

Article

Correlation Statistics and Parameter Optimization Algorithms for RIS-Assisted Marine Wireless Communication Systems

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Abstract: Reconfigurable intelligent surfaces (RISs), as one of the potential key technologies in sixth generation (6G) mobile communications, feature low costs, low energy consumption, and ease of deployment. In this paper, we introduce the RIS technology into the maritime wireless communication scenario, which can transform the wireless transmission environment from uncontrollable to controllable. In the considered communication model, we derive the complex channel impulse response for the RIS propagation link and non-line-of-sight propagation link, respectively. This can be used to capture the physical properties of a communication model from different perspectives. Furthermore, based on the designed communication model, we investigate the correlation properties of propagation links in the space and time domains; they are the space correlation statistics and time correlation statistics. The provided framework addresses the technical bottleneck of the existing RIS channel modeling methods that fail to balance precision and efficiency, improves the channel model matching efficiency in the design process of RIS-enabled near-field maritime communication systems, and provides technical support for the rapid development of the 6G mobile communication industry.



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1. Introduction

With the commercialization of the fifth-generation (5G) mobile communications, mobile data traffic has been growing exponentially. In the face of the rapid development of emerging services such as ultra-high-definition mobile video, virtual/augmented reality, unmanned driving, and integrated air-space-ground-sea ubiquitous networks, which require high bandwidth and massive connections, the demand for spectrum resources in wireless communications has surged [1]. Global researchers have begun to turn their attention to the sixth-generation (6G) mobile communication networks, discussing future communication needs and potential solutions. Therefore, conducting theoretical research on wireless communication channels for maritime communications and solving the bottleneck issues that restrict the design and performance evaluation of maritime communication systems are of significant theoretical value and practical significance for accelerating the formation of new quality productivity [2].

For the design of wireless transmission schemes, channel estimation, analysis of channel capacity, and system performance evaluation in large-scale fading channels, as well as the link budgeting, analysis of network coverage performance, and network/base station (BS) placement and optimization in small-scale multipath channels, the channel model

is always a crucial cornerstone for the system design, theoretical analysis, performance evaluation, and optimization [3]. In light of this, it is critical to propose a physical dynamic channel model that can faithfully reflect the impacts of the physical characteristics of an RIS array on the electromagnetic waves in a wireless environment between the UAV transmitter and ground receiver. In [4], the authors have contributively investigated non-orthogonal multiple access (NOMA)-assisted secure offloading for vehicular edge computing networks in the presence of multiple malicious eavesdropper vehicles. The existing channel models are mainly divided into deterministic channel models and statistical channel models [5–8]. Among them, deterministic channel models simulate the wave propagation characteristics based on electromagnetic wave propagation theory, but they are primarily tailored for specific wireless communication environments and have limited general applicability. Ray tracing, as a common deterministic channel modeling method, can accurately describe the multipath effects in specific environments, but it is costly, time-consuming, and difficult to be widely applied in the design and performance analysis of various mobile communication systems [9]. Statistical channel models, by introducing random variables, can effectively describe wireless communication environments under various parameter configurations, but this modeling method does not accurately describe the propagation mechanisms of signals in the spatial, temporal, and frequency domains, and its accuracy is not ideal. Nevertheless, this modeling method is widely adopted in academia and industry due to its good general applicability and generalization ability. Specifically, statistical channel models are mainly suitable for describing related communication environments that cannot be used to depict specific communication scenarios. These models can use the statistical distribution of channel parameters to model wireless channels and characterize the signal propagation mechanism under different system parameter configurations [10].

Although maritime communication physical layer technologies can typically adapt to the spatial and temporal changes in the wireless environment, signal propagation is inherently random and largely uncontrollable [11]. The existing research works have validated that the use of reconfigurable intelligent surface (RIS) technology between the transmitter and receiver in maritime communication channels makes it is possible to independently adjust the phase (and/or amplitude, even frequency) of the incident signals, solving the problem of strong directionality but insufficient coverage in high-frequency band communications, which mainly leads to an increased achievable rate compared to the system without considering RIS [12–14]. Therefore, exploring the new characteristics of RIS-enabled wireless communication channels is of significant theoretical guidance and practical value for solving problems such as time-domain or frequency-domain non-stationarity, abundant scatterers, and multi-mobility in the maritime communication channel environment. For modeling RIS-enabled near-field maritime communication channels, the traditional statistical channel models cannot be used to describe the independent spatial, temporal, and frequency-domain transmission characteristics of signals in the RIS channel due to the inability to abstract the RIS device as a communication node. Many research teams are currently modeling and analyzing the channels between RIS devices and transmitters or receivers. Studies have shown that the modeling of RIS-enabled wireless communication channels is influenced by the positions of the transmitter, receiver, and RIS, and system simulations require spatial modeling of RIS-enabled near-field maritime communications to accurately evaluate the system performance [15,16]. Therefore, in the existing research, geometry-based statistical channel modeling methods have been widely applied in the analysis of the transmission mechanisms in RIS-enabled maritime channels [17,18].

In maritime communication scenarios, signal propagation is primarily influenced by the special geographical and hydrological environment of the ocean, including long communication distances, sea wave movements, sea surface evaporation ducts, and the curvature of the sea surface. The sparsity of sea surface scatterers due to the sparse distribution of communication nodes on the sea surface, as well as the time-variant non-stationarity of the channel caused by the movement of the sea surface, both become important factors affecting the transmission mechanism of maritime communication channels [19]. Studies

