Impact of rainfall on a Ku-band rotating fan-beam scatterometer

LI Jiamei¹, TJUATJA Saibun², DONG Xiaolong¹, ZHU Di¹

1. Key Laboratory of Microwave Remote Sensing, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100190, China;
2. Wave Scattering Research Center Department of Electrical Engineering, The University of Texas at Arlington UTA Box 19016, Arlington, USA

Abstract: The effects of rainfall backscattering on space-borne rotating fan-beam scatterometer measurements at Ku-band were investigated in this study. A new scattering model based on Integral Equation Method (IEM) for sea surface with precipitation that accounts for the effects of rain column was presented. The relation between rain scattering and incidence was analyzed, and hence the rain effects on a rotating fan-beam scatterometer are obtained. The rain column is modeled as sublayers with different physical characteristics determined by the vertical profile of rainfall. Each sublayer is assumed to be statistically homogeneous, and the gamma distribution is used to model the drop size distribution within each sublayer. Sea surface is modeled as a rough surface, and its backscattering is calculated using the IEM model. Multiple scattering within and interactions between the rain layers and sea surface are accounted for in the matrix doubling formulation. The presented model is validated using published TRMM PR measurements. Results from model analyses show that rain effects are incident angle dependent, which can lead to non-uniform impacts within the footprint of a fan-beam scatterometer; these effects are strongly related to rain column vertical profile and rain rate, as different rain rate corresponds to different physical parameters.

Key words: scatterometer, rainfall, multiple scattering, vertical profile, fan-beam

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1 INTRODUCTION

In sea surface remote sensing, scatterometer measurement is directly related to the intensity and direction of surface wave that satisfies the Bragg resonance condition. Scatterometers, such as the SeaWinds scatterometer on QuikSCAT satellite and ASCAT scatterometer on METOP-A satellite, are proved to be powerful tools for measurement of ocean surface vector wind, which can be very useful in numerical prediction models and oceanic environment monitoring. However, up to ten percent of scatterometer measurement is significantly degraded by noise due to rain (Nie, et al., 2008), especially for scatterometers operating at Ku-band.

Effects of rain on scatterometer measurement can be summarized into three aspects: (1) rain column scatters and attenuates backscattered signal from sea surface; (2) rain column contributes its own backscattered signal to the measurement; (3) rain drops impinging on the sea surface change the sea surface roughness, consequently alter the sea surface scattering and the relationship between the sea surface wind and wave. This paper aims at analyzing the effects of rain scattering and attenuation in atmosphere on rotating fan-beam scatterometer measurements.

The retrieval of ocean surface vector wind by radar scatterometry requires measurement of ocean surface backscattering coefficient (NRCS) with multiple azimuth looking angles. By implementation of this multiple azimuth incidence NRCS measurement, current scatterometer systems can be classified into two different types, fixed fan-beam scatterometers (e.g. SEASAT/SASS, ADEOS-I/NSCAT at Ku-band and ERS/AMI, METOP/ASCAT at C-band) and rotating pencil-beam scatterometers (QuikSCAT/Seawinds, HY-2/SCAT and Oceansat-2/SCAT). Rotating Fan-beam Scatterometer, RFSCAT, is a newly proposed system design of radar scatterometer for ocean surface vector wind measurement. The observation geometry of RFSCAT is shown in Fig. 1 and Fig. 2. Compared with rotating pencil-beam scatterometer, rotating fan-beam system has a wider surface footprint due to its wider beamwidth along the elevation direction, which can provide a wider range of incident angles and more number of azimuth look angles, with moving of the platform and rotating of the antenna. Simulation results show that Ku-band RFSCAT flown on a small satellite can provide equivalent (for low wind speed cases) or better (for large wind speed cases) performances for wind vector retrieval in comparison to the pencil-beam scanning scatterometer (Lin, et al., 2011), especially for a better performance of wind direction
LI Jiamei, et al.: Impact of rainfall on a Ku-band rotating fan-beam scatterometer retrieval. Compared with fixed fan-beam system, RFSCAT has a much more compact antenna system, which requires only rotating antenna, instead of several deployed fixed antennas; and a wider swath, which is decided by the outer incident angle, instead of the elevation beam width for fixed fan beam antenna systems. The scatterometer of CFOSAT, Chinese French Oceanography Satellite, will be the first RFSCAT flown on a satellite.

