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POLARIZATION DIRECTION FINDING AND CONCEALED BALLISTIC LAUNCH DETECTION

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The possibility of simultaneous solution of three interrelated inverse problems: polarization direction finding of a flying ballistic object, determination of its trajectory parameters, and simultaneous determination of the coordinates of launch and expected hit points of the object. Any radio source can be used for side illumination, including nearest transmitter of TV broadcasting center. The novelty of the proposed direction finding approach is the use of the so-called vector antenna intended for simultaneous measuring all three components of the electric field strength vector of the wave reflected from the object toward the receiving point. The properties of the elliptically polarized wave, in particular, that the plane of the radiation polarization ellipse is strictly orthogonal to the wave propagation direction, provide the basis for the proposed approach. Simultaneous application of two spatially separated direction finders allows the positioning problem to be solved. The solution of all three problems in automated mode enables to issue almost instantly a target designation to system of suppression of the detected firing position and thereby to protect the protected area from unauthorized shelling.

Keywords: vector antenna, direction finding, trajectory parameters, ballistic launching.

1. RELEVANCE

Nowadays there are a huge number of publications devoted to a description of methods of radio source positioning that demonstrate the relevance of the problem as a whole. As a rule, various methods of spatially separated radiation reception are proposed [1, 2]. Radio sources used for this purpose can be both transmitters and passive repeaters, for example, aircrafts, tanks, etc. In the present work, we propose to use an artillery projectile fast flying along a ballistic trajectory as a passive repeater, and an installation that has launched this projectile as objects to be positioned. This problem is solved based on polarization measurements of radar signals reflected from the projectile during its motion (Fig. 1). The application of polarization measurements for solving direction finding problems has already been proposed in [3–5]. However, the problem of polarization positioning of ballistic launching has been posed here for the first time.

2. INVERSE BALLISTIC PROBLEM

For ballistic motion of the projectile, its position in space is described by the uniformly accelerated motion equation known already since Newton's times:

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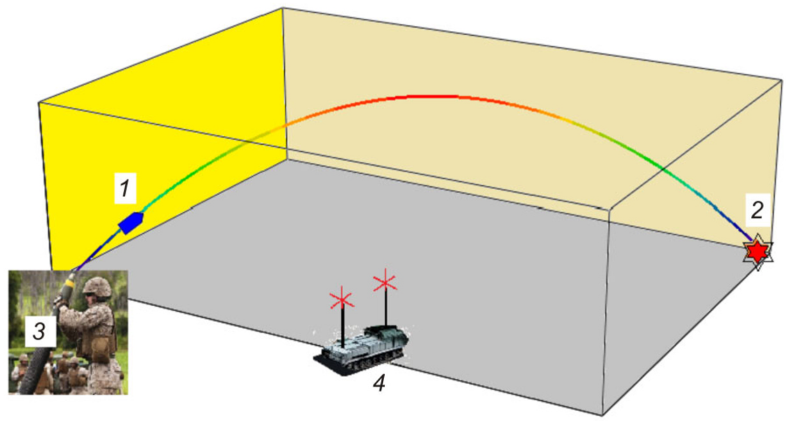

Fig. 1. Trajectory of ballistic projectile (*1*) launched from position (*3*) to hit point (*2*) tracked by polarization direction finder (*4*).

$$x(t) = x_0 + V_x t, \quad y(t) = y_0 + V_y t, \quad z(t) = V_z t + g \cdot t^2/2 .$$

Here (V_x, V_y, V_z) is the velocity vector of the projectile at initial time, g is the free fall acceleration, $(x_0, y_0, 0)$ is the position vector of the launching point to be determined (Fig. 1). These parameters fully describe the ballistic trajectory. The running coordinates of the projectile here are considered measured. For simplicity, we consider that the projectile is launched from the plane Earth surface.

The first inverse problem consists in the determination of the coordinates (x_0, y_0) given that the projectile position is well traced. Its solution is reduced to the determination of vector velocity components of the projectile by simple differentiation of the projectile coordinates (x, y, z) with respect to the current time t:

$$V_x = dx/dt = x'(t), \quad V_y = dy/dt = y'(t), \quad V_z + g\,t = dz/dt = z'(t) .$$

Here time t is counted from the projectile launching time. From here we obtain that the time t must satisfy to the equation

$$z(t) - z'(t)t = -g \cdot t^2/2 .$$

As a result, t is determined from the formula

$$t = \frac{\sqrt{z'(t)^2 + 2z(t)g} - z'(t)}{g} .$$

Then for the position of the ballistic launching point, we obtain

$$x_0 = x(t) - x'(t)t, \quad y_0 = y(t) - y'(t)t .$$

To determine the hit point coordinates (x_k, y_k), the initial vertical velocity component of the projectile

