EFFECTS OF SYSTEM PARAMETER VARIATIONS ON MICROWAVE INTRUSION DETECTOR PERFORMANCE

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Abstract

A mathematical model of a microwave fence used for intrusion detection is described. The model includes the effects of ground reflections by employing images of the antennas and of the target. The bistatic radar cross-section of opaque targets is employed with an appropriate directional gain function for bistatic angles near 180°. A comparison of analytical and experimental results is presented for a system operating at 37 GHz.

Introduction

A widely used method of intrusion detection is the so-called microwave fence in which a transmitter and receiver are mounted on posts separated by tens to hundreds of meters. For given transmitted power and antenna gains a certain quiescent signal level is obtained at the receiver. When an object enters the zone between the antennas, a change in received signal level occurs and is used to detect the occurrence of an intrusion. On the surface, the concept is simple and straightforward. However, in practice there are a number of frequently overlooked factors that enter into the actual system operation to considerably complicate the problem. The single most important factor is the presence of a highly reflective ground plane that occurs because of the very shallow grazing angles of the radiation in this type of system configuration. This means that there are two low attenuation paths for the radiation: directly from the transmitter to the receiver; an via an indirect path involving a ground plane reflection. The net signal at the receiver is the phasor sum of the direct and reflected signals including the effects of amplitude and phase variations resulting from path length differences, antenna directivity, antenna phase shifts across the beam pattern, and the ground reflection coefficient. Raising and lowering the antennas change several of these parameters but has a very marked effect on path length difference and can be readily used to produce constructive or destructive interference of the received signal. In a similar manner when an object or target is placed between the two antennas, its effect must be determined by taking into account direct and reflected signals incident upon it and reradiated by it. Thus, the problem becomes quite complex in the sense of having many parameters that change rapidly as the object is moved about in the detection zone.

In the following sections, a model is described to take into account many of the parameters and to permit computation of system performance for various target positions. Computations are carried out for a system operating at K_a band for targets of known radar scattering characteristics. These results are then compared with those obtained with an experimental system using actual targets.

System Model

Figure 1 shows the rays for the direct and ground reflected paths of the radiation from the transmitter to the receiver. The signals corresponding to the various rays in Figure 1 must be calculated taking into account the antenna gain in the various directions, the directional scattering characteristics of the target, the ground reflection coefficient and other system parameters.

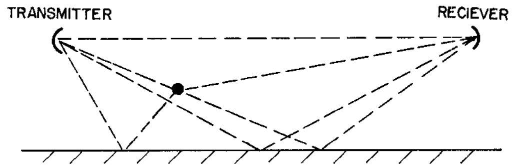

Figure 1. Signal Model Including Ground Reflections

For the bistatic radar configuration of Figure 1, special consideration must be given to the target scattering characteristics. In the model the target scattering cross-section was assumed constant and equal to the radar cross-section, σ, at all bistatic angles except near 180°. In the vicinity of 180° the scattering was assumed to behave like the radiation from a uniformly illuminated aperture having a cross-sectional area of σ and a phase of illumination opposite that of the incident radiation. Such a scatter would have a maximum radar cross-section at 180° of

$$\sigma_{max} = \frac{4\pi\sigma^2}{\lambda^2} \qquad (1)$$

and would fall off in a manner consistant with that of a uniformly illuminated aperture having a half power beamwidth of

$$\beta = 44.7 \frac{\lambda}{\sqrt{\sigma}} \text{ degrees}$$

The angular dependence of the target radar cross-section is then

$$\sigma_r = \frac{4\pi\sigma^2}{\lambda^2} \frac{\sin^2(2.783\theta/\beta)}{(2.783\theta/\beta)^2}$$

where θ is measured from the direction of propagation of the incident radiation. Equation (3) is used throughout the range of θ within the main lobe for which $\sigma_r > \sigma$. For all angles greater than this, it is assumed that $\sigma_r = \sigma$. This scattering model is in general accord with theoretical and experimental studies that have been reported in the literature [1,2]. The reradiated electric field in the vicinity of the 180° bistatic angle is proportional to the square root of the incident power, and it is this quantity with a 180° phase angle that must be added to the unscattered (quiescent) electric field to obtain the total field which is then converted to power by squaring.

