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# **Research on RCS Simulation Characteristics of Fixed Low-Grazing-Angle FOD Radar**

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Abstract. Fixed low-grazing-angel foreign object debris (FOD) radar, which is erected at a designated height beside the airport and scans the runway at a low-grazing angle, is used to detect foreign object debris on airport runways. In operation, it is found that the power of reflected electromagnetic wave decreases significantly when the radar is erected at some height, as a result of which the radar detection rate reduces. In this paper, the electromagnetic reflection and polarization modes of fixed low-grazing-angle radar are analyzed based on some concepts of refraction characteristics of electromagnetic wave, such as Fresnel's Law and Brewster's Angle. Then the paper explains the theoretical reasons for this problem. Meanwhile, the GO & MLFMM algorithm is used to simulate the relationship between radar height and radar reflected power, and finally the theoretical results are verified.

Keywords: Low-grazing-angle FOD radar, Fresnel's Law, Brewster's Angle, GO& MLFMM.

#### 1. Introduction

Foreign Object Debris (FOD) detection radar, currently used for FOD detection of civil airport runway, mainly adopts fixed low-grazing-angle scanning mode, which means that the FOD monitoring radar is fixed beside the airport runway according to the safety regulations of civil aviation airport and monitors FOD on the airport runway by scanning a certain range of the airport runway at a low-grazing angle.

At present, the domestic and foreign mainstream fixed FOD detection radars include FODFinder vehicle-mounted radar system in the USA, Tarsier Radar in the UK, FODetect Radar in Israel [1], i04 Radar of Sine Technology in China, etc. It can be seen that all the FOD radars are fixed at low-grazing angle, except for FODFinder system in the form of vehicle-mounted mobile scanning [2].

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FOD Radar	FODFinder	FODetect	Tarsier Radar	i04 Radar
Nation	USA	Israel	UK	China
Radar Equipment	MW Radar	MW Radar	MW Radar	MW Radar
Detection	Radar scanning	Radar scanning	Radar scanning	Radar scanning
Location	Vehicle	Runway edge light	Pylon	Pylon
Frequency	78~81GHz	77GHz	94.5GHz	94.5 GHz

Table 1. Parameters of FOD detection radars in domestic and foreign Airports

# 2. Theoretical Background

#### 2.1. Fixed FOD radar erection beside the airport runway

In this paper, the FOD monitoring radar is fixed on one side of the runway, and it is erected at a height of 3 to 10 meters according to the airport safety requirements. It works with servo motor to scan the runway back and forth uninterruptedly by transmitting circularly polarized millimeter waves from Variant Card Transceiver Antenna. Four to six radars can cover the whole runway.



Fig.1 Scheme of FOD monitoring radar erection and airport scanning

In the actual operation test, it is found that the electromagnetic echo power received by the radar will be greatly weakened due to the influence of the ground reflection and its own polarization mode, and even zero power reflection reception will occur in some receiving directions. The reasons for the weakening will be analyzed in theory below.

#### 2.2. Analysis of low-grazing-angle electromagnetic incidence of fixed FOD radar

Since the FOD radar uses millimeter wave, the fixed radar erection position is 165 feet (50 meters) from the runway centerline according to *FAA Advisory Circular* AC150/5220-24. Generally, the size of FOD is 1 inch  $\times$  1 inch (3.0cm  $\times$  3.0m), and thus the ratio of transmission distance to the size of FOD is much more than 10. Therefore, the electromagnetic wave can be approximately considered as far-field incidence of plane TEM wave. The electromagnetic wave equation is

$$\varepsilon(z,t) = Esin(\omega t - kz) = \vec{E}_H + \vec{E}_V \tag{1}$$

In this expression, z-axis is the propagation direction of electromagnetic field, z-value is the propagation distance,  $\omega$  is the angular velocity of electromagnetic field. The fixed FOD radar antennas are circular polarized, and the incident electromagnetic wave is left-circularly polarized  $\theta > 0$ . In the plane perpendicular to the transmission direction, the electric field vector can be regarded as linear superposition of two orthogonal electromagnetic vectors, one in the parallel polarization direction (in

the xoy plane) and the other in the vertical polarization direction (perpendicular to the xoy plane). The incidence is shown in the figure below:



**Fig.2** Schematic diagram of electromagnetic reflection on the airport runway According to the reflection law and the Snell's law of retraction:

$$\theta_i = \theta_r \tag{2}$$

$$k_1 \sin \theta_i = k_2 \sin \theta_t \tag{3}$$

Where  $k_1$  and  $k_2$  are the regional wave numbers of atmosphere and airport concrete, respectively. From the reflection coefficient of electromagnetic wave on the interface of two different materials:

$$\Gamma = \frac{\eta 2 \cos \theta t - \eta 1 \cos \theta i}{\eta 2 \cos \theta t + \eta 1 \cos \theta i}$$
(4)

Where  $\eta_1$  and  $\eta_2$  are the wave impedances of air and runway concrete, respectively.

There is a special angle of incidence for horizontal polarization, called the Brewster's Angle, which makes the molecule of the formula above 0.

$$\eta_2 \cos\theta_t - \eta_1 \cos\theta_i = 0 \Rightarrow \theta_b = \arcsin(\frac{1}{\sqrt{1 + \frac{\varepsilon_1}{\varepsilon_2}}})$$
(5)

Where  $\varepsilon_1$  and  $\varepsilon_2$  are the dielectric constants of the two media, respectively.

It can be seen from the above that when the electro-magnetic wave is incident into the boundary of two media at Brewster's angle, there is no reflected wave and the electro-magnetic wave nearly propagates along the boundary of the two media.

