

A Pixel-level Space-based Bistatic Radar Sea Clutter Modeling Method Based on Range Resolution

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Abstract. Traditional space-based bistatic radar sea clutter models often approximate Earth as a sphere, leading to insufficient accuracy. This paper proposes a pixel-level clutter modeling method based on bistatic range resolution. The WGS-84 ellipsoid model and high-precision orbital propagation ensure accurate platform motion data, while the Gerstner wave model captures dynamic sea surface characteristics. A scattering coefficient model achieves high-precision sea clutter simulation. Experimental results validate the method's effectiveness in modeling scattering properties and capturing Doppler broadening phenomena under varying sea states. This approach simplifies geometric computations and enables pixel-level customization of scattering characteristics, providing a novel solution for space-based bistatic sea clutter simulation.

Keywords: Sea Clutter, Bistatic Radar, Space-based Radar, Clutter Modeling

1. Introduction

The spaceborne bistatic observation system, as a new type of space perception technology, demonstrates unique advantages in environmental monitoring and wide-area information acquisition, gradually becoming a key development direction for modern space information service systems. Firstly, in terms of coverage and concealment, this technology employs a geometric configuration with separated transmitting and receiving units combined with high-orbit satellite platforms. This design overcomes the monitoring blind zones caused by geographical barriers in traditional ground-based observation systems, enabling continuous dynamic surveillance of extensive marine, aerial, and terrestrial environments. Secondly, in complex target identification scenarios, optimizing the bistatic angle (The target is located at a point, while the transmitter and receiver are positioned at different locations. The angle between the two lines of sight (the transmission path and reception path) from the target to the transmitter and receiver is called the bistatic angle) configuration effectively enhances detection sensitivity to mobile targets with low reflectivity characteristics[1][2], such as small UAVs and weather balloons. It addresses signal attenuation issues in conventional monostatic systems caused by target surface properties, thereby improving recognition capabilities for objects with special morphological features.

In light of the critical role of high-fidelity echo modeling as the foundation of bistatic radar signal processing, the development of a computationally efficient and highly accurate spaceborne bistatic sea surface clutter modeling methodology constitutes a matter of paramount significance within the domain of remote sensing technology. Current sea clutter modeling approaches mainly include physical modeling, numerical computation methods, and statistical modeling. Physical modeling generates clutter data by simulating sea surface characteristics using sea spectra combined with Kirchhoff approximation methods [3][4][5]. While this approach captures physical sea surface properties authentically, its computational complexity is high. Numerical methods like Finite-Difference Time-Domain (FDTD), Finite Element Method (FEM), and Method of Moments (MOM) simulate electromagnetic scattering characteristics with precision [6][7]. Statistical modeling employs probability distributions to characterize clutter statistics, with methods like ZMNL and SIRP generating specific statistical clutter data [8].

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In space-based bistatic scenarios, radar beam coverage over vast sea areas makes numerical methods computationally prohibitive. Although statistical modeling improves efficiency, it inadequately describes physical clutter characteristics. A hybrid approach using physical modeling for subdivided clutter scattering cells offers a balance between accuracy and computational efficiency. Traditional space-based bistatic sea clutter models often simplify Earth as a perfect sphere or approximate sea surfaces as planes, adopting monostatic-inspired methods like equidistant ring division for clutter cell partitioning. However, such geometric simplifications compromise modeling accuracy and fail to align with target echo characteristics. Additionally, equidistant ring division in bistatic scenarios suffers from high computational complexity and inaccurate spatial distribution representation, limiting practical applicability.

This paper's key contributions include:

- Enhancing sea clutter simulation accuracy through WGS-84 ellipsoid Earth modeling and high-precision satellite orbit propagation for platform motion modeling.
- Simplifying complex computations while enabling precise cell scattering design via bistatic range resolution-based scattering cell partitioning.
- Implementing Gerstner nonlinear wave theory for sea surface spatiotemporal evolution modeling, establishing sea motion states through wave energy spectra to accurately simulate Doppler broadening effects in sea clutter.

The remainder of this paper is organized as follows: Chapter 2 describes the geometric modeling methodology for space-based bistatic scenarios, including Earth modeling, satellite orbit modeling, and clutter scattering cell modeling. Chapter 3 presents the dynamic modeling of sea surface motion. Chapter 4 calculates sea clutter Doppler characteristics and computes clutter amplitude using scattering coefficient models. Chapter 5 provides simulation results of the proposed space-based bistatic sea clutter model. Chapter 6 concludes the paper.