have shown that the mechanism of signal propagation changes continuously with the expansion of the RIS array dimensions [20]. When the RIS array size is not very large, causing the distance from the transmitter/receiver to the RIS array to be greater than the Rayleigh distance, scatterers are generally distributed in the far-field region of the RIS channel. In this case, a plane wave model is needed to model the channel, and the array response vector corresponding to each transmission path is only related to the path angle. With the increase in the number of RIS array elements, the RIS array size becomes larger, and the Rayleigh distance increases accordingly. Scatterers are likely to be distributed in the near-field region of the RIS channel, requiring a more accurate spherical wave model to model the channel, and the near-field array response vector is related to the specific location of the scatterers. Many existing works have conducted experimental and simulation studies on the propagation mechanism of signals in RIS channels, demonstrating that RIS channels are more inclined to operate in the near-field region [21,22]. Therefore, in exploring the performance of RIS-enabled near-field maritime communication systems, it is necessary to consider the network resources in multiple dimensions, such as time, frequency, and space. In the spatial dimension, deploying RIS technology can effectively improve the network energy efficiency; in the temporal dimension, adjusting the dynamic nodes of the transmitter and receiver can achieve optimal energy efficiency; in the frequency domain, increasing the number of frequency channels and enhancing the transmission bandwidth also achieve improved energy efficiency. However, the RIS-enabled maritime communication network is a communication system that combines multiple resource dimensions. The introduction of RIS technology in BS–ship communications generates a large number of channel parameters, which imposes a significant computational burden on the numerical simulations [23]. Although the communication models in the existing literature are continuously being optimized for modeling efficiency, it is still difficult to achieve satisfactory technical indicators with high precision and low complexity. Furthermore, for BS-to-ship communications in marine environments, the ship receiver performs irregular movements on the sea surface, while the existing maritime statistical channel models have not explored the impact of sea surface wave effects on the non-stationary transmission characteristics of signals in the spatial, temporal, and frequency domains. This will lead to a challenge and difficulty in meeting the application requirements of RIS-enabled near-field maritime communication networks [24]. To address these challenges, this paper focuses on the modeling of RIS-enabled BS-to-ship channels in maritime wireless communication scenarios. By separately modeling the BS-to-RIS sub-channel as well as the RIS-to-ship sub-channel in the RIS-enabled BS-to-ship maritime communication scenarios, we propose a modeling framework for signal transmission mechanisms in multiple domains (space, time, and frequency). Afterwards, we establish a parameterized statistical channel model for RIS-enabled BS-to-ship communications in maritime scenarios. This has the ability to reveal the impact of the physical properties of an RIS array as well as the sea surface wave effects on the signal transmission mechanisms in the spatial, temporal, and frequency domains, aiming to solve the technical bottleneck issue of the existing RIS channel modeling methods that have difficulty balancing precision and efficiency. Based on the provided framework, it is helpful for the designers to improve the channel model matching efficiency in the design process of RIS-enabled BS-to-ship maritime communication systems and thereby provide technical support for the rapid developments in the future mobile communication industry.

2. System Model

It is noteworthy to state that the communication models play vital roles for the optimization of RIS-enabled BS-to-ship maritime communication systems. This interesting observation motivates us researchers to look for an effective solution to characterize the impacts of the physical features of an RIS array on the electromagnetic signals in maritime scenarios between the BS transmitter and ship receiver. In the context of maritime wireless communication, the direct transmission path between the UAV and ship on the marine plane is often obstructed by obstacles, which can degrade the quality of communication. It

is worth mentioning that the research literature has demonstrated that the utilization of advanced RIS technology in wireless communication systems has the advantage of enhancing the satisfactory achievable rate when compared to not considering the RIS technology. Based on this background, the research teams throughout the world have conducted a variety of related works on the design and optimization of RIS-enabled BS-to-ship maritime wireless communication systems. As shown in Figure 1, the introduction of RIS technology can provide a virtual direct path for signal transmission between BS and ship receiver, thereby enhancing cost efficiency, energy efficiency, and spectrum efficiency. In this figure, we notice that the RIS is equipment with a controller, which has the ability to manipulate the waves of signals by attaching an additional reflection coefficient during the interaction. In the RIS-enabled BS–ship wireless communication scenario, the height of the BS above the horizontal plane is denoted as H_0 . It is defined that the BS transmitter and the ship receiver are equipped with omnidirectional uniform linear antenna arrays of P and Q elements, respectively [25]. The midpoint at the bottom of the BS is defined as the origin of the global coordinate system, with the positive direction of the x -axis set from the origin pointing towards the ship receiver, the z -axis pointing vertically upwards, and the y -axis following the right-hand rule [26]. At the BS side, the distance vector from the midpoint of the antenna array to the origin of the coordinate axis is represented as $\mathbf{d}_T = [0, 0, H_0]^T$, and the distance vector from the p -th antenna element (where $p = 1, 2, \dots, P$) to the midpoint of the array is represented as follows [27,28]:

$$\mathbf{d}_{T,p} = \frac{P - 2p + 1}{2} \delta_T \begin{bmatrix} \cos \phi_T \cos \psi_T \\ \cos \phi_T \sin \psi_T \\ \sin \phi_T \end{bmatrix}, \quad (1)$$

where ψ_T^{azi} and ψ_T^{ver} represent the angles of the linear antenna array at the BS in the horizontal and vertical planes, respectively, and θ_T denotes the spacing between any two adjacent elements in the linear antenna array at the BS side. On the ship side, the distance vector from the q -th element (where $q = 1, 2, \dots, Q$) to the center of the array is represented as follows:

$$\mathbf{d}_{R,q} = \frac{Q - 2q + 1}{2} \delta_R \begin{bmatrix} \cos \phi_R \cos \psi_R \\ \cos \phi_R \sin \psi_R \\ \sin \phi_R \end{bmatrix}, \quad (2)$$

where ψ_R^{azi} and ψ_R^{ver} represent the angles of the linear antenna array at the ship side in the horizontal and vertical planes, respectively, and θ_R denotes the spacing between any two adjacent elements in the linear antenna array at the ship side.

Due to the sea surface wave effects, the velocity and direction of movement of the ship receiver are non-stationary characteristics at different times; therefore, a single uniform velocity model cannot be used to describe the movement state of the ship receiver. Define the velocity vector of the ship as $\mathbf{v}_R = [v_{R,x}, v_{R,y}, 0]^T$, where $v_{R,x}$ and $v_{R,y}$ represent the velocity components of the ship along the x -axis and y -axis, respectively, and are calculated as follows:

$$v_{R,x}(t) = v_{R,x}(0) + \int_0^t a_{R,x}(t') dt', \quad (3)$$

$$v_{R,y}(t) = v_{R,y}(0) + \int_0^t a_{R,y}(t') dt'. \quad (4)$$

In Equations (3) and (4), $v_{R,x}(0)$ and $v_{R,y}(0)$, respectively, represent the motion velocity components of the ship receiver along the x -axis and y -axis during the initial stage of motion.