In this paper, the wave from the FOD radar is incident into the surface of the airport runway. Under this circum-stance, the medium above the runway is atmosphere, and the runway is made of concrete.

 $\varepsilon_1$ , the dielectric constant of air, equals to 1 for the electromagnetic incidence in the airport runway environment of dry air.  $\varepsilon_2$ , the dielectric constant of airport runway, equals to 6.4 for dense and complete concrete.

So, it can be calculated by the above formula:

$$\theta_b \approx 84^\circ$$
 (6)

The height of the radar is

$$H = L_{max} \tan (90^{\circ} - \theta) \approx 50m \times 0.1051 = 5.255m$$
 (7)

That is to say, when the low-grazing-angle FOD radar is erected at the height of 5.255 meters, a Brewster's angle is formed between the radar incident wave and the surface of the airport runway. As a result, the reflected power of the incident horizontal component equals to zero, and the re-flected power of the radar is greatly reduced.

#### 3. Verification and analysis by electromagnetic simulation

#### 3.1. GO & MLFMM simulation algorithm

At present, the methods to solve the electromagnetic scattering of targets generally include analytical, numerical and high-frequency methods.

The analytical method is to solve the classical Maxwell equations strictly by analyzing the boundary conditions of the actual electromagnetic scattering problems, which is seldom used in engineering due to its huge amount of calculation. The numerical method is applicable to the calculation of the internal electromagnetic conduction of small-scale electrical targets, with a large amount of calculation as well and high requirement of simulation computer [3]. The high-frequency method includes the methods of Geometrical Optics (GO) [4], Physical Optics (PO), Uniform Theory of Diffraction (UTD), and the method of the Geometrical Theory of Diffraction which optimizes the target boundary and the diffraction of the illuminated shadow area, etc. The high-frequency algorithm is mainly applicable to large-scale targets, ignoring the electromagnetic mutual coupling between different parts of the target, and calculating approximately based on the Locality Theory of scattering field.

In this paper, the Radar Cross Section (RCS) of the FOD detection radar is composed of multiple components, which is mainly composed of the electromagnetic scattering of the FOD itself, the secondary scattering of the reflected incident wave from the airport runway to the target, and the composite scattering between the target and the airport runway. The scattering characteristics of the FOD target, which is an electrically large object compared with the radar source with ka  $\approx 62.8$ , can be calculated accurately using Muti-Level Fast Multipole Method (MLFMM) algorithm. Since the surface of the airport runway is approximately smooth plane, the geometric optics (GO) method is suitable here to reduce simulation time and ensure the simulation accuracy. In this paper, FEKO software (GO& MLFMM) algorithm is used to mix the above two algorithms together in the same model [5]. In this way, the electromagnetic characteristics of the FOD target in the background of the airport runway can be accurately simulated, and the time to simulate on the computer can be reduced..

## *3.2. Low-grazing electromagnetic simulation modeling of fixed FOD radar*

In order to accurately simulate the low-grazing incidence of the fixed radar, first, we constructed a 3D model of variant card antenna by using FEKO to model a horn feed and reflector.



Fig.3 FEKO simulation model of variant card antenna

After loading the 94.5GHz electromagnetic source into the horn feed, we obtained the antenna radiation pattern through simulation.



Fig.4 Radiation pattern of variant card antenna

Then we modeled the runway background and FOD. We used Green's Function to build an infinite layered interface to simulate the airport runway, the upper half is air, and the lower half is concrete. We put a cylinder with r = 15mm and h = 30mm on the infinite interface as the model of FOD. We used the simulated antenna as the radar source, and simulated the radiation to the airport runway at a low-grazingangle of 6 ° by using GO & MLFMM algorithm. The simulated three-dimensional electromagnetic scattering field is shown in the figure below:



Fig.5 3D electromagnetic scattering field of airport runway

# 3.3. Analysis of simulation results

We took 6 ° as the low-grazing angle, and separately took 10m, 8m and 5.2m as the height of the feed from the infinite interface, to simulate the electromagnetic radiation field. The simulation results took the horizontal plane at phi =  $6^{\circ}$ , and took theta =  $0^{\circ}$  as the radiation direction of the feed. The simulation range covers  $-90^{\circ}$  to  $90^{\circ}$ . The simulation results of the electromagnetic radiation field are as follows:



**Fig.6** Directional gain curve of electromagnetic reflection field (Phi= $6^{\circ}$ , -90°  $\leq$ Theta $\leq$ 90°)

In the figure, the feed heights of the blue, green and red curves are 10m, 8m and 5.2m respectively. When the feed height is 5.2m (the red line), in the direction of theta =  $0^\circ$ , we can see a significant drop along the directional gain curve.

# 4. Conclusion

Based on the on-site engineering data, in this paper we put forward that the reflection intensity of lowgrazing incident electromagnetic wave of fixed FOD radar is greatly affected by the erection height. Then we used Snell 'law to analyzed the Brewster's angle caused when the wave is incident to the airport runway at a low-grazing angle. Finally, we used FEKO to simulate the model of the low-grazing incidence of actual radar emitter by building an infinite interface between concrete and atmosphere, and GO & MLFMM algorithm was used for simulation. The simulation data show when the radar radiation source is incident at a height of 5.2m, the electromagnetic reflection gain of the whole radar decreases significantly, thus verifying the corollary that the electromagnetic reflection gain of the fixed lowgrazing-angle FOD radar is affected.

In order to avoid this kind of circumstance in engineering practice, we can start from two aspects. One is to modify the plan of radar incident wave to reduce horizontal polarization component as much as possible, which is nevertheless a high-cost and difficult solution because the radar antenna and signal source must be changed. The other solution is to erect the radar at a height to avoid Brewster's angle. This solution, which is low-cost and highly feasible, is generally used in airports..

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