2. Geometric Configuration Modeling

2.1. Space-Based Orbit Modeling and Earth Modeling

The six fundamental orbital elements, also called Keplerian elements, constitute the principal parameters defining a satellite's trajectory: inclination η , argument of periapsis ω , eccentricity e , semi-major axis a , and true anomaly u . Orbital inclination measures the tilt angle of a satellite's orbit relative to Earth's equatorial plane. The argument of periapsis defines the orientation of the orbit's closest approach point relative to its ascending node. Eccentricity quantifies orbital shape deviation from circularity. The semi-major axis determines orbital size and period through Kepler's third law. True anomaly indicates the satellite's current position along its orbital path measured from periapsis.

For space-based bistatic radar clutter modeling, conventional spherical Earth approximations introduce systematic errors in sea clutter characterization. This study addresses this limitation by implementing the WGS-84 (World Geodetic System 1984) reference ellipsoid, a geometrically rigorous terrestrial model [9][10]. The WGS-84 ellipsoid provides sub-meter-level positioning accuracy through its optimized parametrization of Earth's oblate spheroidal geometry and serves as the foundational geospatial reference for the Global Positioning System (GPS) since its adoption in 1987.

This study's spaceborne bistatic radar geometric modeling framework employs a high-precision orbit propagation algorithm that incorporates numerical integration of complex perturbations including Earth's oblateness, lunisolar gravitational effects, and atmospheric drag. Utilizing the WGS-84 ellipsoid model as the geodetic reference, this approach generates high-fidelity platform trajectory data (position/velocity/attitude) with improved accuracy compared to conventional analytical models. The implementation in Earth-Centered Earth-Fixed (ECEF) coordinates eliminates intermediate coordinate transformations, thereby simplifying the coordinate transformation process.

Within the WGS-84 geodetic reference frame, let the position vectors of the spaceborne transmitter and receiver platforms be denoted as $\vec{R}_T = (x_T, y_T, z_T)$ and $\vec{R}_R = (x_R, y_R, z_R)$ respectively, and the antenna boresight vector of the receiver platform be (x_A, y_A, z_A) . The centroid of the clutter generation region can then be mathematically expressed as:

$$\begin{cases} \frac{x-x_R}{x_A} = \frac{y-y_R}{y_A} = \frac{z-z_R}{z_A} \\ \frac{x^2+y^2}{a^2} + \frac{z^2}{b^2} = 1 \end{cases} \quad (1)$$

With reference to the three-dimensional spatial coordinates of the clutter centroid, denoted as $(x_{C_0}, y_{C_0}, z_{C_0})$ and derived analytically from the preceding mathematical formulations, the theoretical derivation of the bistatic range sum R_Σ is formally expressed as:

$$|(x_{C_0}, y_{C_0}, z_{C_0}) - R_T| + |R_R - (x_{C_0}, y_{C_0}, z_{C_0})| \quad (2)$$

2.2. Clutter Scattering Units Division

The traditional clutter modeling method mainly uses the equidistant ring method to divide clutter scattering elements. However, in the space-based bistatic scenario, the satellite distance is far, so the clutter generation area is large, and the Earth and equidistant surface are ellipsoidal models, which is of high computational complexity. In the case of modeling the Earth as an spherical Earth approximation, the isometric ring expression is derived in the reference [11], which is derived in the following way to the case of modeling the Earth as an ellipsoid:

Establish a double base midpoint coordinate system, Coordinate system origin O' is transmitter and receiver baseline midpoint, the X-axis X' along the base line, the Y-axis Y' is perpendicular to the baseline-geocentric plane, the Z-axis Z' points towards Earth. The method of converting a point in a bistatic midpoint coordinate system to the Earth-fixed coordinate system is as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_e = \mathbf{R} \cdot \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}_t + \begin{bmatrix} X_{O'} \\ Y_{O'} \\ Z_{O'} \end{bmatrix}_e \quad (3)$$

Where $\mathbf{R}$ is the rotation matrix, expressed as:

$$\mathbf{R} = [\mathbf{e}_{x'} \quad \mathbf{e}_{y'} \quad \mathbf{e}_{z'}]^T \quad (4)$$

