimates of the accuracy of determining the aircraft bearing and roll angles. Its diagram is shown in Fig. 4.

The prototype contains a ground-based RB that simultaneously emits orthogonally linearly polarized signals with vertical and horizontal polarizations from two points, which are spatially separated by distance d in the horizontal plane. The RB is located at a point with known coordinates. The prototype also includes an onboard microwave single-channel receiver based on a Groza-26 aircraft weather-navigation radar station with a standard Faraday rotator of the polarization plane, which is placed inside the antenna irradiator [10] and operates in a new polarization-modulation mode. The modulation frequency is $\Omega = 40$ Hz.

The receiving onboard antenna was a 760-mm-diameter parabolic mirror. The width of the antenna directivity pattern at the half-power level was 3°, the antenna gain was 25 dB, and the receiver sensitivity was −120 dB/W.

The goniometric polarization-modulation RBS works as follows.

A standard G4-126 generator of high-frequency signals (*G*) emits, e.g., continuous signals at the frequency $f = 9370$ MHz with the radiation power $P = 10$ mW, which pass through a horizontal rotating waveguide joint (RWJ) and enter the input of a double waveguide T-shaped splitter (WS), where the signals branch into two signals with identical amplitudes.

From the outputs of the splitter WS, one signal is transmitted via a 90° waveguide twist (WT) to a horn transmitting horizontal-polarization antenna (HHPA), while the other signal is transmitted via a $\pi/2$ phase shifter (PhS) to another horn transmitting vertical-polarization antenna (HVPA). As a result, orthogonally linearly polarized signals with vertical and horizontal polarizations with equal amplitudes and wavelengths, but with an initial phase difference $\Delta\varphi_0 = \pi/2$, are radiated into the space in the direction α. The appearance of the transmitting horn antennas of the RB is shown in Fig. 5.

The resulting signal, whose Jones vector in the direction α has the form (3), is received on board the aircraft by the all-polarized onboard mirror antenna (BMA) and enters the signal input of the polarization

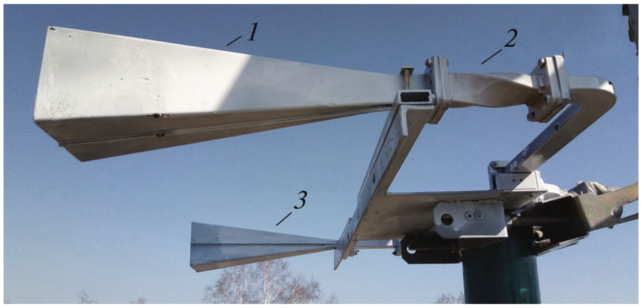

Fig. 5. The appearance of the transmitting horn antennas of the RB: (*1*) horn horizontal-polarization antenna; (*2*) 90° waveguide twist; and (*3*) horn vertical-polarization antenna.

modulator (FR), which is made in the form of a ferrite rotator of the polarization plane of the resulting signal that passes through the FR.

In a waveguide linear polarizer (WLP), which is a transition from a circular waveguide to a rectangular one, the horizontally polarized component of a signal modulated in the orientation angle $\theta = \Omega t$ of the signal polarization plane is extracted. The modulation frequency is set by a master generator (MG) that generates a control harmonic signal $\sin\Omega t$ with a modulation frequency $\Omega = 40$ Hz, which is fed to the control input of the polarization modulator (FR).

The output signal of the polarizer (WLP) from the side of the rectangular waveguide, which has the form (5), enters the input of the logarithmic receiver (LR), where it is detected. The appearance of the prototype of the onboard equipment of the aircraft is shown in Fig. 6.

As a result of rotation of the polarization plane of the input signals with the frequency Ω, a detected signal that is amplitude-modulated by the double frequency of rotation of the polarization plane 2Ω is formed at the output of the logarithmic receiver (*LR*); this signal has the form (8). In this case, the depth of the amplitude modulation of the receiver output signal depends only on the phase difference $\Delta\varphi$ between the orthogonally linearly polarized signals that are emitted by the transmitting horn antennas (HHPA and HVPA) and determines the polarization state of the resulting signal (3) at the reception point on board the aircraft.

In the former (RSF), a reference voltage $\sin 2\Omega t$, which is necessary for the operation of a phase detector (PD), is formed in response to the output signals of the generator MG. The band-pass filter (BF), which is tuned to a frequency of $2\Omega = 80$ Hz, extracts the spectral component at a frequency of 2Ω, which is contained in the spectrum of the output-signal envelope of the logarithmic receiver (LD) of the aircraft and carries navigation information about the aircraft bearing and roll angles. The phase and amplitude detection of this component is carried out in the PhD and AD detectors and their output signals are registered by the RAI and BI indicators, respectively, whose scales are calibrated in accordance with the established relationships (10) and (9) in degrees of the roll γ and bearing α angles.

