MICROWAVE BEAM DIFFRACTION BY MOVING OBJECT IN BISTATIC RADAR APPLICATIONS

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ABSTRACT

The paper proposes a mathematical model describing signals in antenna output (signatures) in a bistatic microwave intrusion link. It shows that a signature is formed according to hologram record principle. The theory deploys Rayleigh's method to describe electromagnetic wave diffraction on the moving silhouette of an intruder in the scalar approximation. The model uses 2d Fourier transform and it is easy to calculate using fast Fourier transform algorithm. Theoretical results were compared with experimental signatures obtained with a 3-cm bistatic radar. They are in a good agreement.

INTRODUCTION

A bistatic radar is commonly used for site security monitoring along with the other types of security systems such as infrared and capacity sensors, Doppler radars, video cameras etc. It seems to us that this type of radar is of interest for it became an integral part of security systems. It has capabilities that cannot be archived by other security systems. For example, the bistatic radar can form an intrusion link with the length of 20-1500 m, operates at different weather conditions and is independent on daytime [1,2]. Normally the antennas of a bistatic radar have narrow directivity diagrams, are pointed to each other to form a detection area. An object crossing the detection area interferes with the electromagnetic field of the transponder and causes receiver antenna output to change in a certain way. As the object moves through the detection area a signature is formed in the receiving antenna output.

The objective of this article is to propose a mathematical model based on Rayleigh's technique that allows obtaining a signature if the behavior of an intruder is known in detection area. In particular the theory can describe signatures when an intruder stands still but waves his hands. In other words according to the model that follows any change in the intruder's silhouette shape or its position leads to a change in receiving antenna output. In the theory we assume that the antennas are pointed to each other, they have narrow directivity patterns, the characteristic size of an object in detection area is greater then a radar wavelength. On such assumptions, the diffraction theory is adopted to build the model [3].

BABINET'S PRINCIPLE IN RADIO HOLOGRAMM FORMATION

According to Kirchoff's formula, complex amplitude of diffraction field E_d at a given point $A(x,y,z)$ can be written as [4]

$$E_d(x,y,z) = \iint_{open} f(E_t(x_s, y', z'))dy'dz' , \tag{1}$$

where the integral is calculated in the silhouette plane over the area that is not closed by the silhouette as shown in Fig.1, E_t is the complex amplitude due to transmitting antenna in the silhouette plane, x_s gives the position of the silhouette plane.

In (1) the explicit view of function *f()* is not important to formulate Babinet's principle. Let us add to and subtract from the right side of (1) the integral over silhouette area of the same function *f()*. The sum of the first and the second integrals gives then the direct field of transmitting antenna as if the silhouette were absent. Combining this sum into one integral leads to

$$E_d(x,y,z)=\iint\limits_{total}*-\iint\limits_{sil}*=E_t(x_r,y,z)-E_s(x_r,y,z)\,. \tag{2}$$

In (2) E_t is the direct complex amplitude of transmitting antenna at the position of receiving antenna in the absence of the silhouette. The integral over silhouette aperture may be treated as silhouette pseudo emission which produces complex amplitude E_s.

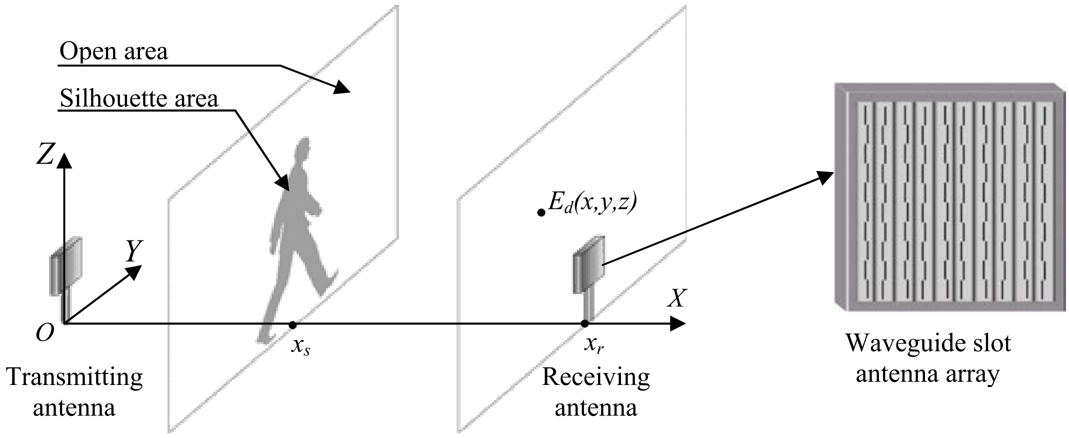

Fig.1. Disposition of transmitting and receiving antennas.