Fig. 2. Vector antenna.

$$\hat{V}_z = z'(t) + g\,t$$

should be estimated first, and then the expected total flight time

$$t_k = 2\hat{V}_z / g$$

should be found. The position of the hit point is

$$x_k = x_0 + x'(t)t_k, \quad y_k = y_0 + y'(t)t_k\,.$$

If the hit point falls within the protected area, then it is necessary first, to destroy the flying projectile and second, to hit the projectile launching point to prevent subsequent shots. In this way, the first inverse problem of positioning of the ballistic launching point and the related problems are solved. To solve them, it is sufficient to trace the spatial position of the projectile by the polarization method. Let us consider this method in more detail below.

3. POLARIZATION DIRECTION FINDING AND PROJECTILE POSITIONING

The second inverse problem to be solved is angular positioning of the projectile relative to the radar station. This problem is typically solved either by two-dimensional spatial separation of receiving antennas or by using large narrow beam antenna [1, 2]. They both create certain difficulties in providing stealth surveillance. The problem of developing of stealthy transmitting antenna is easily solved, for example, by spatial separation of the transmitting and receiving units of the radar complex.

In the present work, we propose to use a vector antenna for polarization rather than spatial signal separation to solve the problem of direction finding [6]. By the vector antenna we mean the combined antenna which performs directional reception of all three mutually orthogonal field components at one point. An example of such antenna combining three orthogonal linear vibrators is shown in Fig. 2. The output signal here is the three-dimensional complex vector of the electric field strength each component of which combines quadrature components $\boldsymbol{I}$ and $\boldsymbol{Q}$ received by vibrator shoulders:

$$\boldsymbol{E} = \boldsymbol{E}_0 \exp\{-i\omega t\}, \quad \boldsymbol{E}_0 = (\boldsymbol{I} + i\boldsymbol{Q})\,.$$

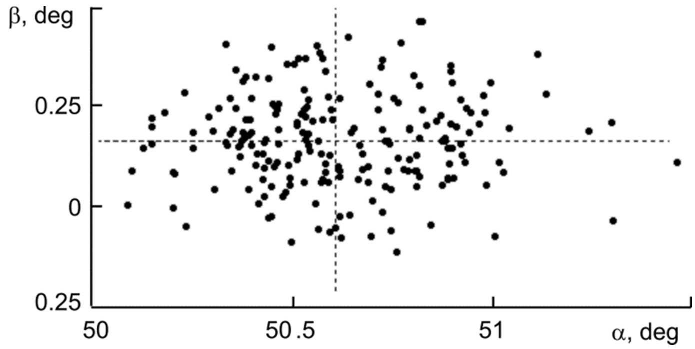

Fig. 3. Azimuthal and elevation angles toward the radiation source taking into account measurement noise.

This vector is a complex value for the elliptically polarized radar signal. This polarization state is most common of all polarization states. It is important that the polarization ellipse always lies in the plane orthogonal to the wave propagation direction [4]. In our case, this direction coincides with the direction toward the source of reflected radiation, that is, toward the projectile. In [6] it was shown that this direction is unambiguously determined by the vector product of the complex conjugate components of the electric field strength vector:

$$\boldsymbol{N} = i\boldsymbol{E}_0 \times \boldsymbol{E}_0^{*} .$$

Here the asterisk means complex conjugation. The unit normal vector is determined by the normalization condition

$$\boldsymbol{n} = \boldsymbol{N} / |\boldsymbol{N}| .$$

The unit real vector $\boldsymbol{n}$ defines the direction toward the projectile at each time. Results of our numerical experiments performed in [6] showed that the azimuthal (α) and elevation (β) angles toward the radiation source are concentrated around average values with an error that did not exceed ±0.5° with allowance for the noise level up to ~1% (Fig. 3). The method keeps working even for small ellipticity coefficients of received radiation down to ~0.01.

The third inverse problem of ballistic launching positioning consists in the determination of the vector of current projectile position. To solve this problem, at least two polarization direction finders spatially separated at a fixed distance $\boldsymbol{D}$ should be used (Fig. 4). With two vector antennas, the current position of the projectile at any measurement time can be determined by solving the equation

$$R_1 \boldsymbol{n}_1 + \boldsymbol{D} = R_2 \boldsymbol{n}_2 .$$

Here it is supposed that the vector $\boldsymbol{D}$ between the antennas has been known precisely, and subscripts 1 and 2 correspond to distances R_1 and R_2 from the two vector antennas to the projectile.