Where $\mathbf{e}_{x'}, \mathbf{e}_{y'}, \mathbf{e}_{z'}$ are:

$$\mathbf{e}_{x'} = \frac{\mathbf{S}_2 - \mathbf{S}_1}{\|\mathbf{S}_2 - \mathbf{S}_1\|} \quad (5)$$

$$\mathbf{e}_{z'} = \frac{1}{\sqrt{\frac{X_{O'}^2}{a_e^4} + \frac{Y_{O'}^2}{a_e^4} + \frac{Z_{O'}^2}{b_e^4}}} \begin{bmatrix} \frac{X_{O'}}{a_e^2} \\ \frac{Y_{O'}}{a_e^2} \\ \frac{Z_{O'}}{b_e^2} \end{bmatrix} \quad (6)$$

$$\mathbf{e}_{y'} = \mathbf{e}_{z'} \times \mathbf{e}_{x'} \quad (7)$$

Where $\mathbf{S}_1$ and $\mathbf{S}_2$ are the position vectors of the transmitting platform and the receiving platform in the Earth-centered fixed coordinate system. After converting the coordinates of the double base midpoint coordinate system into the ellipsoidal equation of WGS-84, it can be obtained:

$$\begin{aligned}
& \frac{(\mathbf{R}_{11}a \cos \phi + \mathbf{R}_{12}b \sin \phi \cos \gamma + \mathbf{R}_{13}b \sin \phi \sin \gamma + X_{O'})^2}{a_e^2} + \\
& \frac{(\mathbf{R}_{21}a \cos \phi + \mathbf{R}_{22}b \sin \phi \cos \gamma + \mathbf{R}_{23}b \sin \phi \sin \gamma + Y_{O'})^2}{a_e^2} + \\
& \frac{(\mathbf{R}_{31}a \cos \phi + \mathbf{R}_{32}b \sin \phi \cos \gamma + \mathbf{R}_{33}b \sin \phi \sin \gamma + Z_{O'})^2}{b_e^2} = 1
\end{aligned} \tag{8}$$

The angles ϕ and γ are parameters in the parametric equations, while a_e and b_e correspond to the parameters a and b in the WGS-84 ellipsoid equations, respectively.

The calculation of equidistant ring and clutter scattering unit is complicated by solving the simultaneous equations. Moreover, because the simulated scattering unit is a ring and covers a large area, it is difficult to simulate the scattering characteristics of different regions in the same equidistant ring more accurately.

The primary basis for scattering units division lies in the system's range resolution capability. The spatial configuration of bistatic radar differs significantly from that of monostatic radar. Therefore, the range resolution of monostatic radar cannot be directly applied to bistatic radar systems. A method for calculating the equivalent range resolution of bistatic radar is introduced as follows:

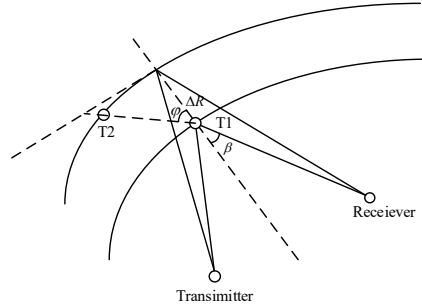


Fig. 1: Schematic Diagram of Bistatic Radar Range Resolution

As shown in the figure, the two arcs are segments of the iso-range contour at a range of ΔR . Here:

β is half the bistatic angle, ϕ is the angle between the line connecting the two targets, like T1 and T2 in the figure, and the angular bisector, c is the speed of light, τ is the pulse width, T1 and T2 denote the two targets located on separate iso-range contours. The actual distance between the two targets can be calculated as follows:

$$\Delta R_\phi \approx \frac{\Delta R_\beta}{\cos \phi} \approx \frac{c\tau}{2 \cos \beta \cos \phi} \tag{9}$$

Based on the bistatic radar range resolution, the following clutter region cell division method is proposed:

- Initial Region Definition:

Tentatively define a rectangular area as the hypothesized clutter scattering region.

- Grid Division:

Subdivide this region along the cardinal directions using the direction-dependent bistatic range resolution to generate grid lines.

- Parameter Extraction:

For each subdivided cell, calculate the following parameters: center coordinates of the cell, cell area, angle between the cell center and the transmitter platform antenna boresight, angle between the cell center and the receiver platform antenna boresight, bistatic range sum of the cell center.