$a_{R,x}(t)$ and $a_{R,y}(t)$ are, respectively, the velocity accelerations of the ship along the x -axis and y -axis in the real-time stage, which can be expressed as

$$a_{R,x}(t) = a_{R,x}(0) + a'_{R,x}(t), \quad (5)$$

$$a_{R,y}(t) = a_{R,y}(0) + a'_{R,y}(t), \quad (6)$$

where $a_{R,x}(0)$ and $a_{R,y}(0)$, respectively, represent the motion acceleration components of the ship along the x -axis and y -axis during the initial stage of motion; $a'_{R,x}(0)$ and $a'_{R,y}(0)$, respectively, represent the gradients of $a_{R,x}(t)$ and $a_{R,y}(t)$. Therefore, the time-varying distance vector of the ship receiver during the motion stage is calculated as

$$\mathbf{d}_R(t) = \begin{bmatrix} d_{R,x}(t) \\ d_{R,y}(t) \\ H_1 \end{bmatrix} = \begin{bmatrix} D_0 + v_{R,x}(t)t \cos \eta_R^{\text{ver}} \cos \eta_R^{\text{azi}} \\ v_{R,x}(t)t \cos \eta_R^{\text{ver}} \sin \eta_R^{\text{azi}} \\ H_1 \end{bmatrix}, \quad (7)$$

where D_0 represents the distance from the midpoint of the antenna array at the ship side to the origin of the coordinate axis, H_1 is the height of the ship receiver, and η_R^{azi} and η_R^{ver} , respectively, represent the angles of the receiving direction of movement in the horizontal and vertical planes.

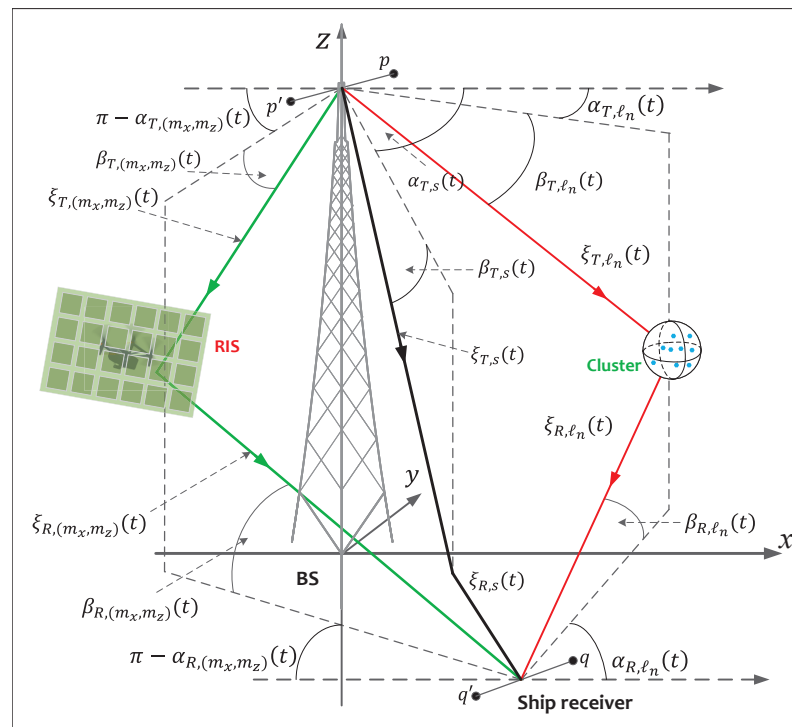


Figure 1. Proposed propagation model for RIS-enabled BS–ship wireless communication scenarios.

3. Sub-Array Configuration Algorithm

In the RIS-enabled BS–ship communication channel, due to the continuous movement of the ship within the RIS channel, the transmission distance between the ship and the RIS array constantly changes, causing the communication channel to fluctuate between the near-field and far-field regions. Therefore, the traditional plane wave model has difficulty in accurately describing the non-stationary transmission characteristics of the RIS-enabled BS–ship communication in terms of spatial, temporal, and frequency domains. Research shows that, when the BS and the ship are in the near-field region, using the spherical wave model to study the channel characteristics can ensure relatively ideal computational accuracy, but it results in very high computational complexity and hardware costs. Conversely,

using the plane wave model to study the channel characteristics can reduce computational complexity, but it does not guarantee the accuracy of the simulation results for the channel characteristics. Therefore, this paper proposes an RIS sub-array slicing scheme for the RIS-enabled BS–ship communication system. By dividing the RIS array into multiple small-scale sub-arrays, it can be ensured that the channel parameter estimation in each sub-array meets the requirements of the plane wave model. Define M_x and M_z as the number of elements in the horizontal and vertical axes of the RIS array, respectively, and d_M as the spacing between any two elements in the RIS array. Then, the Rayleigh distance for the RIS-enabled BS–ship communication channel is represented as follows:

$$L_{\text{RIS}} = \frac{2((M_x - 1)^2 + (M_z - 1)^2)d_M^2}{\lambda}. \quad (8)$$

To reduce the computational complexity of the characteristics of the RIS-enabled BS–ship communication channel, it is necessary to ensure that both the sub-channel between the BS and the RIS array and the sub-channel between the RIS array and the ship are in the far-field region. Therefore, the geometric distance from the midpoint of the antenna array at the BS to the midpoint of the RIS array, denoted by $\zeta_{T,\text{RIS}}$, and the geometric distance from the midpoint of the antenna array at the ship to the midpoint of the RIS array, denoted by $\zeta_{R,\text{RIS}}$, should, respectively, satisfy the following conditions:

$$\zeta_{T,\text{RIS}}(t) \geq \frac{2(P\delta_T + \sqrt{2}(M_{x/z,\text{max}}^{\text{sub}}(t) - 1)d_M)^2}{\lambda}, \quad (9)$$

$$\zeta_{R,\text{RIS}}(t) \geq \frac{2(Q\delta_R + \sqrt{2}(M_{x/z,\text{max}}^{\text{sub}}(t) - 1)d_M)^2}{\lambda}. \quad (10)$$

