Analysis and simulation of rainfall clutter of primary surveillance radar for civil aviation
Air Traffic Control

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Abstract. To evaluate the influence of rain clutter on the detection performance of Air Traffic Control (Hereinafter referred to as ATC) primary surveillance radar (Hereinafter referred to as PSR), paper takes the scattering area of rainfall clutter as the object of study. By using the equivalent sphere as the equivalent model, the RCS mathematical statistical model of rainfall clutter at different levels is quantitatively analyzed in combination with the rainfall clutter sign. At the same time, from the angle of the rainfall clutter itself and the wet radome with different thickness of water film, the influence of the detection distance of ATC PSR under rainfall condition is analyzed and studied.

1. Introduction

Civil aviation surveillance provides air traffic management system with real-time dynamic information of targets (including air vehicles and airport surface moving targets), which is the basis of air traffic management. Air traffic control and other operation units use the monitoring information to judge and track the position of the moving target of the air vehicle and the airport surface, obtain the identification information of the monitoring target, master the flight path and intention of the aircraft, the aircraft interval and the operation situation of the monitoring airport surface, and improve the guarantee ability of air traffic safety [1]. Clutter refers to the radar echo which is not expected to interfere with the normal operation of radar. It can be divided into two important types: surface clutter and body clutter. Surface clutter includes trees, vegetation, land surface, man-made structures and sea surface (also known as sea clutter). Body clutter usually has a large range (size), including chaff, rain, birds and insects, body clutter has good predictability. Rain clutter is a kind of body clutter.

2. THE SCATTERING AREA OF A GENERAL SIMPLE TARGET

The primary characteristic of a radar target is the ability to return power to the receiving antenna. The parameter used to describe this capability is the radar target scattering cross-sectional area RCS, also known as effective reflection area or backscattering coefficient [2]. In the case of the same incident wave power, the scattering cross-sectional area of targets with different geometric shapes and sizes is different, even if the backscattering area of the same radar target is different at different angles. The target size or radius of curvature is greater than the incident wavelength of radar premise (except dipole), Table 1 describes the general simple mathematical statistical model of target scatter shot cross-sectional area, and presents the target RCS spins a week’s peak, disc number, main lobe width of quantitative parameters, such as, complicated target can be represented by general simple target approximate combination.
TABLE 1. MULTIPATH CLASSIFICATION AND SSR SYSTEM DISTORTION OR INTERFERE CAUSED BY MULTIPATH

| Target         | $\sigma_{\text{max}}$ | $\sigma_{\text{min}}$ | Main lobe number | Main lobe width |
|----------------|------------------------|------------------------|------------------|-----------------|
| Sphere         | $\pi a^2$              | $\pi a^2$              | 1                | $2\pi$          |
| Ellipsoid      | $\pi a^2 b^2 / c^2$    | $\pi b^2 c^2 / a^2$    | 2                | $\approx c/a$   |
| Cylinder       | $2 \pi a L^2 / \lambda$| 0                      | $8 L / \lambda$  | $\lambda / L$   |
| Tablet         | $4 \pi A^2 / \lambda^2$| 0                      | $8 L / \lambda$  | $\lambda / L$   |
| Harmonic dipole| 0.86a $\lambda^2$      | 0                      | 2                | $\pi / 2$       |

3. THE RAINDROP IS EQUIVALENT TO THE SCATTERING AREA OF THE SPHERE

The parameter used to describe this capability is the radar target scattering cross-sectional area RCS, also known as effective reflection area or backscattering coefficient [3]. In the case of the same incident wave power, the scattering cross-sectional area of targets with different geometric shapes and sizes is different, even if the backscattering area of the same radar target is different at different angles. The target size or radius of curvature is greater than the incident wavelength of radar premise (except dipole). Table 1 describes the general simple mathematical statistical model of target scatter shot cross-sectional area, and presents the target RCS spins a week's peak, disc number, main lobe width of quantitative parameters, such as, complicated target can be represented by general simple target approximate combination[4].

Since raindrops can be regarded as ideal spheres, we can use Rayleigh approximation of ideal spheres to estimate the RCS of raindrops [5]. If the refractive index of the media is not considered, Rayleigh is approximately:

$$\sigma = 9 \pi r^2 (kr)^4$$  \hspace{1cm} (1)

Formula 1: $k = 2\pi / \lambda$, $r$ is the radius of the raindrop.