- Clutter Modeling:

Integrate the extracted parameters to finalize the sea clutter modeling.

The detailed implementation methodology is as follows:

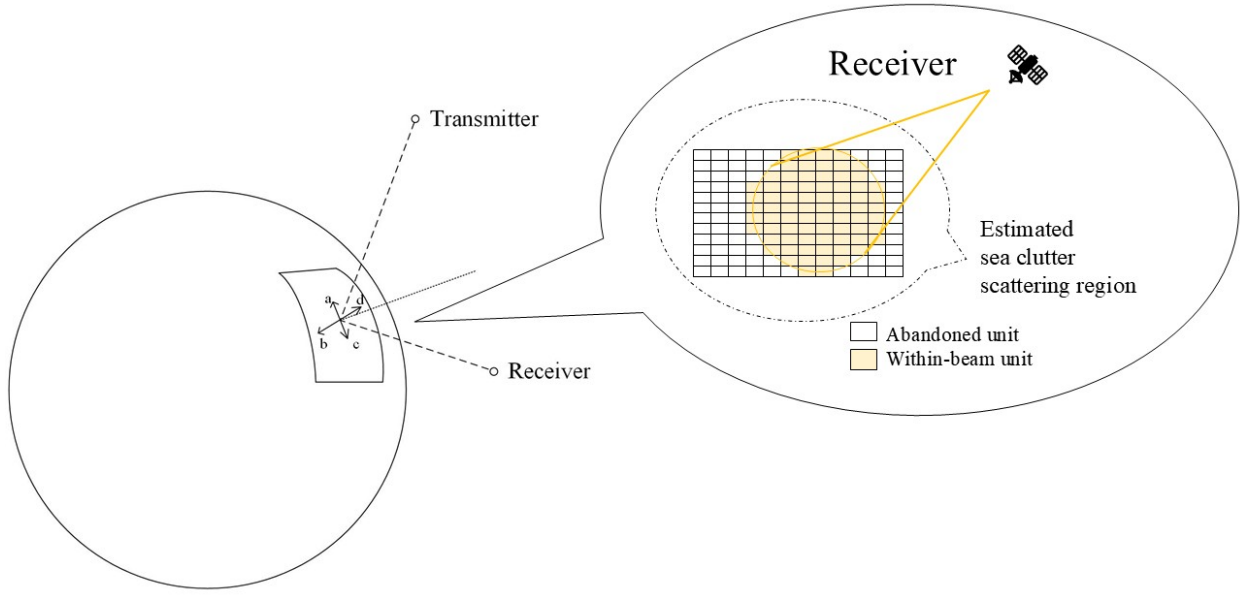


Fig. 2: Schematic Diagram of Clutter Scattering Unit Division

In the figure above, the square area represents the hypothetical clutter scattering region. As shown, the bistatic resolutions in the four directions (a, b, c, d) are calculated separately. The dashed line in the diagram indicates the angular bisector of the bistatic angle, which is represented as:

$$\overrightarrow{R_{biscetor}} = \overrightarrow{R_T} + \overrightarrow{R_R} - 2(x_{C_0}, y_{C_0}, z_{C_0}) \quad (10)$$

The directions of $\vec{b} = (x_b, y_b, z_b)$ and $\vec{d} = (x_d, y_d, z_d)$ are defined as pointing from the core of the clutter scattering region toward the east and west, respectively. it means $z_b = 0, z_d = 0$, The normal vector of this point is obtained by the ellipsoidal equation as follows: $\vec{V} = (\frac{2x_{C_0}}{a^2}, \frac{2y_{C_0}}{a^2}, \frac{2z_{C_0}}{b^2})$. Solve $\vec{b} = (x_b, y_b, z_b), \vec{d} = (x_d, y_d, z_d)$ from $\vec{b} \cdot \vec{V} = 0$ and $\vec{d} \cdot \vec{V} = 0$. And then we solve $\vec{a} = (x_a, y_a, z_a), \vec{c} = (x_c, y_c, z_c)$ from $\begin{cases} \vec{c} \cdot \vec{V} = 0 \\ \vec{c} \cdot \vec{b} = 0 \end{cases}$ and $\begin{cases} \vec{a} \cdot \vec{V} = 0 \\ \vec{a} \cdot \vec{d} = 0 \end{cases}$.