Additionally, let $M_{x/z,\text{max}}^{\text{sub}}(t)$ denote the sub-array located at the x -th row and z -th column within the RIS, where $x = 1, 2, \dots, M_x$ and $z = 1, 2, \dots, M_z$. Then, the sub-array $M_{x/z,\text{max}}^{\text{sub}}(t)$ of the RIS array should satisfy the following constraint conditions:

$$M_{s/z,\text{max}}^{\text{sub}}(t) = \begin{cases} \min \left\{ \left\lfloor \frac{\sqrt{\lambda\zeta_{T,\text{RIS}}}}{2d_M} - \frac{P\delta_T}{\sqrt{2}d_M} + 1 \right\rfloor, \left\lfloor \frac{\sqrt{\lambda\zeta_{R,\text{RIS}}(t)}}{2d_M} - \frac{Q\delta_R}{\sqrt{2}d_M} + 1 \right\rfloor, M \right\}, \\ \text{if} \left\{ \left\lfloor \frac{\sqrt{\lambda\zeta_{T,\text{RIS}}}}{2d_M} - \frac{P\delta_T}{\sqrt{2}d_M} + 1 \right\rfloor, \left\lfloor \frac{\sqrt{\lambda\zeta_{R,\text{RIS}}(t)}}{2d_M} - \frac{Q\delta_R}{\sqrt{2}d_M} + 1 \right\rfloor, M \right\} > 1 \\ 1, \text{if} \left\{ \left\lfloor \frac{\sqrt{\lambda\zeta_{T,\text{RIS}}}}{2d_M} - \frac{P\delta_T}{\sqrt{2}d_M} + 1 \right\rfloor, \left\lfloor \frac{\sqrt{\lambda\zeta_{R,\text{RIS}}(t)}}{2d_M} - \frac{Q\delta_R}{\sqrt{2}d_M} + 1 \right\rfloor, M \right\} = 1 \end{cases} \quad (11)$$

where $\lceil x \rceil$ represents the smallest integer greater than or equal to x . Based on the determined number of control units in the RIS sub-array, the dimension of the RIS array is represented as

$$M_{x/z}^{\text{sub}}(t) = \begin{cases} \frac{M_{x/z} - \text{mod}(M_{x/z}, M_{x/z,\text{max}}^{\text{sub}}(t))}{M_{x/z,\text{max}}^{\text{sub}}(t)} + 1, \text{if } \text{mod}(M_{x/z}, M_{x/z,\text{max}}^{\text{sub}}(t)) \neq 0 \\ \frac{M_{x/z}}{M_{x/z,\text{max}}^{\text{sub}}(t)}, \text{if } \text{mod}(M_{x/z}, M_{x/z,\text{max}}^{\text{sub}}(t)) = 0 \end{cases} \quad (12)$$

where $\text{mod}(a, b)$ represents the remainder obtained by dividing the integer a by the integer b . Since the parameters a and b can be set to any value, the proposed algorithm can be applied to RIS arrays with any configuration of control units.

4. RIS-Enabled BS–Ship Channel Modeling

In the BS–ship wireless communication scenario, electromagnetic wave signals are easily blocked by obstacles such as trees and buildings, making it difficult for the signals emitted by the BS to reach the receiving end via a direct path. Therefore, deploying RIS arrays on the surfaces of buildings and using the virtual direct paths formed by the RIS array control ensure the performance of the wireless communication system. In the proposed channel model, the signals emitted by the BS reach the ship through three types of links: (1) the RIS path, where the signal reaches the RIS array and then undergoes amplitude/phase control to reach the ship receiver; (2) the non-direct path, where the signal is reflected by scatterers near the BS and then reaches the ship receiver; and (3) the specular reflection path, where the signal is reflected by the sea surface and then reaches the ship receiver. In describing the position distribution of the RIS array, the distance vector from the origin of coordinates to the center of the RIS array is defined as $\mathbf{d}_{\text{RIS}} = [x_{\text{RIS}}, y_{\text{RIS}}, z_{\text{RIS}}]^T$. In the scatterer path, we set L scatterer clusters around the BS, and the distance vector from the origin to the n -th scatterer in the ℓ -th ($\ell = 1, 2, \dots, L$) scatterer cluster is defined as $\mathbf{d}_{\ell n} = [x_{\ell n}, y_{\ell n}, z_{\ell n}]^T$.

Furthermore, in describing the specular reflection path, we propose to use scatterers to simulate the specular reflection points on the sea surface. Specifically, the arrival horizontal azimuth angle and arrival vertical azimuth angle of the specular reflection path are calculated based on the geometric positions of the BS and ship receiver, and then these angles are used as means to generate multiple arrival angles with a Gaussian distribution, thereby simulating multiple specular reflection paths on the sea surface [29]. In this paper, S specular reflection paths are considered. Due to the movement of the ship, the specular reflection paths are constantly changing. The time-varying distance vector from the origin to the s -th ($s = 1, 2, \dots, S$) specular reflection point is defined as $\mathbf{d}_s(t) = [x_s(t), y_s(t), z_s(t)]^T$.

Assuming that the aforementioned three kinds of transmission paths are mutually independent, the physical characteristics of the entire system channel model can be described using the matrix $\mathbf{H}(t) = [h_{pq}(t, \tau)]_{Q \times P}$, where $h_{pq}(t, \tau)$ represents the complex impulse response of the transmission path between the p -th antenna at the BS side and the q -th antenna at the ship side, which can be denoted as [30]

$$h_{pq}(t, \tau) = h_{pq}^{\text{RIS}}(t) \delta(\tau - \tau^{\text{RIS}}(t)) + h_{pq}^{\text{specular}}(t) \delta(\tau - \tau^{\text{specular}}(t)) + h_{pq}^{\text{cluster}}(t) \delta(\tau - \tau^{\text{cluster}}(t)). \quad (13)$$

In Equation (13), τ^{RIS} , τ^{specular} , and τ^{NLoS} , respectively, represent the time-varying transmission delays for the RIS path, the sea surface specular reflection path, and the NLoS path, which are calculated as

$$\tau^{\text{RIS}}(t) = \frac{\|\mathbf{d}_{\text{RIS}} - \mathbf{d}_T\| + \|\mathbf{d}_{\text{RIS}} - \mathbf{d}_R(t)\|}{c}, \quad (14)$$

$$\tau^{\text{specular}}(t) = \frac{\|\mathbf{d}_s(t) - \mathbf{d}_T\| + \|\mathbf{d}_s(t) - \mathbf{d}_R(t)\|}{c}, \quad (15)$$

$$\tau^{\text{NLoS}}(t) = \frac{\|\mathbf{d}_{\text{cluster}} - \mathbf{d}_T(t)\| + \|\mathbf{d}_{\text{cluster}} - \mathbf{d}_R(t)\|}{c}, \quad (16)$$

where c represents the speed of light.