Fig. 6. The appearance of the prototype of the onboard aircraft equipment based on the Groza 26 aircraft radar station: (*1*) mirror antenna; (*2*) exciter with a built-in ferrite rotator of the polarization plane; (*3*) antenna column; and (*4*) receiving and measuring equipment.

EXPERIMENTAL RESULTS

The ground-based RB was installed at a distance of 3 km from the onboard radio receiver.

To simulate a change in the bearing α, the HHPA and HVPA horn transmitting antennas of the RB (Fig. 4) were connected to the output of the waveguide joint (RWJ), which rotated in the horizontal plane, via a T-shaped waveguide splitter WS. This made it possible to change the orientation of the equisignal direction, which coincided with the perpendicular to the middle of the base *d* that was formed by the horn transmitting antennas (RAGP and RAVP) with a discrete step of 0.5°. The base *d* was 20 cm long. The rotating waveguide joint (RWJ) was installed so that the horn transmitting antennas (RAGP and RAVP) could rotate with a step of 1° in the vertical plane to simulate a change in the roll angle γ.

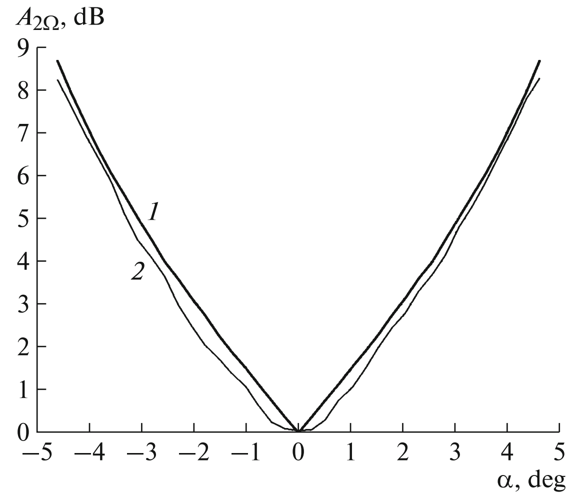

Fig. 7. The dependence of the amplitude of the spectral component at the frequency 2Ω on the bearing α: (*1*) theory and (*2*) experiment.

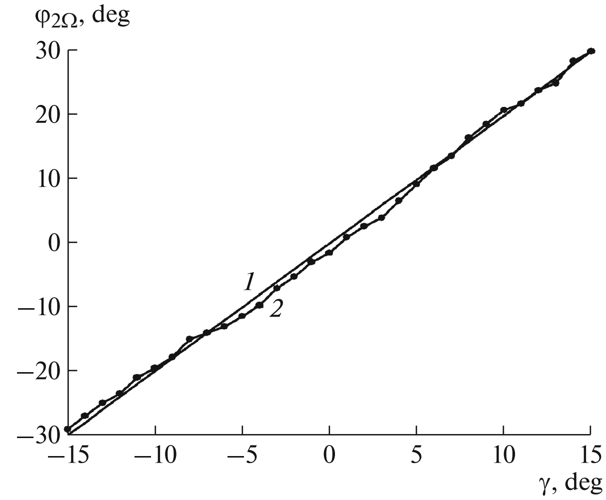

Fig. 8. The dependence of the phase $\varphi_{2\Omega}$ on the roll angle γ: (*1*) theory and (*2*) experiment.

The receiving antenna (BMA) of the onboard radio receiver was installed on the roof of the TUSUR radio-engineering building at a height of 18 m and was oriented in the direction to the RB. The polarization-modulation frequency of the received resulting signals was determined by the master generator (MG) and was equal to $\Omega = 40$ Hz. The spectral component at the frequency $2\Omega = 80$ Hz was extracted at the output of the logarithmic receiver (LR), and its amplitude $A_{2\Omega}$ and phase $\varphi_{2\Omega}$ were measured; the latter are associated with the bearing α and roll γ angles, respectively.

The observed parameters included the average (over several polarization-modulation periods) level of received signals, which exceeds the intrinsic noise of the receiver by 20 dB, as well as the amplitude and phase of the spectral component at the frequency 2Ω. Their estimate was formed by averaging 30-second realizations.

Figure 7 shows the results of measuring the dependence of the amplitude of the spectral component at the frequency 2Ω on the bearing α. The theoretical dependence (curve *1*) was obtained by calculation in accordance with (12) for the ratio $d/\lambda = 7.8$ at $\lambda = 3.2$ cm and $d = 20$ cm; curve *2* was obtained experimentally.

It is seen that the dependences are ambiguous. The width of the sector of a unique measurement of α depends on the d/λ ratio and the definition by relationship (13).