The complex amplitude at point A is formed according to the hologram formation principle. In (2) the first integral represents the illuminating wave and the second integral is the object wave with antiphase. Here we do not take the ground into account as only the silhouette penetrates into the most sensitive area, the first diffractive Fresnel's ellipsoid, and not the ground [5].

In the next section we obtain an expression that gives complex amplitudes E_t and E_s for antenna and silhouette emission accordingly by treating them as emitting apertures.

COMPLEX AMPLITUDE OF EMITTING APERTURE

In work [6] an expression was obtained for a circular emitting aperture that relates complex amplitude at a point at some distance with complex amplitude distribution in the emitting aperture plane in the narrow beam approximation. It is possible to obtain a common expression that relates the two-dimensional Fourier spectrum of complex amplitude distribution on an arbitrary aperture, of the size much greater than an emission wavelength, with the complex amplitude distribution on a parallel plane at a distance of x in the narrow beam approximation. Omitting bulky calculations that expression can be written as follows

$$E(x,y,z)=\frac{\exp\left[i\left(kx-\pi/2\right)\right]}{\lambda x}\exp\left[i\frac{\pi}{\lambda x}\left(y^2+z^2\right)\right]\hat{E}\left(k\frac{y}{x},k\frac{z}{x}\right). \tag{3}$$

In (3) coordinates x, y, z give the position of a point in the reference connected to the emitting aperture, λ is a wavelength, k is the corresponding wavenumber, $\hat{E}(u_1,u_2)$ is the two-dimensional Fourier transform of the complex amplitude distribution on the emitting aperture.

In the next section we consider waveguide slot antenna deployed in the radar to calculate corresponding complex amplitude using (3).

COMPLEX AMPLITUDE OF WAVEGUIDE SLOT ANTENNA

Fig.1 shows the transmitting and receiving antenna deployed by the radar. The antennas consist of 10 rectangular waveguides placed one after another forming an array. The waveguides are fed with H_{10} wave type with $\Lambda = 3$ cm of wavelength. Along the wide side each waveguide has 10 rectangular slots with the size of 1.5x15 mm. The centers of the slots placed at the distance of *Λ/2* from each other along the waveguide on both sides of the wide side middle line. The distribution of the slots is such that they are excited in-phase and the excitation amplitude is the same for each slot. We consider that the field distribution in a single slot is constant and equals to E_0. The precise knowledge of the distribution is not important as it is known that antenna field for an array in the far region depends mainly upon the array factor. For such an antenna under assumptions stated above the 2d Fourier spectrum is calculated analytically and can be expressed by the following formula

$$\hat{E}_t\left(u_1,u_2\right)=E_0 l_y l_z \frac{\sin\left(l_y u_1/2\right)}{l_y u_1/2}\frac{\sin\left(l_z u_2/2\right)}{l_z u_2/2}\sum_{j=0}^{N-1}\exp\left(-i\left(u_1 y_j+u_2 z_j\right)\right). \tag{4}$$

As soon as (4) is obtained we can use it in (3) to find the complex amplitude of the antenna at a given observation point.

DIFFRACTION ON MOVING OBJECT

Complex amplitude due to diffraction on a moving object may be considered as diffraction on a screen that repeats the shadow silhouette of the object [3]. For this purpose we use (3) to calculate both the transmitting antenna complex amplitude and the silhouette complex amplitude in the opening plane of receiving antenna. To obtain some value at the receiving antenna output corresponding to a given silhouette position we integrate complex amplitude over the receiving antenna opening. To obtain a signature, the receiving antenna output should be found for every position of the silhouette as it moves through the detection area and changes its shape.