4.1. Complex CIRs for RIS Transmission Paths

Based on the RIS sub-array slicing algorithm proposed earlier, this paper next proposes a parametric statistical channel modeling method for the RIS-enabled BS–ship wireless communication scenario. When the signal emitted by the p -th element of the antenna array

at the BS side reaches the q -th element of the antenna array at the ship side after being processed by the $m_{x/z}^{\text{sub}}$ -th sub-array of the RIS array, the complex impulse response of the channel is represented as

$$h_{pq}^{\text{RIS}}(t) = \sum_{m_{x/z}^{\text{sub}}=1}^{M_{x/z,\text{max}}^{\text{sub}}} \gamma_{m_{x/z}^{\text{sub}}}(t) e^{j\vartheta_{m_{x/z}^{\text{sub}}}(t)} e^{-j\frac{2\pi}{\lambda} \left(\xi_{p,m_{x/z}^{\text{sub}}} + \xi_{q,m_{x/z}^{\text{sub}}}(t) \right)} \times e^{j\frac{2\pi}{\lambda} \left(\langle \mathbf{d}_{T,p}, \mathbf{e}_{T,m_{x/z}^{\text{sub}}} \rangle + \langle \mathbf{d}_{R,q}, \mathbf{e}_{R,m_{x/z}^{\text{sub}}}(t) \rangle \right)}. \quad (17)$$

In Equation (17), $\gamma_{m_{x/z}^{\text{sub}}}(t)$ and $\vartheta_{m_{x/z}^{\text{sub}}}(t)$, respectively, represent the control amplitude and control phase of the $m_{x/z}^{\text{sub}}$ -th sub-array in the RIS array. It is noteworthy to state that the optimal reflection phase configuration of the RIS transmission path can be obtained by optimizing the phase configurations of RIS array. This aims at compensating the phase difference between different transmit–receive pairs of transmission paths to achieve satisfactory technical indicators with the maximum power gain. The $\xi_{p,m_{x/z}^{\text{sub}}}$ and $\xi_{q,m_{x/z}^{\text{sub}}}(t)$, respectively, represent the path length from the p -th element of the BS antenna array and the q -th element of the ship antenna array to the $m_{x/z}^{\text{sub}}$ -th sub-array in the RIS array, calculated as $\xi_{p,m_{x/z}^{\text{sub}}} = \|\mathbf{d}_{m_{x/z}^{\text{sub}}} - \mathbf{d}_T - \mathbf{d}_{T,p}\|$ and $\xi_{q,m_{x/z}^{\text{sub}}}(t) = \|\mathbf{d}_{m_{x/z}^{\text{sub}}} - \mathbf{d}_R(t) - \mathbf{d}_{R,q}\|$. Here, $\mathbf{d}_{m_{x/z}^{\text{sub}}}$ represents the steering vector of the $m_{x/z}^{\text{sub}}$ -th sub-array in the RIS array, which is expressed as $\mathbf{d}_{m_{x/z}^{\text{sub}}} = [x_{m_{x/z}^{\text{sub}}}, y_{m_{x/z}^{\text{sub}}}, z_{m_{x/z}^{\text{sub}}}]^T$. Additionally, $\mathbf{e}_{T,m_{x/z}^{\text{sub}}}$ and $\mathbf{e}_{R,m_{x/z}^{\text{sub}}}$, respectively, represent the steering vectors of the BS and the ship corresponding to the $m_{x/z}^{\text{sub}}$ -th sub-array in the RIS array, expressed as

$$\mathbf{e}_{T,m_{x/z}^{\text{sub}}} = \begin{bmatrix} \cos \alpha_{T,m_{x/z}^{\text{sub}}}^{\text{ver}} \cos \alpha_{T,m_{x/z}^{\text{sub}}}^{\text{azi}} \\ \cos \alpha_{T,m_{x/z}^{\text{sub}}}^{\text{ver}} \sin \alpha_{T,m_{x/z}^{\text{sub}}}^{\text{azi}} \\ \sin \alpha_{T,m_{x/z}^{\text{sub}}}^{\text{ver}} \end{bmatrix}, \quad (18)$$

$$\mathbf{e}_{R,m_{x/z}^{\text{sub}}}(t) = \begin{bmatrix} \cos \alpha_{R,m_{x/z}^{\text{sub}}}(t)^{\text{ver}} \cos \alpha_{R,m_{x/z}^{\text{sub}}}(t)^{\text{azi}} \\ \cos \alpha_{R,m_{x/z}^{\text{sub}}}(t)^{\text{ver}} \sin \alpha_{R,m_{x/z}^{\text{sub}}}(t)^{\text{azi}} \\ \sin \alpha_{R,m_{x/z}^{\text{sub}}}(t)^{\text{ver}} \end{bmatrix}, \quad (19)$$

where $\alpha_{T,m_{x/z}^{\text{sub}}}^{\text{azi}}$ and $\alpha_{T,m_{x/z}^{\text{sub}}}^{\text{ver}}$, respectively, represent the departure horizontal azimuth angle and the departure vertical elevation angle of the BS corresponding to the $m_{x/z}^{\text{sub}}$ -th sub-array in the RIS array, calculated as [31]

$$\alpha_{T,m_{x/z}^{\text{sub}}}^{\text{azi}} = \arctan \frac{y_{m_{x/z}^{\text{sub}}}}{x_{m_{x/z}^{\text{sub}}}}, \quad (20)$$

$$\alpha_{T,m_{x/z}^{\text{sub}}}^{\text{ver}} = \arctan \frac{z_{m_{x/z}^{\text{sub}}} - H_0}{\sqrt{x_{m_{x/z}^{\text{sub}}}^2 + y_{m_{x/z}^{\text{sub}}}^2}}. \quad (21)$$

Additionally, $\alpha_{R,m_{x/z}^{\text{sub}}}^{\text{azi}}(t)$ and $\alpha_{R,m_{x/z}^{\text{sub}}}^{\text{ver}}(t)$, respectively, represent the time-varying arrival horizontal azimuth angle and the time-varying arrival vertical elevation angle of the ship corresponding to the $m_{x/z}^{\text{sub}}$ -th sub-array in the RIS array, calculated as

$$\alpha_{R,m_{x,z}^{\text{sub}}}^{\text{azi}}(t) = \pi - \arctan \frac{y_{m_{x,z}^{\text{sub}}} - d_{R,y}(t)}{x_{m_{x,z}^{\text{sub}}} - d_{R,x}(t)}, \quad (22)$$

$$\alpha_{R,m_{x/z}^{\text{sub}}}^{\text{ver}}(t) = \arctan \frac{z_{m_{x,z}^{\text{sub}}} - d_{R,z}(t)}{\sqrt{(x_{m_{x,z}^{\text{sub}}} - d_{R,x}(t))^2 + (y_{m_{x,z}^{\text{sub}}} - d_{R,y}(t))^2}}. \quad (23)$$