Fig. 1  Rotating fan-beam observation geometry

Fig. 2  Rotating fan-beam resolution cell

The fan-beam design, however, makes the analysis of rainfall effects more complicated due to its larger instantaneous surface coverage. As a result, we need to determine the rain effects at a larger range of incident angles. The scattering model presented in this paper is designed to meet the requirement for analyzing scattering measurements from space-borne fan-beam scatterometers. The scattering model for rain column over sea surface is presented in Section 3. Section 4 provides model analysis, model validation, and model extension for a fan-beam system. The wind vector cells (WVC) power for fan-beam measurements will be computed using the radar equation,

$$P_e = \frac{\lambda^2 P_t G^2}{(4\pi)^3 r^4} \sigma^0 A_e$$  \hspace{1cm} (1)

where $P_e$ is received power, $P_t$ is transmitted power, $r$ is the distance between radar and target, $G$ is antenna gain, $\sigma^0$ is backscattering coefficient, and $A_e$ is effective illuminated area of target.

2  BACKGROUND

A rain column attenuates, through absorption and scattering, signal scattered by sea surface. At the same time, the rain layer volume scattering contributes to the scatterometer measurement. Wave-medium interactions within the rain column involve complex multiple scattering and attenuation process. The effect of rain on sea surface mainly depends on the wavelength of surface wave. Surface wave with the shortest wavelength is more susceptible to the rain effects. Rain decreases sea surface roughness when the sea surface spatial wavelength is larger than 10 cm, and increases the sea surface roughness when its spatial wavelength is less than 5 cm (Zou, 2009). The critical transition value, however, has not been determined due to the complexity of this problem. The three aspects of rain effects are related to rain rate as well as the drop size distribution (DSD). Using QuikSCAT and TRMM data, Draper and Long (2004) demonstrated that scattering from sea surface with precipitation is dominated by sea surface scattering at low rain rates, and by atmospheric (rain column) scattering at high rain rates. Tournadre and Quilfen (2003) presented theoretical analysis based on radiative transfer formulation that showed scatterometer measurements are strongly affected by rain, and that they are extremely sensitive to rain drop size distribution within scatterometer resolution cell.

A number of parametric forms of the DSD have been presented in literatures, including exponential, lognormal, and gamma. The gamma distribution has been shown to represent a wide range of naturally occurring DSDs (Cifelli, et al., 2010) and was used in this study. The gamma distribution is fully characterized by three parameters as below.

$$N(D) = N_0 \mu D^{\sigma - 1} \exp(-\Lambda D)$$  \hspace{1cm} (2)

where $N_0$ (mm\(^{-1}\)·m\(^{-3}\)) is scaling parameter, $\mu$ is distribution shape parameter, $\Lambda$ (mm\(^{-1}\)) is slope term and $D$ (mm), a random variable, is the spherical equivalent volume diameter. All three parameters are related to rain rate. The DSD can vary considerably within storms, such as for convective rain and stratiform rain, among different storms, and from region to region.

The measured DSD (Table 1) in this paper comes from Joss-Waldvogel Disdrometer (JWD). Rain rate and parameters for gamma model can be calculated from the measured data using $k$th moments method (Lakshmi, et al., 2010).

Rain volume fraction is another important rain parameter, which affect effective permittivity of rain column. It can be calculated in Eq. (3),

$$\nu_r = \frac{\pi}{6} \int_0^D D^2 N(D)dD$$  \hspace{1cm} (3)

where $D$ is rain drop radius, $N(D)$ is the rain drop number corresponds to $D$. The volume fractions for three different rain rates are listed in Table 2.

3  A SCATTERING MODEL FROM SEA SURFACE WITH RAIN

3.1 Modeling approach

This study focuses on effects of rain column on space-borne scatterometer measurements; simplifying assumptions were made...
on sea surface scattering. One scale rough surface was used to describe the sea surface with a set of kr and \( k_r \); the same surface roughness was used in the model analysis of rain scattering effects. The interaction between rain and wind is ignored, i.e. rain drops are assumed to descend vertically. As scattering from the cloud layer in the microwave region is much smaller than responses from the rain column and sea surface, the effect of cloud is assumed negligible in this study.