Now, determine the bistatic range resolution in each direction:

$$\cos \beta = \frac{\overrightarrow{R_T} \cdot \overrightarrow{R_{biscetor}}}{|\overrightarrow{R_T}| |\overrightarrow{R_{biscetor}}|} \quad (11)$$

$$\cos \varphi_\xi = \frac{\overrightarrow{R_{biscetor}} \cdot \vec{\xi}}{|\overrightarrow{R_{biscetor}}| |\vec{\xi}|} \quad (12)$$

$$L_\xi \approx \frac{c\tau}{2 \cos \beta \cos \varphi_\xi} \quad (13)$$

$$\xi = a, b, c, d \quad (14)$$

Calculate the bistatic range resolutions in four directions as L_a, L_b, L_c, L_d .

In the true north-south direction, the division of unit boundaries can be determined by calculating the meridional radius of curvature at the point, while for the east-west direction unit boundaries, they are determined by solving integral equations. By calculating the angle between each unit center and the antenna pointing direction, different antenna gains corresponding to various units are determined. Units outside the beamwidth are removed to obtain a more precise clutter generation area.

3. Sea Surface Modeling

Reference [4] mentions three common digital sea surface modeling methods: the harmonic sea surface model, the Gerstner wave model, and the wave equation modeling method.

Among these, the wave equation method provides the most accurate modeling but is computationally intensive. Due to the large sea surface area required for sea clutter simulation, the wave equation method is not considered. The harmonic sea surface model, based on Fourier transforms and harmonic theory, can accurately describe the spectral characteristics of sea surface waves. However, it underperforms the Gerstner wave model in representing sharp wave crests and complex dynamic behaviors of ocean waves. Although the Gerstner wave model involves slightly higher computational costs compared to the harmonic model, it effectively simulates sharp wave crests and intricate wave dynamics, making it the preferred choice for sea surface modeling in sea clutter simulations.

The Gerstner wave model was first introduced in image processing by Fournier and Reeves in 1986, as mentioned in [5]. This model dynamically describes the motion state of each particle on the sea surface. By integrating the JONSWAP wave spectrum and extending the Gerstner model to three dimensions, the following equation can be derived [5]:

$$\begin{cases} x = x_0 - \sum_i \sum_j \sqrt{S_{JONSWAP}(\omega_i, \theta_j)} d\omega d\theta \cos \theta_j \cdot \sin \left[\frac{\omega_i^2}{g} (x_0 \cos \theta_j + y_0 \sin \theta_j) - \omega_i t + \phi_j \right] \\ y = y_0 - \sum_i \sum_j \sqrt{S_{JONSWAP}(\omega_i, \theta_j)} d\omega d\theta \sin \theta_j \cdot \sin \left[\frac{\omega_i^2}{g} (x_0 \cos \theta_j + y_0 \sin \theta_j) - \omega_i t + \phi_j \right] \\ z = z_0 - \sum_i \sum_j \sqrt{S_{JONSWAP}(\omega_i, \theta_j)} d\omega d\theta \cdot \cos \left[\frac{\omega_i^2}{g} (x_0 \cos \theta_j + y_0 \sin \theta_j) - \omega_i t + \phi_j \right] \end{cases} \quad (15)$$

Where $S_{JONSWAP}$ is the wave energy spectrum, which can be expressed in the following form:

$$S_{JONSWAP}(\omega, \theta) = S(\omega)G(\theta) \quad (16)$$

The relationship between $S(\omega)$, $G(\theta)$, where $S(\omega)$ the energy distribution of the waves, and $G(\theta)$ characterizes their directional distribution, and sea state levels can be referenced in [3]. Assuming the velocity vector of each scattering point on the sea surface is $\vec{v}_{C_n} = (v_{xC_n}, v_{yC_n}, v_{zC_n})$, it can be derived by differentiating the particle position modelled by the Gerstner wave model as follows:

$$\begin{cases} v_{xC_n} = \sum_i \sum_j \sqrt{S_{JONSWAP}(\omega_i, \theta_j)} d\omega d\theta \cos \theta_j \cdot \omega_i \cdot \cos \left[\frac{\omega_i^2}{g} (x_0 \cos \theta_j + y_0 \sin \theta_j) - \omega_i t + \phi_j \right] \\ v_{yC_n} = \sum_i \sum_j \sqrt{S_{JONSWAP}(\omega_i, \theta_j)} d\omega d\theta \sin \theta_j \cdot \omega_i \cdot \cos \left[\frac{\omega_i^2}{g} (x_0 \cos \theta_j + y_0 \sin \theta_j) - \omega_i t + \phi_j \right] \\ v_{zC_n} = - \sum_i \sum_j \sqrt{S_{JONSWAP}(\omega_i, \theta_j)} d\omega d\theta \cdot \omega_i \cdot \sin \left[\frac{\omega_i^2}{g} (x_0 \cos \theta_j + y_0 \sin \theta_j) - \omega_i t + \phi_j \right] \end{cases} \quad (17)$$