Let *XYZ* be the reference frame connected with transmitting antenna (Fig. 1). Coordinates x_s, x_r define positions of the silhouette plane and the receiving antenna opening plane correspondingly. Let $T(x_s,y,z)$ be the silhouette mask function which equals to 1 if a point (x_s,y,z) falls into the silhouette and equals to 0 otherwise. The direct complex amplitude from the transmitting antenna in the receiving antenna opening plane $E_t(x_r,y,z)$ is obtained substituting (4) into (3) which gives

$$E_t\left(x_r,y,z\right)=\frac{\exp\left[i\left(kx_r-\pi/2\right)\right]}{\lambda x_r}\exp\left[i\frac{\pi}{\lambda x_r}\left(y^2+z^2\right)\right]\hat{E}_t\left(k\frac{y}{x_r},k\frac{z}{x_r}\right) \tag{5}$$

To obtain complex amplitude due to the silhouette aperture pseudo emission in the receiving antenna opening it is necessary to define complex amplitude distribution E_{ts} in the silhouette plane due to transmitting antenna. Using (5) with appropriate argument change we get

$$E_{ts}\left(x_s,y,z\right)=E_t\left(x_s,y,z\right)T\left(x_s,y,z\right) \tag{6}$$

Denoting by $\hat{E}_{ts}(x_s,u_1,u_2)$ the corresponding Fourier spectrum of (6) and substituting it into (3) with $\Delta x=x_r-x_s$ instead of x, we obtain complex amplitude due to the silhouette aperture pseudo emission at the position of receiving antenna

$$E_s\left(\Delta x,x_s,y,z\right)=\frac{\exp\left[i\left(k\Delta x-\pi/2\right)\right]}{\lambda\Delta x}\exp\left[i\frac{\pi}{\lambda\Delta x}\left(y^2+z^2\right)\right]\hat{E}_{ts}\left(x_s,k\frac{y}{\Delta x},k\frac{z}{\Delta x}\right). \tag{7}$$

The complex amplitude E_d due to diffraction in view of (2) is the difference between (5) and (7). Then the antenna output is the integral of E_d over the receiving antenna opening (Fig. 1). The signature is the antenna output for every function *T()* in (6) which varies as the silhouette moves through detection area and changes its shape.

Simulated signatures were obtained on the basis of (2), (5), and (7) and compared with experimental data obtained during the experiment. Fig.2 reflects corresponding data. The distance between antennas was 200 m and the man was crossing the link in the middle moving in perpendicular direction. The antennas were 1.3 m above the ground. The left graph in Fig.2 presents the signatures for a man walking straight. The right graph in Fig.2 has the signatures for a crawling man. As it is seen in Fig.2 the experimental and simulated curves are in a good agreement. As the experiments were made without registering precise behavior of an intruder in detection area, it was not possible to reconstruct precisely silhouette motion and shape variations. This allows for the observed divergence between signatures in Fig.2.

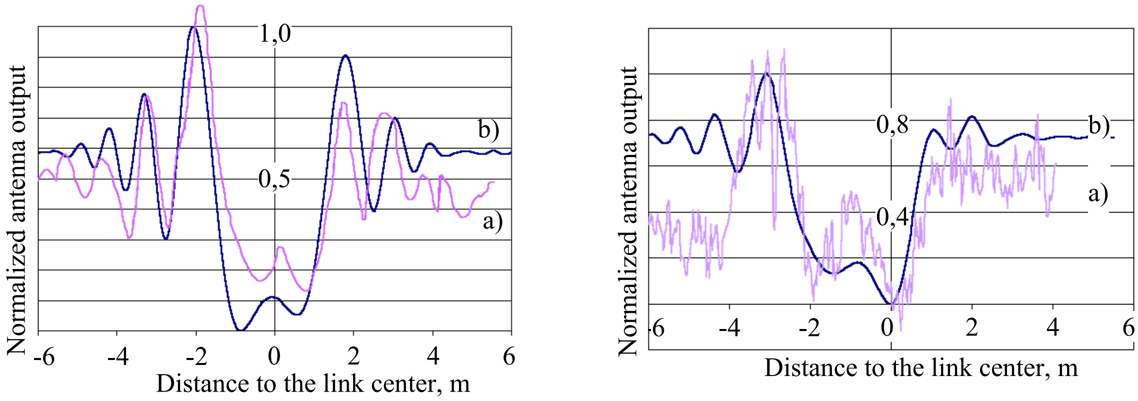

Fig.2. Experimental and simulated signatures obtained when a man was crossing detection area walking straight (left) and crawling (right); a) – experimental, b) – simulated signatures.

CONCLUSION

The article proposes a mathematical model for the description of signatures observed at the antenna output in a bistatic microwave intrusion link. The problem is considered as diffraction on the silhouette of a moving object and based on Rayleigh's technique. Complex amplitude at a receiving antenna opening is described as a radiohologramm i.e. the diffraction field is the sum of the direct complex amplitude of the transmitting antenna and the complex amplitude of silhouette pseudo emission with phase inversion. The simulations on a moving object in the detection area were done on the basis of developed algorithms. Experimental signatures proved to be in a good agreement with simulated ones.

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