Chapter 13
Modeling of Foreign Objects Debris Detection Radar on Airport Runway

Dandan Ao, Xuegang Wang and Hong Wang

Abstract Based on the fixed environment of airport runway where foreign objects debris detection radar on airport runway works on, geometric model is established by using method of coordinate system transformation. Meanwhile, approximation of model parameters is used in order to simplify the calculation. This paper analyses echo signal to establish the model of corresponding target signal and uses statistical model to produce clutter. As the main source of clutter is from meadow and runway, the backscatter coefficient of the composite scene is calculated combine with geometric model. Clutter of random sequences and echo is simulated based on MATLAB and the result is given.

Keywords Foreign objects debris (FOD) detection · Millimeter-wave radar · Geometric model · Echo signal

13.1 Introduction

Airport runways foreign object debris (FOD, Foreign Object Debris abbreviation) mean foreign objects that don't belong to airport but may appear in the operation of the airport area and cause loss or harm to the aircraft [1]. Harm brought by FOD not only damage aircraft and take away precious lives, but also accompanied by economic losses. Currently most airports use the approach of artificial visited regularly, which not only time-consuming taking up valuable time of runway use

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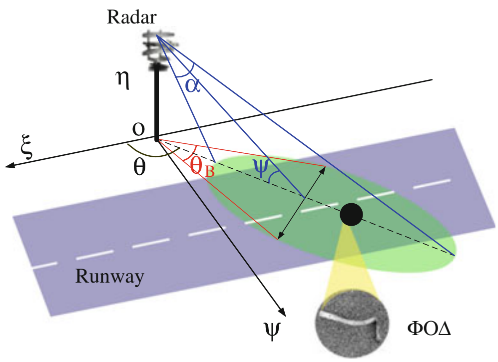

Fig. 13.1 FOD radar geometry relationship diagram

and led to security risks subject to weather and other factors. Therefore, effective and reliable monitoring of FOD is a problem need to be solved urgently.

Since the Concorde Tragedy in 2000, many countries have started to develop FOD detection system. View from several reported FOD monitoring system [2–4], radar monitoring systems for FOD mainly use millimeter-wave radar and commonly use frequency modulated continuous wave (FMCW) radar system.

FOD radar in this paper is fixed radar to scan the land and land clutter is the main factor to affect its detection performance [5]. Therefore, the radar clutter model plays an important role in assessment of FOD radar work performance.

This paper discusses FOD detection radar model. According to the specific work environment of radar, geometric model is established by using coordinate system transformation method. Then echo signal model is discussed, including target echo, clutter and noise, while clutter is focus. The backscatter coefficient of the composite scene is calculated combining with geometric model according to grass-runway composite scene. The paper uses statistical model to produce clutter and discuss its probability density function and power spectral density function.

13.2 Geometric Model

FOD detection radar is land search radar working in airport runway. Its geometric relationship is shown in Fig. 13.1. Taking the shadow of radar on the ground, O, as the origin, the coordinate system is established as shown. In Fig. 13.1, green oval area is land area of radar beam irradiation, h is the height of radar, θ_B is radar beam azimuth width, α is the width of radar beam tilt, Ψ is grazing angle, θ is antenna scan angle. Figure 13.2 is a ground top view. The oval area is formed by two semi-elliptical that have same elliptic short half shaft and different elliptic semi-major axis.

The installation mode of radar is to install several radar sensors along runway. The installation position depends on the advisory bulletin released by the FAA AC 150/5220-24: Sensors are located 50.0 m or more from the runway center line [6].

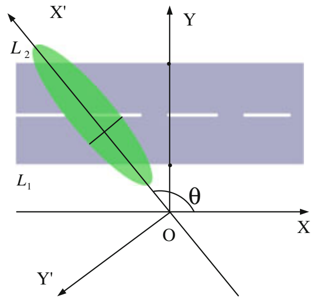

Fig. 13.2 Ground top view

As radar is mounted height limited, thus glancing angle Ψ is very small, such as $\Psi = 2.29°$ when radar is located 50 m from the runway in height of 2 m. Radar only rotated in the horizontal orientation and does not move in the pitch orientation, which means that h, θ_B, α, Ψ would not change, only the antenna scan angle θ varies with time. Therefore, the land area of the radar beam irradiation is fixed.