Table 1 Thresholds of drop size bins and measured rain drops from JWD

<table>
<thead>
<tr>
<th>Bin ( i )</th>
<th>Lower bound ( D_i )/mm</th>
<th>Upper bound ( D_i )/mm</th>
<th>Mean value ( D_i )/mm</th>
<th>Time/min</th>
<th>Rain rate/(mm/h)</th>
<th>Date: 1995-02-26</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.31</td>
<td>0.41</td>
<td>0.36</td>
<td>5</td>
<td>5</td>
<td>22.80</td>
</tr>
<tr>
<td>2</td>
<td>0.41</td>
<td>0.51</td>
<td>0.46</td>
<td>35</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>0.51</td>
<td>0.60</td>
<td>0.55</td>
<td>36</td>
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<td>59</td>
</tr>
<tr>
<td>4</td>
<td>0.60</td>
<td>0.72</td>
<td>0.66</td>
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<td>50</td>
</tr>
<tr>
<td>5</td>
<td>0.72</td>
<td>0.83</td>
<td>0.77</td>
<td>41</td>
<td>52</td>
<td>56</td>
</tr>
<tr>
<td>6</td>
<td>0.83</td>
<td>1.00</td>
<td>0.91</td>
<td>87</td>
<td>99</td>
<td>88</td>
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<tr>
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<td>12</td>
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<tr>
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<tr>
<td>15</td>
<td>3.01</td>
<td>3.39</td>
<td>3.20</td>
<td>1</td>
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</tr>
<tr>
<td>16</td>
<td>3.39</td>
<td>3.70</td>
<td>3.54</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: X means no rain drops in measured data

Table 2 Volume fraction for three rain rates

<table>
<thead>
<tr>
<th>Rain rate/(mm/hr)</th>
<th>Rain volume fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.20</td>
<td>2.50e-06</td>
</tr>
<tr>
<td>10.45</td>
<td>5.33e-06</td>
</tr>
<tr>
<td>22.80</td>
<td>1.04e-06</td>
</tr>
</tbody>
</table>

Scattering and attenuation effects of rain column are fully accounted for in our model. The rain column (an inhomogeneous medium) is discretized vertically into N sublayers. Each sublayer within the inhomogeneous medium is assumed to be statistically homogeneous. The DSD within each sublayer is assumed to be gamma distributed. The averaged rain drop size is used as effective drop size for each sublayer. Rain drops in each sublayer are modeled using Mie scatterers. Scattering characteristics for sublayer \( l \) are described by the backward and forward scattering phase matrices, denoted by \( S_l \) and \( T_l \), respectively, for \(-Z\) incident direction, \( S'_l \) and \( T'_l \) for \(+Z\) incident direction. The total scattering phase matrix of sea surface with precipitation \( S_{\text{cr}} \), is determined using the following algorithm.

1. Determine the volume-scattering phase-matrix set for each sublayer, \( P_l = \{ S_l, T_l, S'_l, T'_l \} \) where \( i = 1, \ldots, N \) using matrix-doubling method.
2. Determine total volume scattering phase-matrix set for the rain column, \( P_{\text{rain}} = \{ S_{\text{rain}}, T_{\text{rain}}, S'_{\text{rain}}, T'_{\text{rain}} \} \), using \( P_{\text{rain}} = P_l \otimes P_l \otimes \ldots \otimes P_l \) where \( \otimes \) denotes matrix doubling operation.
3. Determine the effective reflected and transmitted scattering phase matrices for the cloud-rain interface: \( R_c \) and \( Q_{\text{cr}} \) for \(-Z\) incidence, and \( R'_c \) and \( Q'_{\text{cr}} \) for \(+Z\) incidence. Determine the effective reflected scattering phase matrix for the sea surface \( R_{\text{surf}} \). Both of the two surface scattering phase matrices are calculated using IEM model.
4. The total scattering phase matrix for the sea surface with rain is determined by

\[
S_T = R_{\text{cr}} + Q_{\text{cr}} (I - T_{\text{cr}} R_{\text{surf}} R_{\text{cr}})^{-1} T_{\text{cr}} R_{\text{surf}} R_{\text{cr}} Q_{\text{cr}}
\]

The scattering coefficients for the sea surface with rain are obtained from \( S_T \) using the method described in Tjuatja, et al. (1993) and Fung (1994).