Quiescent Signal Level

For purposes of computation it is convenient to break the problem into two parts: calculation of the (no target) quiescent signal; and calculation of the

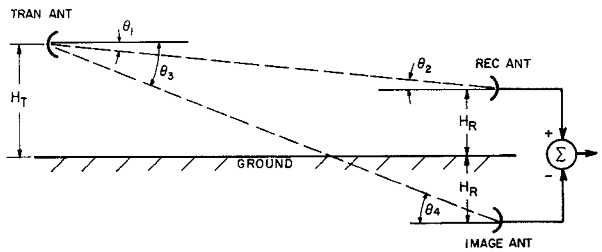

Figure 2. Quiescent Signal Level Calculation

target scattered signal. Figure 2 shows the model used for ambient signal calculation. For this case the net received power is given by

$$P_o = \frac{P_T G_1 G_2 \lambda^2}{(4\pi)^2} \left| \frac{g(\theta_1) g(\theta_2)}{R_1} e^{\frac{-1j2\pi R_1}{\lambda}} + \frac{\sqrt{\Gamma}\, g(\theta_3) g(\theta_4)}{R_2} e^{\frac{-j2\pi R_2}{\lambda} - j\theta_\Lambda} \right|^2 \qquad (4)$$

where

P_o = ambient power level (w)
P_T = transmitted power (w)
G_1 = power gain of transmitting antenna
G = power gain of receiving antenna
λ = wavelength (m)
$g_1(\theta)$ = (voltage) pattern function of transmitting antenna in elevation
$g_2(\theta)$ = (voltage) pattern function of receiving antenna in elevation
R_1 = direct path length from transmitting antenna to receiving antenna
R_2 = reflected path length from transmitting antenna to receiving antenna. This is also the distance from the transmitting antenna to the receiving antenna image.
Γ - power reflection coefficient of the ground
θ_Γ = phase angle of (voltage) reflection coefficient of ground

Considerable simplification of this expression is possible for engineering calculations. In all cases of interest in this study the transmitting and receiving antennas are identical so $G_1=G_2$ and $g_1(\theta) = g_2(\theta) = g(\theta)$. The difference between R_1 and R_2 is on the order of one wavelength out of many thousand so that these quantities in the denominator can be equated and taken outside the brackets. When the antennas are maintained with the boresight horizontal $\theta_1=\theta_2$, $\theta_3=\theta_4$ and the path length difference is given by

$$\Delta R = R_2 - R_1 \approx \frac{2H_T H_R}{R} \qquad (5)$$

where H_T and H_R are the heights of the transmitting and receiving antennas, respectively. With these simplifications the received quiescent power is given by

$$P_o = \frac{P_T G^2 \lambda^2}{(4\pi R)^2} \left[g^4(\theta_1) + g^4(\theta_3) + 2\Gamma g^2(\theta_1) g^2(\theta_3) \cos\left(\frac{4\pi H_T H_R}{\lambda R} + \theta_\lambda \right) \right] \qquad (6)$$

For purposes of calculation, the antenna pattern will be approximated as that of a paraboloid of revolution with tapered illumination giving a sidelobe level of -24 dB. The antenna (voltage) pattern function is given by:

$$g(\theta) = \frac{\cos(1.2\pi \frac{\theta}{\beta})}{1-(2.4\frac{\theta}{\beta})^2} \qquad (7)$$

This antenna pattern falls to 0.7 at $\theta=\beta/2$ and has its first null at $\theta=1.25\beta$.

Signal Due to Target

When a target enters the space between the antennas, it interferes with the signals traveling from the transmitting to the receiving antenna. The interference can occur with the direct signal, the reflected signal, or both. The signal corresponding to the target is taken to be the difference between the received power when the target is absent and the received power when the target is present.

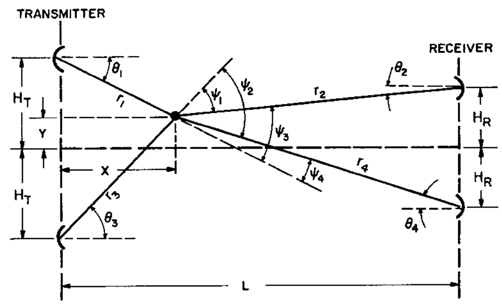

Figure 3. Target Signal Calculation

Figure 3 shows the geometry for calculation of the target signal when image antennas are used. The power from the image transmitting antenna is assumed to be equal to that of the real transmitting antenna multiplied by the power reflection coefficient of the ground, and to have a phase shift relative to the real transmitted signal equal to the phase angle of the (voltage) reflection coefficient which is usually near 180° for the low angles of incidence encountered here. The real and image transmitted signals each produce a scattered signal from the target which in turn produces signals at the real and image receiving antennas.