Let $\eta$ be the RCS per unit resolution volume $V_w$, which can be calculated by the sum of the RCS of all independent scatterers per unit volume:

$$\eta = \sum_{i=1}^{N} \sigma_i$$  \hspace{1cm} (2)

Where $n$ is the total number of scatterers in the resolution volume. Therefore, the total RCS in a single resolution volume is

$$\sigma_w = \sum_{i=1}^{N} \sigma_i V_w$$  \hspace{1cm} (3)

The resolution volume unit can be approximated as

$$V_w \approx \frac{\pi}{8} \theta_\varphi \theta_\varphi R^2 c \tau$$  \hspace{1cm} (4)

The propagation medium with refractive index $m$ is considered. In this medium, the RCS of the first raindrop is approximately

$$\sigma_i \approx \frac{\pi^5}{\lambda^4} K^2 D_i^6$$  \hspace{1cm} (5)

$$K^2 = \left| \frac{m^2 - 1}{m^2 + 2} \right|^2$$  \hspace{1cm} (6)
$D_i$ is the diameter of the $i$ raindrop. For example, if the temperature is between 32 °F and 68 °F, then

$$\sigma_i \approx 0.93 \frac{\pi^5}{\lambda^4} D_i^6$$

Substituting Eq.5 into Eq.2:

$$\eta = \frac{\pi^5}{\lambda^4} R^2 Z$$

In the formula 7, the meteorological clutter coefficient $Z$ is defined as

$$Z = \sum_{i=1}^{N} D_i^6$$

Based on the above calculation and analysis, the equivalent simulation results of a single drop of rainfall clutter are shown in Fig.1. It can be seen from the simulation results that the RCS of an ideal conductive sphere is constant in the optical region.

![Figure 1](image_url)

**Figure 1** Scattering cross-sectional area of equivalent sphere of rain drop

### 4. SCATTERING AREA OF RAINFALL CLUTTER

#### 4.1 Mathematical statistics of rainfall clutter RCS

The rainfall clutter belongs to the body clutter, which is the comprehensive result of the backscattering of incident waves by raindrops in the body effectively irradiated by radar [6]. Since there is relative motion between raindrops, and this relative motion is random, the clutter actually observed is the synthesis of backscattering of numerous raindrops, suspended water particles or snowflakes in the radar resolution unit. At the same time, under the circumstance that the incident wave power of ATC PSR is the same, the cross-sectional area of backscattering rate of rainfall clutter is proportional to the size of rainfall rate, and the statistics of specific number values are shown in Table 2.

| Level | Rainfall rate(mm/h) | Scattering rate(dBz) | Rain type       |
|-------|---------------------|----------------------|-----------------|
| 1.    | 0.49~2.7            | 18≤SR<30             | Small drizzle   |
| 2.    | 2.7~13.3            | 30≤SR<41             | Moderate rain   |

| TABLE 2. MULTIPATH CLASSIFICATION AND SSR SYSTEM DISTORTION OR INTERFERE CAUSED BY MULTIPATH |
4.2. Rainfall clutter RCS simulation
The mathematical simulation model of the equivalent sphere scattering cross-sectional area of a single raindrop is taken as the basic computing unit. The simulation results of rainfall clutter RCS are obtained as shown in Fig.2 and Fig.3, through the distribution and statistics of rainfall clutter, which represents the dynamic relationship between rainfall clutter and ATC PSR detection distance.

![Figure 2 Normalized RCS under different radius of equivalent sphere](image1)

![Figure 3 Dynamic curve of clutter under different slant distance](image2)

5. ATTENUATION ANALYSIS OF WET RADOME WATER FILM
Radomes are usually coated with surfaces that are not easily wetted by water to prevent the formation of a continuous water film. However, due to the aging of materials, long-term exposure to the atmosphere, and erosion by sand, stone and rain, the ability of making the radome to convert water into droplets is reduced. In this case, a thin film of water is likely to appear in the radome when it rains. ATC PSR radome water film make radome surface shape asymmetry, result in horizontal polarization and vertical polarization of attenuation, etc., not to prevent transmission of pure circular polarization of rain clutter, leading to day line cover water film of the radar signal attenuation, and the magnitude of the attenuation increases and center frequency radar signal proportional relations[7]. The loss statistics of the canopy under different thickness of water film are shown in Table 3.

| 3. | 13.3~27.3 | 41≤SR<46 | Heavy rain |
|----|-----------|----------|------------|
| 4. | ≥133.2    | ≥57      | Extreme rain |

Table 3. Loss statistics of the canopy under different thickness of water film.
TABLE 3. MULTIPATH CLASSIFICATION AND SSR SYSTEM DISTORTION OR INTERFACE CAUSED BY MULTIPATH

| Water film thickness (mm) | Radome loss (dB) | Reflector loss (dB) |
|--------------------------|-----------------|---------------------|
| 0.05                     | —               | ≤ 0.01              |
| 0.13                     | 1.1             | ≤ 0.01              |
| 0.25                     | 1.1             | ≤ 0.01              |
| 0.38                     | 4.2             | ≤ 0.01              |
| 0.50                     | 5.6             | ≤ 0.01              |

6. CONCLUSIONS
This paper analyzes the statistical parameters of the cumulative number theory for radar simple target scattering, and also obtains the simulation model of the backscattering rate of the general simple target. Rain clutter scattering cross section area is presented, and the results of the analysis of mathematical statistics and different levels of rainfall rate of rain clutter backscatter rate statistical model is given. From the two aspects of water film under the rain clutter of ATC PSR, attenuation caused by rain clutter and wet radome is analyzed. Paper gives the quantitative dynamic relationship between the two points mentioned above, and lay basic foundation for air traffic control radar detection performance analysis and improvement.

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