After the application of the vector product operation to the last equation

$$R_1 \boldsymbol{n}_1 \times \boldsymbol{n}_2 + \boldsymbol{D} \times \boldsymbol{n}_2 = 0 ,$$

the distance from the first direction finder to the projectile

$$R_1 = \frac{|\boldsymbol{D} \times \boldsymbol{n}_2|}{|\boldsymbol{n}_1 \times \boldsymbol{n}_2|}$$

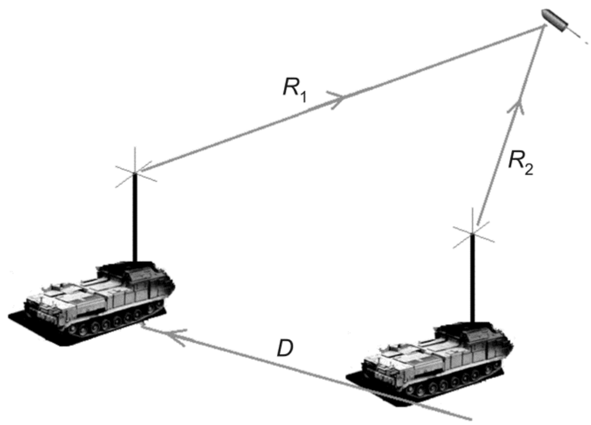

Fig. 4. Polarization determination of the current projectile position.

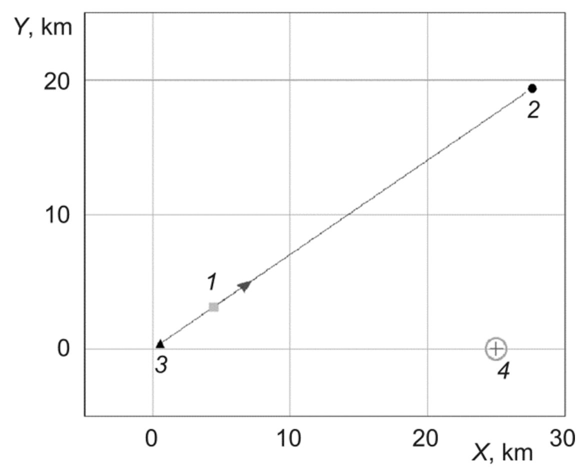

Fig. 5. Horizontal projection of the trajectory of projectile (*1*) onto hit point (*2*) for launching from (*3*) whose position is determined with the polarization direction finder located at point (*4*).

can be determined. Then the vector of the current position of the projectile is written as follows:

$$\boldsymbol{R}_1(t) = \boldsymbol{n}_1 R_1 = \boldsymbol{n}_1 \frac{|\boldsymbol{D} \times \boldsymbol{n}_2|}{|\boldsymbol{n}_1 \times \boldsymbol{n}_2|} = \{x(t),\ y(t), z(t)\}.$$

Imitational modeling completely confirmed the working capacity of the proposed method of solving the problem of positioning projectile (*1*), ballistic launching point (*3*), and hit point (*2*) from polarization measurements (Fig. 5). The initial projectile velocity was set equal to 1.8 km/s. The total flight time to the target was 4.3 min, and the time required for direction finding was 37.5 s for the projectile elevation angle above the horizon equal to 11.2°. The polarization direction finders were separated at the distance $D =$ 1.4 m. It appeared that in this case, the positioning error did not exceed 1 m, which is quite sufficient for suppression of the ballistic launching point.

CONCLUSIONS

In this work, the possibility has been demonstrated of simultaneous solution of three related inverse problems: polarization direction finding of a flying ballistic projectile, determination of the parameters of its trajectory, and calculation of the coordinates of points of expected hit and launching of the projectile. The novelty of the proposed approach to direction finding is the use of the so-called vector antenna that allows all components of the electric field strength vector of the wave reflected from the projectile to be measured simultaneously. It was assumed that this wave was elliptically polarized and that the radiation polarization ellipse is strictly orthogonal to the wave propagation direction. Simultaneous application of two spatially separated direction finders enables the problem of target (projectile) positioning to be solved unambiguously. The solution of all three above-formulated problems in the automated mode enables one to issue almost instantly a target designation to the system of suppression of the detected firing position and thereby to protect the protected area from unauthorized shelling.

It is important that the proposed system is passive and transmits no radiation that can unmask it. As a source of side illumination, any arbitrary radio source can be used, including that of regional TV broadcasting center. The considered approach is new and presumes to solve many problems of safety of people and territories during local wars or other critical situations [7–9].

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