4.2. Complex CIRs for Sea Surface Transmission Paths

When the signal emitted by the BS is reflected by the sea surface and reaches the ship receiver, the expression for the complex impulse response function between the p -th transmitting antenna element and the q -th receiving antenna element is as follows:

$$h_{pq}^{\text{specular}}(t) = \sum_{s=1}^S e^{j\varphi_s - j\frac{2\pi}{\lambda}(\xi_{p,s}(t) + \xi_{q,s}(t))} \times e^{j\frac{2\pi}{\lambda}(\langle \mathbf{d}_{T,p}(t), \mathbf{e}_{T,s}(t) \rangle + \langle \mathbf{d}_{R,q}(t), \mathbf{e}_{R,s}(t) \rangle)}, \quad (24)$$

where φ_s represents the random sea surface fluctuation factor. $\xi_{p,s}(t)$ and $\xi_{q,s}(t)$, respectively, represent the time-varying path length from the p -th element of the antenna array at the BS and the q -th element of the antenna array at the unmanned ship to the sea surface, which are calculated as $\xi_{p,s}(t) = \|\mathbf{d}_s(t) - \mathbf{d}_p - \mathbf{d}_{T,p}\|$ and $\xi_{q,s}(t) = \|\mathbf{d}_s(t) - \mathbf{d}_q - \mathbf{d}_{R,q}\|$, respectively. Additionally, in Equation (24), $\mathbf{e}_{T,s}(t)$ and $\mathbf{e}_{R,s}(t)$, respectively, represent the unit distance vectors from the midpoint of the antenna array at the BS and the unmanned ship to the s -th specular scatterer, which are calculated as follows:

$$\mathbf{e}_{T/R,s}(t) = \begin{bmatrix} \cos \alpha_{T/R,s}^{\text{ver}}(t) \cos \alpha_{T/R,s}^{\text{azi}}(t) \\ \cos \alpha_{T/R,s}^{\text{ver}}(t) \sin \alpha_{T/R,s}^{\text{azi}}(t) \\ \sin \alpha_{T/R,s}^{\text{ver}}(t) \end{bmatrix}, \quad (25)$$

where $\alpha_{T,s}^{\text{azi}}(t)$ and $\alpha_{T,s}^{\text{ver}}(t)$, respectively, represent the time-varying departure horizontal azimuth angle and the time-varying departure vertical elevation angle of the specular reflection path signal, which are calculated as follows:

$$\alpha_{T,s}^{\text{azi}}(t) = \arctan \frac{y_s(t)}{x_s(t)}, \quad (26)$$

$$\alpha_{T,s}^{\text{ver}}(t) = \arctan \frac{z_s(t) - H_0}{\sqrt{x_s^2(t) + y_s^2(t)}}. \quad (27)$$

Similarly, $\alpha_{R,s}^{\text{azi}}(t)$ and $\alpha_{R,s}^{\text{ver}}(t)$, respectively, represent the time-varying arrival horizontal azimuth angle and the time-varying arrival vertical elevation angle of the scatterer's path signal, which are calculated as follows:

$$\alpha_{R,s}^{\text{azi}}(t) = \pi - \arctan \frac{y_s(t) - d_{R,y}(t)}{x_s(t) - d_{R,x}(t)}, \quad (28)$$

$$\alpha_{R,s}^{\text{ver}}(t) = \arctan \frac{z_s(t) - d_{R,z}(t)}{\sqrt{(x_s(t) - d_{R,x}(t))^2 + (y_s(t) - d_{R,y}(t))^2}}. \quad (29)$$

To describe the azimuthal distribution of scatterers, we introduced the von Mises distribution in the modeling to generate the arrival angle's horizontal azimuth and vertical elevation at the initial time, with its probability density function defined as follows:

$$f(\alpha) = \frac{e^{\kappa \cos(\alpha - \mu_\alpha)}}{2\pi I_0(\kappa)}, \quad (30)$$

where κ represents the angular spread control of the scatterer, μ_α denotes the average value of α , and I_0 is the zeroth-order modified Bessel function [32–34].

4.3. Complex CIRs for NLoS Transmission Paths

When the signal emitted by the BS is reflected by obstacles and reaches the ship receiver, the expression for the complex impulse response function between the p -th transmit antenna element and the q -th receive antenna element is [35]

$$h_{pq}^{\text{cluster}}(t) = \sum_{\ell \in L} \sum_{n=1}^{\ell_N} e^{j\varphi_{\ell_n} - j\frac{2\pi}{\lambda}(\xi_{p,\ell_n} + \xi_{q,\ell_n}(t))} \times e^{j\frac{2\pi}{\lambda}(\langle \mathbf{d}_{T,p}, \mathbf{e}_{T,\ell_n} \rangle + \langle \mathbf{d}_{R,q}, \mathbf{e}_{R,\ell_n}(t) \rangle)}, \quad (31)$$

where φ_{ℓ_n} represents the independently and uniformly distributed random phase. ξ_{p,ℓ_n} and $\xi_{q,\ell_n}(t)$ denote the path lengths from the p -th element of the BS antenna array and the q -th element of the ship antenna array to the ℓ -th scatterer in the n -th scattering cluster, calculated as $\xi_{p,\ell_n} = \|\mathbf{d}_{\ell_n} - \mathbf{d}_T - \mathbf{d}_{T,p}\|$ and $\xi_{q,\ell_n}(t) = \|\mathbf{d}_{\ell_n} - \mathbf{d}_R(t) - \mathbf{d}_{R,q}\|$. Additionally, they represent the unit distance vectors from the midpoint of the BS and the ship antenna arrays to the ℓ -th scatterer, calculated as [36]

$$\mathbf{e}_{T,\ell_n} = \begin{bmatrix} \cos \alpha_{T,\ell_n}^{\text{ver}} \cos \alpha_{T,\ell_n}^{\text{azi}} \\ \cos \alpha_{T,\ell_n}^{\text{ver}} \sin \alpha_{T,\ell_n}^{\text{azi}} \\ \sin \alpha_{T,\ell_n}^{\text{ver}} \end{bmatrix}, \quad (32)$$

$$\mathbf{e}_{R,\ell_n}(t) = \begin{bmatrix} \cos \alpha_{R,\ell_n}^{\text{ver}}(t) \cos \alpha_{R,\ell_n}^{\text{azi}}(t) \\ \cos \alpha_{R,\ell_n}^{\text{ver}}(t) \sin \alpha_{R,\ell_n}^{\text{azi}}(t) \\ \sin \alpha_{R,\ell_n}^{\text{ver}}(t) \end{bmatrix}, \quad (33)$$

where $\alpha_{T,\ell_n}^{\text{azi}}(t)$ and $\alpha_{T,\ell_n}^{\text{ver}}(t)$, respectively, represent the time-varying departure azimuth angle and the time-varying departure elevation angle of the scatterer path signal, calculated as

$$\alpha_{T,\ell_n}^{\text{azi}} = \arctan \frac{y_{\ell_n}}{x_{\ell_n}}, \quad (34)$$

$$\alpha_{T,\ell_n}^{\text{ver}} = \arctan \frac{z_{\ell_n} - H_0}{\sqrt{x_{\ell_n}^2 + y_{\ell_n}^2}}. \quad (35)$$