Coordinate transformation can be used to obtain the elliptic equation and its parameters easily. As shown in Fig. 13.2, when coordinates transformed from XOY into X′OY′, origin is unchanged and the straight line connecting the beam center with the origin O will be regarded as the X axis, corresponding to the rotate the XOY coordinate system counterclockwise by angle of θ to obtain X′OY′ coordinates. First directly obtain the equation of the ellipse in coordinates X′OY′, as following

$$\begin{cases} (x' - x_0)^2/a_1^2 + y'^2/b^2 = 1, \ x' \le h/\tan\psi \\ (x' - x_0)^2/a_2^2 + y'^2/b^2 = 1, \ x' > h/\tan\psi \end{cases} \tag{13.1}$$

Where $a_1 = h/\tan\psi - h/\tan(\psi + \alpha/2)$, $a_2 = h/\tan(\psi - \alpha/2) - h/\tan\psi$, $b = h\tan(\theta_B/2)/\sin\psi$, $x_0 = h/\tan\psi$ are obtained from geometric relationship.

As radar is installed with height limited and near the runway, α and Ψ would be very small. Thus a_1, a_2, b, x_0, all can be $x_0 = h/\psi$ $a_1 = h/\psi - h/(\psi + \alpha/2)$, $a_1 = h/(\psi - \alpha/2) - h/\psi$,, $b = h\tan(\theta_B/2)/\psi$, here α and Ψ use radians unit. As θ_B takes 5° and α takes 3°, parameters error analysis is shown in Fig. 13.1. It can be seen that approximation of parameters is practicable (Fig. 13.3).

Thus, coordinates X′OY′ can be directly converted to the coordinate system XOY. Coordinate transformation is shown in Fig. 13.2. Transformation formula is

$$\begin{cases} x' = x\cos\theta + y\sin\theta \\ y' = y\cos\theta - x\sin\theta \end{cases} \tag{13.2}$$

Formula (13.2) and the parameters are substituted into the formula (13.1) to obtain elliptic equations in the XOY coordinates, as shown in formula (13.3).

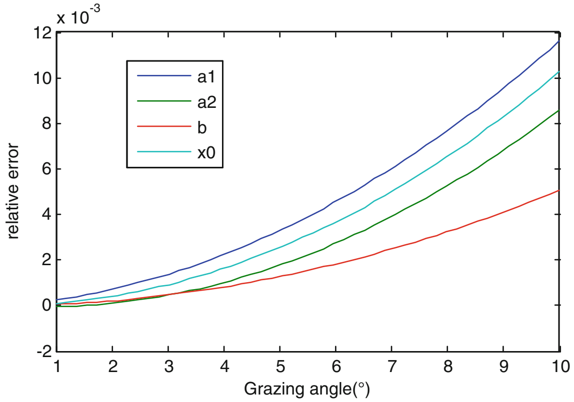

Fig. 13.3 Parameters error analysis

$$\begin{cases} x\cos\theta + y\sin\theta \leq h/\psi, \dfrac{(x\cos\theta + y\sin\theta - h/\psi)^2}{[h/\psi - h/(\psi+\alpha/2)]^2} + \dfrac{(y\cos\theta - x\sin\theta)^2}{(h\tan(\theta_B/2)/\psi)^2} = 1 \\ x\cos\theta + y\sin\theta > h/\psi, \dfrac{(x\cos\theta + y\sin\theta - h/\psi)^2}{[h/(\psi-\alpha/2) - h/\psi]^2} + \dfrac{(y\cos\theta - x\sin\theta)^2}{(h\tan(\theta_B/2)/\psi)^2} = 1 \end{cases} \tag{13.3}$$

13.3 Echo Signal Model

The echo signal received by radar includes target echo signal, clutter and noise. Assuming target as point target, noise as an additive white Gaussian noise, then the land clutter echo signal is the focus. Set $S_R(t)$ as the echo signal, then

$$S_R(t) = S_{RV}(t) + S_{RC}(t) + n(t) \tag{13.4}$$

Here $S_{RV}(t)$ is target echo signal, $S_{RC}(t)$ is clutter, n(t) is noise.

13.3.1 Echo Model

LFMCW radar transmit signal in the *n*th cycle can be presented as

$$S_T(t) = A\cos[2\pi(f_0 t + \mu t^2/2) + \Phi_0], 0 < t < T \tag{13.5}$$

Where A, Φ_0 are respectively the amplitude random phase of the transmission signal, f_0 is carrier frequency, $\mu = B/T$ is frequency modulation slope, B is signal bandwidth, T is scanning cycle.

In detection of FOD, FOD mainly refer to stationary object. Here assuming that target is point target, target echo signal that has distant R from radar is as follows.

$$S_{RV}(t) = KA\cos[2\pi(f_0(t-\tau) + \mu(t-\tau)^2/2) + \Phi_0 + \theta_0] \tag{13.6}$$

Where K is target reflection coefficient, $C = 3 \times 10^8$ m/s is speed of light, $\tau = 2R/C$ is target echo delay, θ_0 is the additional phase shift caused by the object reflector.