4. Space-Based Bistatic Sea Clutter Modeling

4.1. Doppler Modeling

In the spaceborne bistatic radar context, Doppler modeling of sea clutter is primarily influenced by the motion velocities of the transmitter platform, receiver platform, and Earth's rotation. However, since the entire sea clutter modeling process in this study is conducted within the WGS-84 ECEF coordinate system, all motion data (including platform velocities) are inherently defined in the ECEF frame. Therefore, the Doppler effect caused by Earth's rotation is intrinsically accounted for in the coordinate system, eliminating the need for additional calculations.

Proof:

Let the satellite's angular velocity in a space-fixed inertial frame (e.g., J2000) be $\vec{\omega}_s$, the Earth's angular velocity in the inertial frame be $\vec{\omega}_e$, the satellite's position in the ECEF coordinate system be $\vec{R}_s$, and the target point's position in the ECEF frame be $\vec{R}_e$. The relative displacement between the satellite and the target point is $\vec{R}_{se}$, and the satellite's velocity vector in the ECEF frame is $\vec{V}_{pe}$.

$$\begin{aligned}
& \frac{(\vec{\omega}_s \times \vec{R}_s) \cdot \vec{R}_{se}}{|\vec{R}_{se}|} - \frac{(\vec{\omega}_e \times \vec{R}_e) \cdot \vec{R}_{se}}{|\vec{R}_{se}|} \\
&= \frac{(\vec{\omega}_s \times \vec{R}_s - \vec{\omega}_e \times \vec{R}_e) \cdot \vec{R}_{se}}{|\vec{R}_{se}|} \\
&= \frac{((\vec{\omega}_s - \vec{\omega}_e) \times \vec{R}_s - \vec{\omega}_e \times \vec{R}_{se}) \cdot \vec{R}_{se}}{|\vec{R}_{se}|} \\
&= \frac{\vec{V}_{pe} \cdot \vec{R}_{se}}{|\vec{R}_{se}|}
\end{aligned} \tag{18}$$

From the above equations, it can be concluded that after using STK software to directly simulate the platform's motion data in the ECEF coordinate system, this data can be directly utilized to calculate clutter Doppler.

Let the velocity of the spaceborne transmitter platform in the ECEF coordinate system be $\vec{V}_T$, and the velocity of the spaceborne receiver platform in the ECEF frame be $\vec{V}_R$. The Doppler frequency $f_{D,n}$ generated by the n th clutter unit center $(x_{C_n}, y_{C_n}, z_{C_n})$ ($n=1,2,\dots,N$) (where N is the total number of clutter units) can be expressed as:

$$\begin{aligned}
f_D = \frac{1}{\lambda} \frac{dR_{\Sigma}}{dt} = \frac{1}{\lambda} & \left(\frac{\vec{V}_T \cdot ((x_{C_n}, y_{C_n}, z_{C_n}) - \vec{R}_T)}{|(x_{C_n}, y_{C_n}, z_{C_n}) - \vec{R}_T|} + \frac{\vec{V}_R \cdot (\vec{R}_R - (x_{C_n}, y_{C_n}, z_{C_n}))}{|(x_{C_n}, y_{C_n}, z_{C_n}) - \vec{R}_R|} \right. \\
& \left. + \frac{\vec{v}_{C_n} \cdot ((x_{C_n}, y_{C_n}, z_{C_n}) - \vec{R}_T)}{|(x_{C_n}, y_{C_n}, z_{C_n}) - \vec{R}_T|} + \frac{\vec{v}_{C_n} \cdot (\vec{R}_R - (x_{C_n}, y_{C_n}, z_{C_n}))}{|(x_{C_n}, y_{C_n}, z_{C_n}) - \vec{R}_R|} \right)
\end{aligned} \tag{19}$$

4.2. Sea Clutter Scattering Coefficient Model

Numerous scholars worldwide have proposed various sea clutter scattering coefficient models to address the challenges of sea clutter modeling. Researchers abroad have developed models such as the SIT model, GIT model, TSC model, HYB model, and gamma model [12]. The NRL backscattering coefficient model was developed through optimized fitting of the Nathanson dataset [13]. In reference [14], a bistatic form of the gamma model was proposed, expressed as:

$$\sigma^0 = \gamma \sin(\theta_g) \tag{20}$$

In the context of sea clutter scenarios, as discussed in [12]:

$$\gamma = 6(ss + 1) - 10 \lg(\lambda) - 64 \tag{21}$$

ss is sea state.