3.2 Matrix doubling method

For an infinitesimally thin layer (Fig. 3) with optical thickness \( \Delta \tau \), multiple-scattering matrix for the layer can be calculated using single-scattering phase matrix \( P(\theta_i, \pi, \theta_i, \phi_i) \), which can be written as (Ulaby, et al., 1986) below.

\[
S(\theta_i, \theta, \phi_i - \phi) = a U^{-1} P(\theta_i, \pi - \theta, \phi_i - \phi) \Delta \tau
\]

\[
T(\theta_i, \theta, \phi_i - \phi) = a U^{-1} P(\pi - \theta_i, \theta, \phi_i - \phi) \Delta \tau
\]

\[
S'(\theta_i, \theta, \phi_i - \phi) = a U^{-1} P(\pi - \theta_i, \theta, \phi_i - \phi) \Delta \tau
\]

\[
T'(\theta_i, \theta, \phi_i - \phi) = a U^{-1} P(\theta_i, \pi - \theta, \phi_i - \phi) \Delta \tau
\]

where \( U \) is the diagonal matrix containing the directional cosines of the scattered angle and \( a \) is the single-scattering albedo of the medium. Combining two adjacent optical layers of thickness \( \Delta \tau_1 \) and \( \Delta \tau_2 \) into one optical layer of thickness \( \Delta \tau_1 + \Delta \tau_2 \) (Fig. 4), the phase matrices can be presented as

\[
S = S_1 + T_1 S_2 T_1 + T_1 S_3 T_1 + \cdots = S_1 + T_1 S_2 \left( I - S_1 S_2 \right)^{-1} T_1
\]

\[
T = T_1 \left[ I + T_1 S_2 \left( I - S_1 S_2 \right)^{-1} T_1 \right]/T_1
\]

\[
S' = S'_1 + T'_1 S'_2 \left( I - S'_1 S'_2 \right)^{-1} T'_1
\]

\[
T' = T'_1 \left[ I + T'_1 S'_2 \left( I - S'_1 S'_2 \right)^{-1} T'_1 \right]/T'_1
\]

where \( I \) is the identity matrix. Therefore, the phase matrices for a layer of any desired thickness can be calculated by repeating Eq.(5).
3.3 IEM method

The vector formulation of the IEM model (Fung, et al., 1994) is based on the vector Green’s second theorem. The tangential surface fields on the interface is determined by solving the governing integral equations.

\[
\begin{align*}
\mathbf{n} \times \mathbf{E} &= 2\mathbf{n} \times \mathbf{E}' - \frac{2}{4\pi} \mathbf{n} \times \int \mathbf{E} ds' \\
\mathbf{n} \times \mathbf{H} &= 2\mathbf{n} \times \mathbf{H}' - \frac{2}{4\pi} \mathbf{n} \times \int \mathbf{H} ds'
\end{align*}
\]

Then the bistatic scattering coefficient matrix can be expressed as

\[
\mathbf{\sigma} = \frac{4\pi}{A} \langle \mathbf{S} \rangle
\]

where \(A\) is the illuminated area and the matrix \(\langle \mathbf{S} \rangle\) is given by

\[
\begin{bmatrix}
\langle k_{zz} \rangle^2 & \langle k_{zz} \rangle^* \textrm{Re}\langle s_{zz} s_{zz}^* \rangle - \textrm{Im}\langle s_{zz} s_{zz}^* \rangle \\
\langle k_{zz} \rangle^* \textrm{Re}\langle s_{zz} s_{zz}^* \rangle & \langle k_{zz} \rangle^* \langle s_{zz} s_{zz}^* \rangle - \langle s_{zz} s_{zz}^* \rangle \\
2\textrm{Re}\langle s_{zz} s_{zz}^* \rangle & 2\textrm{Re}\langle s_{zz} s_{zz}^* \rangle + \langle s_{zz} s_{zz}^* \rangle + \langle s_{zz} s_{zz}^* \rangle - \langle s_{zz} s_{zz}^* \rangle \\
2\textrm{Im}\langle s_{zz} s_{zz}^* \rangle & 2\textrm{Im}\langle s_{zz} s_{zz}^* \rangle + \langle s_{zz} s_{zz}^* \rangle + \langle s_{zz} s_{zz}^* \rangle - \langle s_{zz} s_{zz}^* \rangle
\end{bmatrix}
\]