Take transmitter signal with the received signal to do mixing, and through low-pass filtering can obtain beat signal, as shown in formula (13.7).

$$S_{IF}(t) = 0.5KA^2\cos[2\pi(f_0\tau + t\mu\tau - \mu\tau^2/2) + \theta_0] \tag{13.7}$$

Thus beat signal frequency can be presented as $f_{IF} = B\tau/T = 2BR/TC$, then $R = f_{IF}TC/2B$. R can be calculated by doing FFT of beat signal to get f_{IF}.

13.3.2 Land Clutter

Land clutter is the main factor affecting FOD detection Performance. The ground reflected clutter signal can be considered as the echo signal of a large number of scattering body superposed on each other within the effective area on the ground of FOD radar irradiation in a certain time.

According to the radar work environment, there are two terrain, grass and runway, in the radar beam irradiation area. In order to more closely simulate clutter, clutter backscatter coefficient need to consider influences from both grass and runway. According to Ref. [7], backscatter coefficient of the composite scene can be expressed as

$$\sigma^0 = (A_{grass}\sigma^0_{grass} + A_{way}\sigma^0_{way})/A \tag{13.8}$$

Here A, A_{grass}, A_{way} express the whole area, and grass and runway area within the beam; σ^0_{grass}, σ^0_{way} express clutter backscatter coefficient of grass and runway.

In order to save the amount of calculation in the simulation, backscatter coefficient, σ^0_{grass}, σ^0_{way}, use empirical model. This paper uses model proposed by Kulemin in Ref. [8] which is presented as

$$\sigma^0 = A_1 + A_2\log\psi/20 + A_3\log f/10 \tag{13.9}$$

Here f is the frequency in GHz, and Ψ is the grazing angle in degrees. The $A_1 - A_3$ coefficients for grass and runway are presented in Table 13.1.

As shown in Fig. 13.4, Elliptical area is the beam irradiation region, L1, L2 is runway edge. Meshing unit is divided within the effective area of radar beam according to radar range resolution ΔR and azimuth resolution $\Delta\theta$. Coordinates of any grid unit A is $A(x_{mn}, y_{mn})$.

Table 13.1 The $A_1 - A_3$ coefficients in clutter model

Terrain type	A_1	A_2	A_3
Concrete	−49	32	20
Grass	−(25–30)	10	6

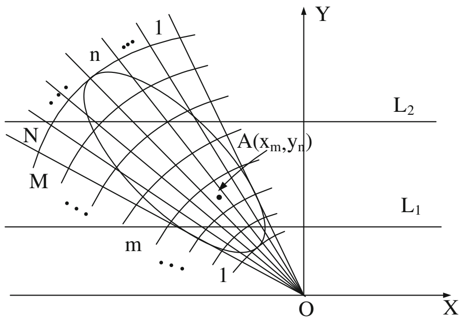

Fig. 13.4 Divide meshing units

When meet the constant Doppler theory [9], the clutter signal generated on a single grid unit can be presented as

$$S_{RC}(t; m, n) = S_T(t - \tau_{mn})e^{j2\pi f_d(t-\tau_{mn})}\left[\frac{\lambda^2 G(t)^2}{(4\pi)^3 \mathrm{R}_{mn}^4}\right]^{1/2}\sqrt{\sigma_{mn}}, \quad 1 \le \mathrm{n} \le \mathrm{N}, 1 \le \mathrm{m} \le \mathrm{M} \tag{13.10}$$

Where G(t) is one-way antenna power gain, λ is the radar wavelength, R is the distance from clutter unit to the radar, τ_{mn} is clutter unit two-way delay time, $\mathrm{f_d}$ is the Doppler center frequency for clutter unit. σ_{mn} is scattering area of ground clutter within the grid cell, can be presented as

$$\sigma_{mn} = \sigma_{mn}^0 A_{mn},\ A_{mn} = \Delta R \Delta\theta \sqrt{x_{mn}^2 + y_{mn}^2} \tag{13.11}$$

Here m and n indicate geographical location of clutter cell, σ_{mn}^0 is the backward scattering coefficient and $\mathrm{A_{mn}}$ is the corresponding ground mesh cell area.

Gaussian distribution to describe the clutter amplitude probability distribution model is used in this paper. The mean and variance of Gaussian distribution is μ and σ^2. The mean of clutter is generally regarded as zero and variance is determined by backscatter coefficient.

As FOD radar is fixed land radar, the clutter power spectrum reflected from various regions of the ground generally is available to be described in the Gaussian function [10]. The power spectral density function can be expressed as

$$S(f) = \exp(-f^2/2\delta_c^2) \tag{13.12}$$

Here, δ_{c} is the clutter power spectral broadening impacted by the radar transmit signal and the antenna scans.