The grazing angle θ_g is equivalently calculated in the bistatic scenario using the following equation [13]:

$$\theta_g = \sqrt{\sin \theta_{gR} \sin \theta_{gT}} \tag{22}$$

θ_{gR} and θ_{gT} are the grazing angles of the receiver and transmitter, respectively.

5. Simulation Process and Results

Based on the aforementioned methods and the data provided in the following sections, conduct the sea clutter modeling and simulation as follows:

Parameter Name	Setting Value
Radar carrier frequency	10 GHz
Radar bandwidth	10 MHz
Radar pulse width	1×10^{-5} s
Pulse repetition interval	1×10^{-4} s
Number of pulses	400
Sea state level	3,5
LLA of Transmitter	-0.136° , 175.386° , 35788163.121m
LLA of Receiver	140° , 42° , 1000003.115m

The simulation results are shown in the figure below:

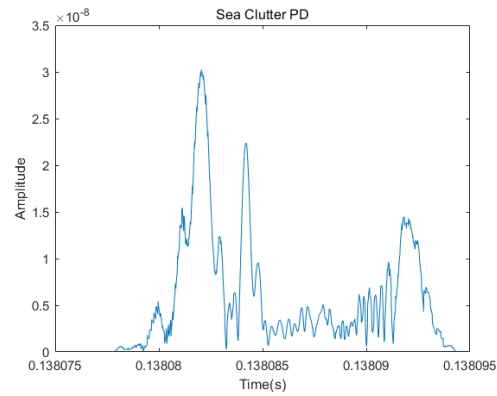


Fig. 3: Simulated sea clutter amplitude

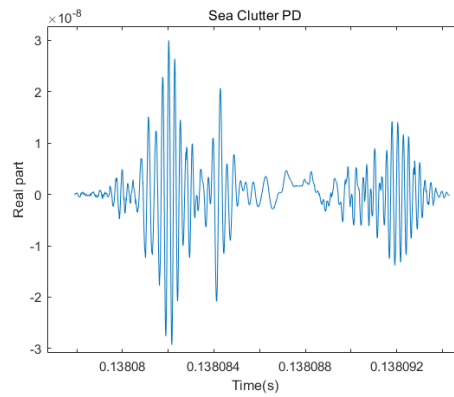


Fig. 4: Simulated real part of sea clutter

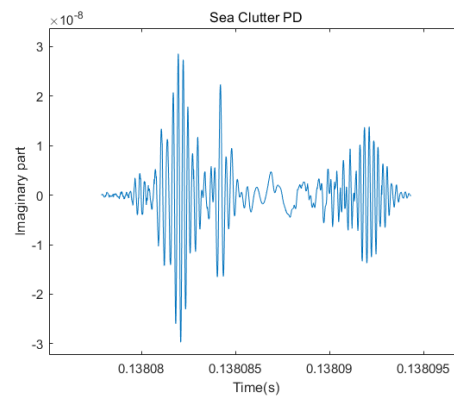


Fig. 5: Simulated imaginary part of sea clutter

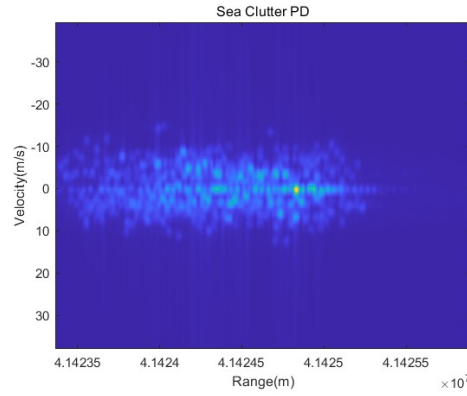


Fig. 6: Simulated sea clutter velocity and distance image under level 5 sea condition