(1) Reflected bistatic scattering

Each of the above matrix elements has the form

\[
\langle S_{zz} \rangle_{\alpha\beta} = \frac{\kappa^2}{8\pi} \exp(-\kappa^2\sigma - k_z^2\sigma') \sum_{n=0}^{\infty} \frac{\sigma^{2n}}{n!} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F_{\alpha\beta}(k_{\alpha}, k_{\beta}) W^{(n)}(k_{\alpha}, k_{\beta}) dk_{\alpha} dk_{\beta}
\]

where

\[
F_{\alpha\beta}(k_{\alpha}, k_{\beta}) = (k_{\alpha} + k_{\beta}) F_{\alpha\beta} \exp(-\kappa^2 k_z^2) + \frac{k^2}{2} F_{\alpha\beta} (-k_{\alpha}, -k_{\beta})
\]

and \(W^{(n)}(k_{\alpha}, k_{\beta})\) is the Fourier transform of the \(n\)th power of the surface correlation function. Here we choose natural correlation

(Ulaby, et al., 1984), \(k_x = k \sin \theta \cos \phi, k_y = k \sin \theta \sin \phi, k_z = k \cos \theta, k_x = k \sin \theta \cos \phi, k_y = k \sin \theta \sin \phi, k_z = k \cos \theta\).

(2) Transmitted bistatic scattering

\[
\langle S_{zz} \rangle_{\alpha\beta} = \frac{k^2}{8\pi} \exp(-k^2\sigma - k_z^2\sigma') \sum_{n=0}^{\infty} \frac{\sigma^{2n}}{n!} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F_{\alpha\beta}(k_{\alpha}, k_{\beta}) W^{(n)}(k_{\alpha}, k_{\beta}) dk_{\alpha} dk_{\beta}
\]

\[
\langle k_{\alpha} = k_x, k_{\beta} = k_y \rangle
\]

\[
F_{\alpha\beta}(k_{\alpha}, k_{\beta}) = (k_{\alpha} + k_{\beta}) F_{\alpha\beta} \exp(-\kappa^2 k_z^2) + \frac{k^2}{2} F_{\alpha\beta} (-k_{\alpha}, -k_{\beta})
\]

while \(\eta = v_{\eta}/\eta\) is the ratio of the intrinsic impedance of the lower to the upper medium. \(k_x = k \cos \theta, \theta\) is measured from the negative z-axis in the lower medium.

4 MODEL ANALYSIS

4.1 Model results

As mentioned above, the three aspects of the effects of rain on scatterometer measurement are related to rain rate and DSD. In this study the rain column are divided into twelve sublayers. Each sublayer has different physical characteristics determined by gamma DSD. Assumed vertical rain drop size profiles used in this study are shown in Fig. 5. Parameters used in model analysis are listed in Table 3.

Fig. 6 shows the NRCS for sea surface with and without precipitation as a function of incident angle at Ku-band. The used raindrop radius vertical profile is the reference size profile shown

![Different vertical profiles with constant rate for model analysis](image)
in Fig. 5. At small incident angle, the difference between NRCS for VV and HH polarizations were negligible in both cases. But at a larger incident angle, the polarization gap in rainy condition is smaller than that without rain, which means that rain effects are related to incident angle. Also in Fig. 5, we can see that $\sigma$ for VV is bigger than that for HH without rain, but in rainy condition $\sigma$ for HH is bigger than that for VV. We can use dual-polarized radar to determine if rain is in scatterometer resolution cell.

Using the same rain drop size vertical profile, NRCS for two different rain drop volume fractions are presented in Fig. 7. It shows that as the rain volume fraction increases, the NRCS decreases. The reason is that the loss factor of rain column increases with the increasing of rain volume fraction, suggesting that the attenuation by rain drop is the predominant aspect in this condition. This result is in agreement with the conclusion given in Draper and Long (2004) that scattering from rain column is dominated mainly by the surface perturbation at low rain rates, and by atmospheric scattering at high rain rates. Fig. 8(a) and Fig. 8(b) illustrate the NRCS with different rain drop size profiles (Fig. 5) but with the same rain rate. Fig. 8(b) shows that NRCS increases with increasing average rain drop size at big incident angles; which is contrary to that with small incident angle condition shown in Fig. 8(a). This is because rain drop with larger radius has higher albedo, i.e. the ratio of scattering coefficient to extinction coefficient is higher. Correspondingly, the ratio of the volume scattering of rain drop to rain attenuation is increasing. When the incident angle is big, rain volume scattering is the main factor in scatterometer measurement. The NRCS increases as rain drop albedo increases. Yet at small incident angle, sea surface scattering is the main factor in scatterometer measurement. The rain attenuation to sea surface overwhelmed the rain volume scattering, which causes NRCS to decrease.
4.2 Model validation and fan beam analysis