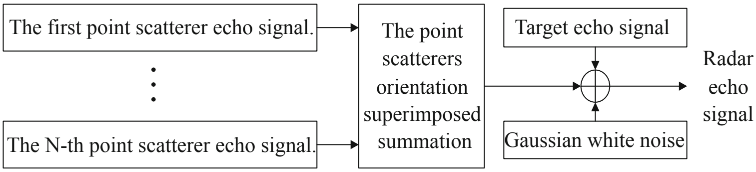

Fig. 13.5 Radar echo simulation flowchart

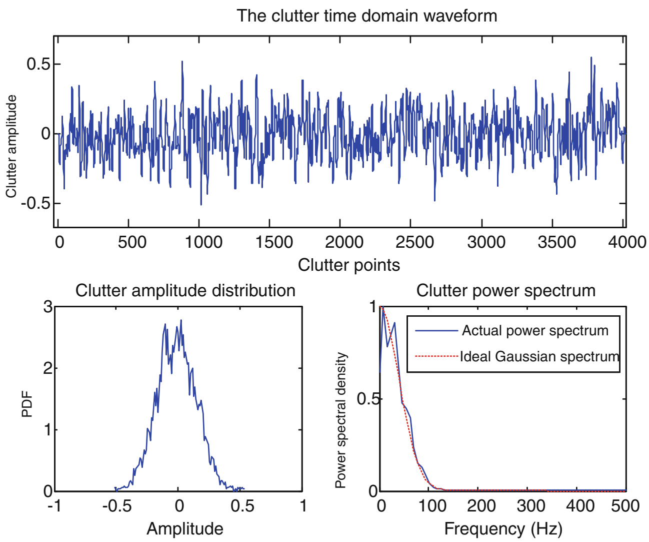

Fig. 13.6 Random sequence consistent with the Gaussian distribution

13.3.3 Noise

In the millimeter wave band, the main source of radar system noise is the internal noise of the radar system which is usually seen as a white Gaussian noise.

By simulating clutter, target signal and noise, we can get the radar echo signal. Figure 13.5 shows a flowchart of the radar echo simulation.

13.4 Simulation

The focus of echo modeling in this paper is clutter. Gaussian white noise sequence is first generated, and then the sequence through a linear filter having a Gaussian spectral Gaussian random sequence. The simulation result is shown in Fig. 13.6. As can be seen, amplitude of generating a random sequence satisfy the Gaussian

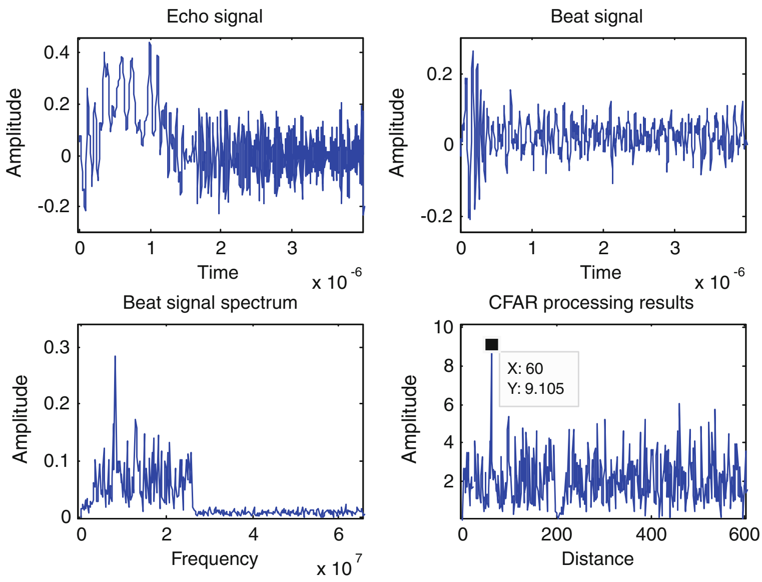

Fig. 13.7 Echo signal and signal processing

distribution, the power spectrum is also consistent with the Gaussian distribution, i.e. the random sequence obtained is correct.

Echo simulation result is shown in Fig. 13.7, including echo signal, the beat signal, the beat signal spectrum diagram and CFAR processing result. A target in distance of 60 m is simulated and can be seen in CFAR processing result.

13.5 Conclusions

FOD radar echo modeling has important guiding significance for study of performance and detection accuracy of radar system, clutter interference. This paper establishes geometric model according to radar work environment, discusses echo signal model, using statistical modeling to model clutter and then do simulation in MATLAB. From simulation results, the clutter sequence obtained is correct.

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