The net signal at the receiver is the phasor sum of the ambient signal and the target scattered signals. The equations for the target signal are derived in exactly the same way as for the ambient signal, except that the angular scattering pattern of the target given by (3) must be taken into account. For purposes of evaluating system performance, the important quantity is the change in received power that occurs when a target enters the inter-antenna space. This quantity is obtained by subtracting the received power when the target is present from the received power when the target is not present. This change in power level is what causes the change in detector output that permits detection of the presence of a target. If the ambient (no target) signal has a power of P_A and a phase angle of θ_A, and the net signal scattered from the target has a power of P_T and a phase angle of θ_T, then the change in power occurring when the target is present is given by

$$\Delta P = P_A - \left| \sqrt{P_A} e^{j\theta_A} + \sqrt{P_T} e^{j\theta_T} \right|^2 \qquad (8)$$

This is the quantity that would be measured if the system detector was a power detector. If the system detector is a voltage detector, the change in output power would be given by

$$\Delta P_{\nu} = \left| \sqrt{P_A} - \left| \sqrt{P_A} e^{j\theta_A} + \sqrt{P_T} e^{j\theta_T} \right| \right|^2 \qquad (9)$$

Computed and Measured Results

Because of the presence of the reflecting ground plane, the antenna lobe structure contains grating lobes; and as the antenna heights are varied, the quiescent signal fluctuates through maxima and minima. Typical variations in the quiescent signal are shown in Figure 4. The largest change in output power

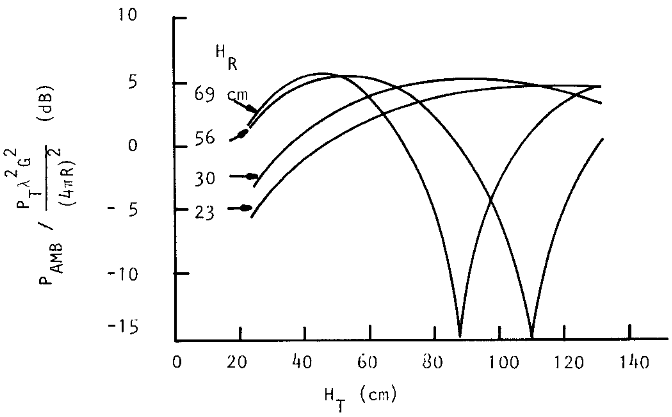

Figure 4. Calculated Quiescent Signal

resulting from an incremental change in received field strength due to a target occurs when the antennas are at heights corresponding to a maximum. Therefore, if receiver noise or instability is significant, it is desirable to operate at or near a maximum.

In general, the most difficult targets to detect are those at ground level. Accordingly, a primary design objective is to configure the system so that returns from such targets exceed the detection threshold throughout the detection zone. Measured and computed signal levels for an experimental system are shown in Figure 5. The experimental system operated at 37 GHz with a power of 30 mW and employed parabolic antennas with 2° beamwidths. For the results shown, the system was operating over an asphalt test surface with an antenna spacing of 150 m and antenna heights of 30.5 cm and 65.6 cm for the transmitter and receiver, respectively. These antenna heights correspond to a maximum of the quiescent signal. The targets employed were metal spheres with diameters of 25.4 cm and 35.6 cm. The tests were repeated using wooden spheres of the same diameter and gave results that were virtually identical. The computed signal levels are also shown in Figure 5 and indicate generally good agreement with the measured values.

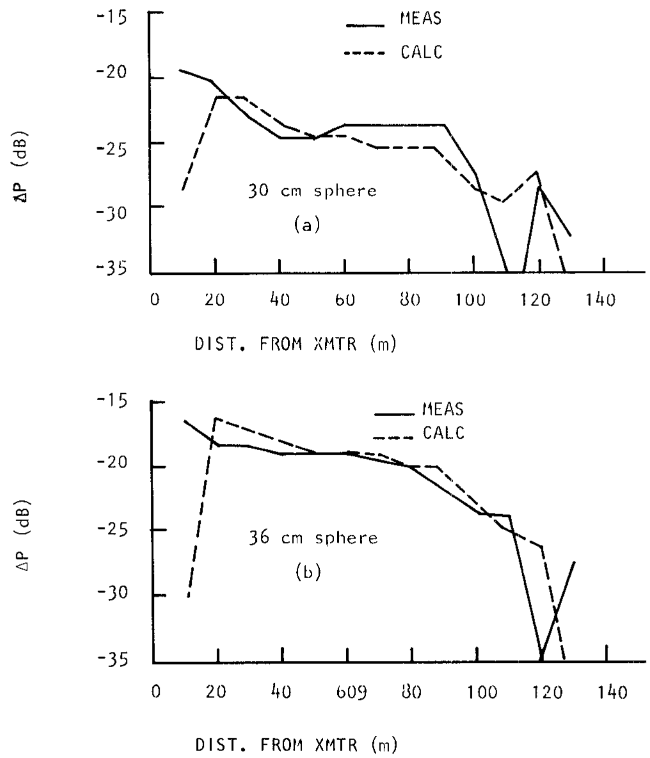

Figure 5. Measured and Calculated Target Signal

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2. Caspers, J. W., "Bistatic and Multistatic Radar," Radar Handbook (Ed. M. Skolnik), McGraw-Hill Book Co., Inc., NY, 1970, pp. 36-13,14.