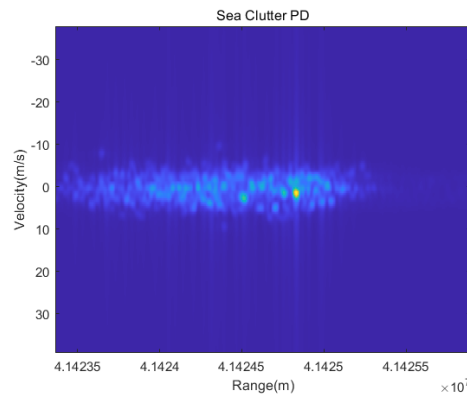


Fig. 7: Simulated sea clutter velocity and distance image under level 3 sea condition

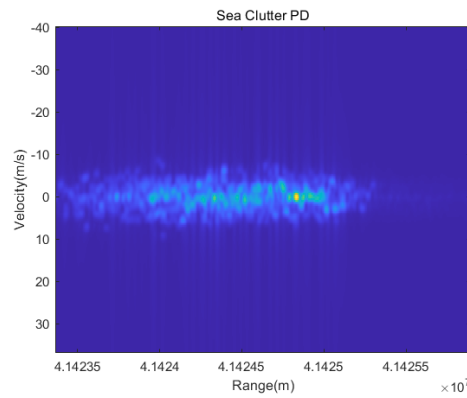


Fig. 8: Simulated sea clutter velocity distance image with part of sea level 3 and part of sea level 5

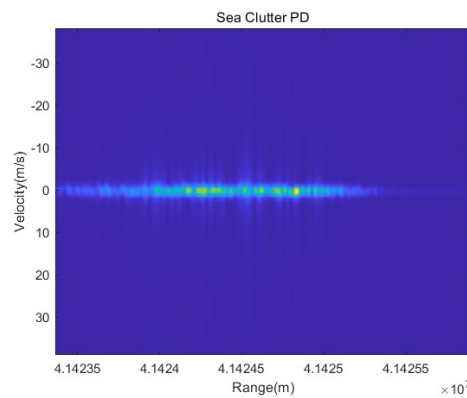


Fig. 9: Simulated sea clutter velocity-range image in Class 5 sea state without considering sea surface motion

Figures 3, 4, and 5 illustrate the temporal-domain characteristics of sea clutter.

Comparative analysis of Figures 6, 7, and 9 reveals that dynamic sea surface motion generates significant Doppler broadening effects within maritime clutter environments, which presents substantial challenges for target detection in oceanic observation systems. Furthermore, higher sea state levels result in more pronounced Doppler broadening. This is because higher sea states correspond to stronger wind speeds, which influence $S_{JONSWAP}(\omega, \theta)$ in the sea surface motion model, thereby affecting the scale of Doppler broadening.

As shown in Figure 8, the pixel-level sea clutter modeling method allows individual design of the surface characteristics for each clutter scattering unit. This highlights a key advantage over traditional iso-range ring methods: pixel-level modeling enables independent definition of scattering characteristics for each unit, significantly raising the upper limit of precision in sea clutter modeling. Additionally, this method can simulate scenarios where parts of the sea surface correspond to Level 3 sea states while others correspond to Level 5 sea states, as illustrated in Figure 8.

The proposed clutter scattering unit division method based on equivalent bistatic range resolution serves as a pixel-level clutter modeling approach. Through division of hypothetical clutter scattering areas and coordinate conversions between the ECEF coordinate system and latitude-longitude coordinates, this method avoids extensive complex geometric computations. Meanwhile, each pixel independently represents a medium wave source, thus enabling more precise simulation of scattering characteristics in different regions.

6. Conclusion

This paper proposes a **spaceborne bistatic sea clutter modeling method** based on **scattering unit division with bistatic range resolution**. By employing **pixel-level** clutter scattering unit division grounded in bistatic radar range resolution for geometric modeling, this approach offers a novel framework for improving the precision of sea clutter simulation while simplifying the intricate geometric computations inherent in traditional methods. Furthermore, the integration of the **WGS-84 Earth model** for geospatial referencing and the application of **high-precision orbit propagation models** to generate platform motion data further enhance the model's accuracy and applicability. The researching achievement establish a critical foundation for advancing clutter suppression and target detection in spaceborne bistatic radar systems.

7. References

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