Similarly, $\alpha_{R,\ell_n}^{\text{azi}}(t)$ and $\alpha_{R,\ell_n}^{\text{ver}}(t)$, respectively, represent the time-varying arrival azimuth angle and the time-varying arrival elevation angle of the scatterer path signal, calculated as

$$\alpha_{R,\ell_n}^{\text{azi}}(t) = \pi - \arctan \frac{y_{\ell_n} - d_{R,y}(t)}{x_{\ell_n} - d_{R,x}(t)}, \quad (36)$$

$$\alpha_{R,\ell_n}^{\text{ver}}(t) = \arctan \frac{z_{\ell_n} - d_{R,z}(t)}{\sqrt{(x_{\ell_n} - d_{R,x}(t))^2 + (y_{\ell_n} - d_{R,y}(t))^2}}. \quad (37)$$

5. Channel Transmission Characteristics Analysis

The previous derivation shows that the expression of the channel impulse response function is jointly affected by factors such as time, space, and frequency, meaning that, at the same time node but different spatial nodes or different frequency points, the physical characteristics of the channel exhibit significant differences. This is because the deployment of a large number of elements in the RIS array, the high-speed movement of the ship, and the transmission of signals with large bandwidth each contribute to the non-stationary characteristics of the RIS-enabled BS–ship communication channel in terms of spatial, temporal, and frequency resource nodes. Therefore, in order to address the non-stationary transmission characteristics of the RIS-enabled BS–ship communication channel, it is necessary to define channel model parameters from the perspectives of spatial nodes, temporal nodes, and frequency nodes, defined as follows:

$$\rho_{h_{pq}h_{p'q'}}(t, \Delta t) = \frac{\mathbb{E}[h_{pq}(t)h_{p'q'}^*(t + \Delta t)]}{\sqrt{\mathbb{E}[|h_{pq}(t)|^2]\mathbb{E}[|h_{p'q'}(t + \Delta t)|^2]}}, \quad (38)$$

where $h_{p'q'}(t)$ represents the complex impulse response of the channel from the p' -th element of the BS antenna array to the q' -th element of the antenna array at the ship side; $\mathbb{E}[\cdot]$ denotes the mathematical expectation; and $(\cdot)^*$ signifies the complex conjugate. In this paper, the multi-domain signal propagation mechanism of RIS communication is applied to the near-field communication channel modeling, and a communication channel model for RIS-enabled BS–ship communications based on the RIS sub-array slicing algorithm is proposed. This model breaks through the technical bottleneck of achieving a balance between modeling accuracy and computational complexity, characterizing the joint non-stationary transmission characteristics of the channel at spatial, temporal, and frequency multi-domain resource nodes, as well as the mapping relationship between the parameters, such as sea surface wave effects, physical attributes of the RIS array, and scattering environment configuration.

6. Simulation Results and Discussion

It is worth mentioning that channel models are of significant importance to the design, optimization, and performance evaluation of air-to-ground wireless communication systems. In light of this, it is critical to propose a physical dynamic channel model that can faithfully reflect the impacts of the physical characteristics of an RIS array on the electromagnetic waves in a wireless environment between the UAV transmitter and ground receiver. Unless otherwise indicated, the parameter settings of the simulated results are according to [17–19], which are as follows: $f = 5$ GHz, $P = 3$, $Q = 4$, $H_0 = 30$ m, $H_1 = 3$ m, $D_0 = 150$ m, $\delta_T = \delta_R = \lambda/2$, $\psi_T^{\text{azi}} = \psi_R^{\text{azi}} = 0$, $t = 2$ s, $x_{\text{RIS}} = 60$ m, $y_{\text{RIS}} = 25$ m, $z_{\text{RIS}} = 20$ m, $M_x = M_z = 50$, and $d_M = \lambda/2$.

Figure 2 depicts the mechanism relationship between the modeling error of the RIS-enabled BS–ship communication channel at different times and the size of the RIS. The simulation results indicate that, when the RIS size is small, causing the distance between the RIS and the BS/ship to be greater than the Rayleigh distance, the far-field plane wave model can be effectively used to analyze the channel transmission characteristics. Under this condition, the traditional plane wavefront channel model and the proposed sub-array slicing-based channel model show similar performance in terms of modeling error, achieving relatively equal accuracy. However, as the RIS array size continuously increases, causing the distance between the RIS and the BS/ship to be less than the Rayleigh distance, the near-field spherical wave model becomes more suitable for describing the channel transmiss-

sion characteristics. Combining the simulation results, it can be observed that the proposed sub-array slicing scheme can ensure modeling accuracy while reducing computational complexity compared to the traditional channel modeling methods. Furthermore, since the distance between the RIS and the ship changes at different time nodes, it directly affects the modeling performance of the RIS-enabled maritime communication channel. Based on the aforementioned observations, it can be concluded that the provided sub-array-based modeling solution is helpful to achieve satisfactory technical indicators with high precision and low complexity, thus providing standard guidance for the research designers to optimize the performance of the RIS-enabled BS-to-ship wireless communication systems.