Figure 7 shows that the experimentally obtained dependence is close to the theoretical one. The standard deviation of the measured parameter α from the specified value was $\sigma_\alpha = 0.48°$ for a sector of unambiguous measurements of $\Delta\alpha = 9.2°$.

Figure 8 shows the dependences of the phase $\varphi_{2\Omega}$ of the spectral component at the frequency 2Ω on the roll angle γ, where the theoretical dependence (curve *1*) was obtained by calculations in accordance with (10), while curve *2* is experimental.

It follows from Fig. 8 that the experimentally measured dependence is also close to the theoretical one. The standard deviation of the measured roll angle γ from the specified one was $\sigma_\gamma = 0.35°$.

CONCLUSIONS

(1) A polarization-modulation method for estimating the bearing and roll angle of an aircraft according to radiated orthogonally linearly polarized RB signals using a ferrite rotator of the polarization plane with the frequency Ω of the received signals on board the aircraft was proposed and tested.

(2) The connection of the amplitude and phase of the spectral component at the frequency 2Ω with the aircraft bearing α and roll angle γ for the studied polarization modulator was theoretically investigated and established.

(3) Experimental estimates of the accuracy of measuring not only the bearing but also the aircraft roll angle using an electronic polarization modulator in the form of a Faraday rotator of the polarization plane were obtained.

(4) The error of measuring the bearing by the proposed method in comparison with the method using a polarization modulator in the form of a mechanically rotating half-wave phase plate [7] has a slightly higher value, which is probably due to the nonlinearity of the modulation characteristic of the ferrite rotator of the polarization plane.

However, the speed of measurements is higher in this case and is determined by the frequency of the polarization modulation of the received signals.

(5) The described method can be used in aircraft orientation systems during instrument approach, as well as in space navigation during spacecraft docking. The method is technically simple to implement, since the measurement of navigation elements is performed at the receiver output at a frequency that is multiple of the polarization-modulation frequency.

FUNDING

This study was supported by the Ministry of Science and Education of the Russian Federation, project no. FEWM-2020-0039, March 1, 2020.

This study was performed using the equipment of the Impuls Center of the Shared Use (the project was supported by the Ministry of Science and Education of the Russian Federation no. 075-15-2019-1644, ID RFMEFI62119X002).

REFERENCES

1. Skrypnik, O.N., *Radio Navigation Systems for Airports and Airways,* Springer, 2019.
2. Pel'por, D.S. and Yagodkin, V.V., *Giroskopicheskie sistemy* (Gyroscopic Systems), Moscow: Vysshaya Shkola, 1988.
3. Kozlov, A.I., Logvin, A.I., and Sarychev, V.A., *Polyarizatsiya radiovoln "Radiolokatsionnaya polyarimetriya"* (Radio-Wave Polarization "Radar Polarimetry"), Moscow: Radiotekhnika, 2007.
4. Gulko, V.L. and Meshcheryakov, A.A., *Dokl. Tomsk. Gos. Univ. Sist. Upr. Radioelektron.,* 2015, no. 2, pp. 5–9.
5. Gulko, V.L. and Mescheryakov, A.A., *Rus. Phys. J.,* 2020, vol. 62, no. 12, p. 2340. https://doi.org/10.1007/s11182-020-01986-9
6. Gulko, V.L. and Meshcheryakov, A.A., *Dokl. Tomsk. Gos. Univ. Sist. Upr. Radioelektron.,* 2016, vol. 19, no. 1, pp. 5–8. https://doi.org/10.21293/1818-0442-2016-19-1-5-8
7. Gulko, V.L. and Meshcheryakov, A.A., *25-aya Vserossiiskaya otkrytaya nauchnaya konferentsiya "Rasprostranenie radiovoln"* (Proc. 25th All-Russian Open Scientific Conference "Radio-Wave Propagation"), Tomsk, 2016, vol. 3, pp. 21–24.
8. Bogorodskii, V.V., Konoreikin, D.B., and Kozlov, A.I., *Polyarizatsiya rasseyannogo i sobstvennogo radioizlucheniya zemnykh pokrovov* (Polarization of Scattered and Intrinsic Radio Emission of the Earth's Surface), Leningrad: Gidrometeoizdat, 1981.
9. Yarlykov, M.S., *Statisticheskaya teoriya radionavigatsii* (Statistical Theory of Radio Navigation), Moscow: Radio i Svyaz', 1985.
10. Davydov, P.S., Kozlov, A.I., Uvarov, V.S., Lutin, E.A., and Gruzdev, B.G., *Radiolokatsionnye sistemy vozdushnykh sudov* (Aircraft Radar Systems), Moscow: Transport, 1988.

Translated by A. Seferov