Results from model analyses presented in the previous section are consistent with conclusions in published measurement and modeling studies. Since the measured DSD comes from the JWD, which is used in tropical regions, the model validation choose published TRMM PR data, which also covers tropical regions. Standard PR data products used here include incidence angle with respect to nadir in degrees (incAngle) from level 2A21, level 2A25 estimated rain rate at the actual surface (e_SurfRain), level 2A25 normalized backsckattering radar cross section of the surface (sigmaZero, dB) (NRCS) for the 49 angles bins in the radar scan. The assumed rain drop vertical profiles used in model validation are shown in Fig. 9.

Fig. 10 shows good agreements between model predictions and TRMM PR measurements, which cover only a small range of incident angles, at a rain rate of 4.20 mm·h⁻¹, 10.45 mm·h⁻¹ and 22.80 mm·h⁻¹. The rms difference and correlation coefficient between TRMM measurements and model results as a function of incidence are shown in Table 4. The rms difference is calculated as

\[ \text{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\sigma^m_i - \sigma^t_i)^2} \]  

where \( \sigma^m \) is simulated backscattering coefficient using our model, \( \sigma^t \) is TRMM measured backscattering coefficient, and \( n \) is the number of the TRMM measurements.

As the samples from TRMM measurement for rain rate 22.80 mm·h⁻¹ is much less than the other two rain rates, and the \( k_a \) and \( k_L \) for sea surface are assumed to be constant for the three rain rate, rms for 22.80 mm·h⁻¹ is a little higher and correlation coefficient for 22.80 mm·h⁻¹ is a little lower.

Using model parameters from TRMM data comparisons, back-scattering model calculations and slice power on rotating fan-beam system at large incident angles (25°—50°) are shown in Fig. 11 and Fig. 12. Fig. 11 shows the backscattering coefficients for sea surface with and without rain. As incident angle increases,
Table 4  The rms between TRMM and Model for each rain rate

<table>
<thead>
<tr>
<th>Rain rate / mm · h⁻¹</th>
<th>rms</th>
<th>Correlation coefficient</th>
</tr>
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<tr>
<td>4.20</td>
<td>2.2821</td>
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<td>10.45</td>
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<td>22.80</td>
<td>3.0051</td>
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</table>

Fig. 11  Backscattering coefficient comparison between with and without rain at three rain rates on fan beam

Fig. 12  Slice energy comparison between with and without rain on fan-beam at three rain rates
backscattering coefficients for sea surface with rain decreases much slower compared to the direct surface scattering. Fig. 12 compares received slice energy for cases with and without precipitation. Unlike backscattering coefficient, slice power for sea surface with rain increases as incidence increase. This is caused by the observation geometry of fan-beam. It is evident from Fig. 11 and Fig. 12 that rain scattering effects are significant at large incident angles.

5 CONCLUSION

This paper presents a novel model to analyze effects of rainfall on space-borne scatterometer measurements. The model accounts for multiple scattering within the rain column with vertical profile, as well as the interactions between the rough surface and the precipitation layer. Model analysis results agree well with observations and conclusions given in published studies; model predictions also agree well with TRMM measurements. The model is robust and, in addition to geophysical parameters, can readily be incorporated into system parameters, such as antenna pattern.

Since the focus of this study is on the effects of rain scattering, simplifying assumptions were made on sea surface scattering and the effects of rain on sea surface. However, the presented model formulation is robust and can be readily incorporated into state-of-the-art sea surface scattering models, such as models that account for wind and rain drops effects. A more robust sea surface model and incorporate the wind effects on sea surface scattering will be utilized in our continuing study.

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REFERENCES


降雨对 Ku 波段旋转扇形波束散射计影响

李佳美1, TJUATJA Saibun2, 董晓龙1, 朱迪1

1. 中国科学院空间科学与应用研究中心 微波遥感重点实验室，北京 100190；
2. 美国德州大学阿灵顿分校电机工程波散射理论研究中心，阿灵顿

摘 要：星载散射计测量的归一化后向散射截面是有关海面毛细重力波的大小和方向的函数；散射计的回波强度与海面毛细重力波的振幅成正比；风向对后向散射系数具有调制作用。因此，可以利用散射计的数据，根据地球物理模型反演出具有高精确度、无雨和中低风速条件下的海面风场矢量。然而高达 10%的散射计测量数据会受到降雨影响（Nie, et al., 2008），尤其工作在 Ku 波段的散射计。降雨对海面散射幅度的影响主要包括：(1) 降雨对雷达波的衰减和散射；(2) 雨改变海面水形和海面粗糙度。

本文建立了计及降雨衰减和散射影响后的海面散射正演模型，分析 Ku 波段不同入射角情况下降雨对海面后向散射系数的影响，进而通过雷达方程将降雨影响加入到扇形波束系统中进行分析。

模型是基于降雨均匀分布在散射计视场范围内这一假设建立的。我们把整个降雨区分为垂直分布的 12 个子层，每一层用一特定值，即平均雨滴尺寸，来代表该子层的雨滴尺寸，而(每一个子层中雨滴尺寸随高度变化信息被忽略)。这 12 个子层对应 12 个雨滴尺寸，从而描述了雨滴降落过程中尺寸的变化。本文忽略了雨滴下落过程中形状的变化，将雨滴均假设为球形，并用 Mie 散射理论计算出雨滴的双向散射相位矩阵。之后，按照矩阵法计算出每一子层的相位矩阵。子层中降雨的水平分布用 Gamma 模型进行描述，从而计算不同降雨量时雨滴的体积含量。降雨与海面的下分界面和降雨与云的上分界面的面散射相位矩阵用面散射积分方程 IEM(Integral Equation Method) 进行计算。最后，再次应用矩阵耦合法(matrix doubling method)，将 12 个降雨子层的相位矩阵和上下两个分界面的相位矩阵整合为降雨影响下海面风场的散射。模型的建立过程如下：

(1) 首先将整个降雨层分成垂直分布的 12 个子层，假设每一子层是统计均匀的，而且每一子层中雨滴尺寸不随垂直高度发生变化。采用 Gamma 模型描述子层中雨滴分布，根据 Mie 散射理论计算雨滴散射相位矩阵，

\[ P_{12} = \{S_{12}, T_{12}, S^*_{12}, T^*_{12}\}, \]

(2) 将各个子层体散射相位矩阵整合为整个降雨结构的总体散射相位矩阵

\[ \mathbf{P}_{\text{rain}} = \{S_{\text{rain}}, T_{\text{rain}}, S^*_{\text{rain}}, T^*_{\text{rain}}\}, \]

(3) 利用 IEM 计算 +Z 和 –Z 入射时，反射及传输情况下降雨云与降雨分界面的有效面散射相位矩阵

\[ \mathbf{R}_{\text{cr}}, \mathbf{Q}_{\text{cr}} \] 和

\[ \mathbf{R}_{\text{surface}}, \mathbf{Q}_{\text{surface}} \]

(4) 利用以上计算出的体散射相位矩阵和面散射相位矩阵求出整个降雨层的总的散射矩阵，进一步得出受降雨影响的海洋表面的散射系数

\[ S_{\text{rain}} = R_{\text{cr}} + \mathbf{Q}_{\text{cr}} (I - T_{\text{cr}}, R_{\text{rain}}, T_{\text{rain}}, R_{\text{cr}})^\dagger T_{\text{cr}} R_{\text{rain}}, T_{\text{rain}} \mathbf{Q}_{\text{cr}} \]

(5) 对比模型结果与卫星测量数据，调整模型参数以优化模型，将优化后模型于卫星参数相结合，从而分析不同降雨情况下降雨对扇形波束散射计海面风场散射的影响。

按照以上思路建立了降雨影响下海面的正演散射模型。其中用以模拟子层中雨滴分布的 Gamma 模型是利用位于赤道地区(新加坡)的 Joss-Waldvogel Disdrometer (JWD) 雨滴测量器计算得到。本文利用同样覆盖赤道地区的 TRMM PR 降雨雷达测量数据对模型进行了验证。验证结果显示，在 3 种降雨量情况下模型结果与 TRMM 测量数据都可以较好地吻合。

利用验证后的模型，我们对降雨参数以及散射计系统参数对降雨影响下海面散射情况进行了分析，可以计算出散射计工作频率、极化情况、雨滴大小以及雨滴含量都会产生较显著的影响，而且不同入射角对降雨对海面散射的影响不同。该模型满足了分析降雨在不同入射角情况下对散射计测量影响的需求，从而分析了扇形波束下降雨对海面散射的影响。

关键词：散射计，降雨，多次散射，垂直分布，扇形波束