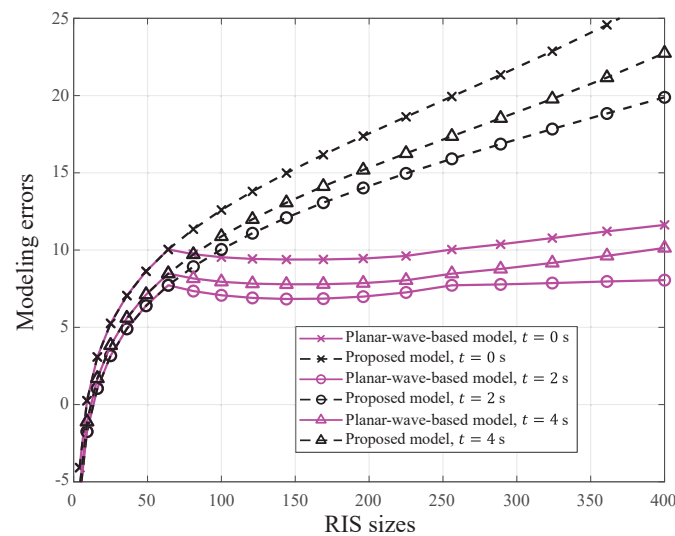


Figure 2. Modeling error comparison of the RIS-enabled BS-ship communication channel based on the proposed sub-array method versus the traditional method.

By utilizing Equations (28)–(30), the correlation characteristics of the path links within the considered communication model for various propagation links are depicted in Figure 3. Specifically, Figure 3 illustrates the spatial cross-correlation characteristics of the proposed channel model at different spatial positions of the RIS array. It is evident that the values of the correlation features of the propagation links in the space domain drop slowly as we increase the value settings of the antenna intervals. This observation can also be observed in [27], corroborating the accuracy of our simulated results. It is worth considering that not only Equations (28) and (29) but also Equation (30) are all Bessel functions, thereby leading to a fluctuation observation with the rising value setting of the antenna spacing. Nonetheless, the general changing curves of the spatial correlation features decrease when increasing the antenna spacing. The simulation results show that, as the distance between the receive antennas continuously increases, the spatial correlation between the different transmission paths in the proposed channel model exhibits a gradual decreasing trend. These simulation results fit well with the findings in [37], verifying the accuracy of the derivation and simulation results of the spatial cross-correlation characteristics of the channel model presented in this paper. Additionally, when the spatial position of the RIS array changes, the curves of the spatial correlation of the proposed channel model show significant differences. This phenomenon is helpful for the researchers to conclude that the physical properties of the RIS array, such as its position, play an obvious role in the investigation of RIS-enabled BS-to-ship channel statistics. In light of this, when we design the RIS-enabled BS-to-ship wireless communication systems, it is important to consider the aforementioned conclusions.

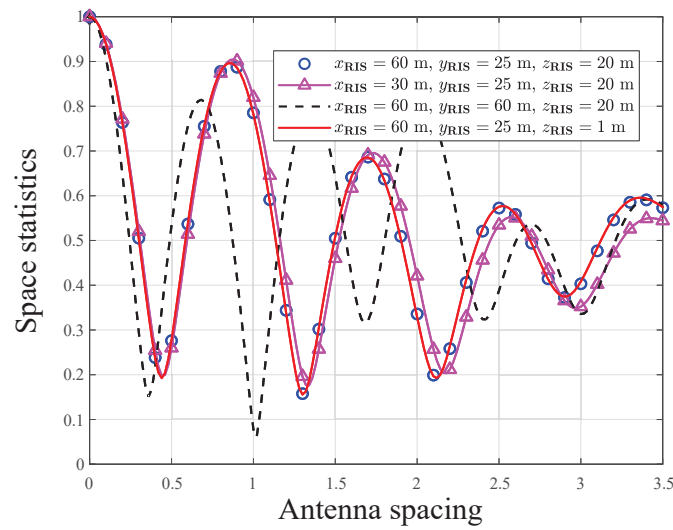


Figure 3. Spatial cross-correlation characteristics of the RIS-enabled BS–ship communication channel under different spatial positions of the RIS array.

Figure 4 depicts the spatial cross-correlation characteristics of the proposed channel model under different distance parameters D_0 . The simulation results indicate that, when the distance parameter D_0 is set to different values, the spatial cross-correlation characteristics between different transmission paths exhibit different trends of change, indicating that the proposed model has non-stationary features in the spatial domain. Moreover, when the value of the distance parameter D_0 is greater than 200 m, the ship receiver is within the far-field range of the RIS. In conjunction with the above simulation results, it can be observed that, as the distance parameter D_0 in the RIS-enabled BS–ship communication channel gradually increases, the spatial correlation of the proposed channel model also increases, which is consistent with the conclusions in [37], verifying the correctness of the obtained results.

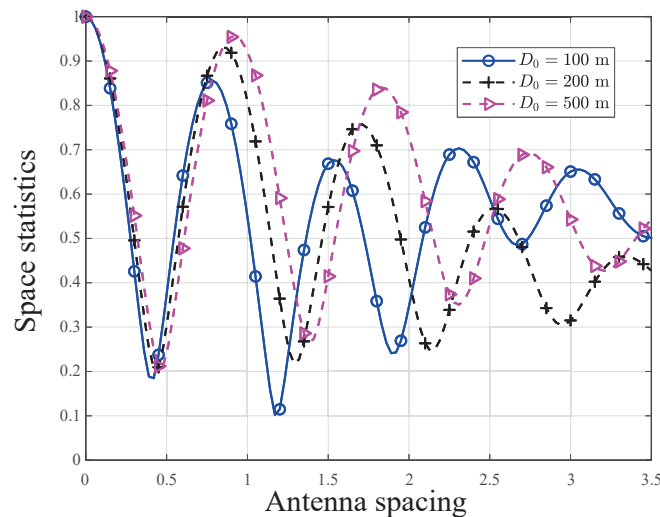


Figure 4. Spatial correlation characteristics of the RIS-enabled BS–ship communication channel model under different distance parameters.

By using Equation (31), Figure 5 illustrates the correlation characteristics of the path links in the time domain within the considered model. Specifically, Figure 5 illustrates the time-domain autocorrelation characteristics of the proposed channel model at different moments of motion and under different spatial positions of the RIS array. The simula-

tion results indicate that, when different values are set for the motion time parameter t , the time-domain autocorrelation characteristics between the transmission paths exhibit different trends of change, indicating that the proposed model possesses non-stationary features in the time domain. Furthermore, as the motion time t continuously increases, the decline in the autocorrelation curve of the proposed channel model becomes significantly more pronounced, which is consistent with the simulation results in [38–40], verifying the accuracy of the derivation and simulation results of the time-domain autocorrelation characteristics of the channel model presented in this paper. The simulation results also show that the spatial deployment position of the RIS array has a significant impact on the time correlation of the proposed channel model. On the whole, the aforementioned simulation results can provide important technical references for the subsequent research and design of RIS communication systems.

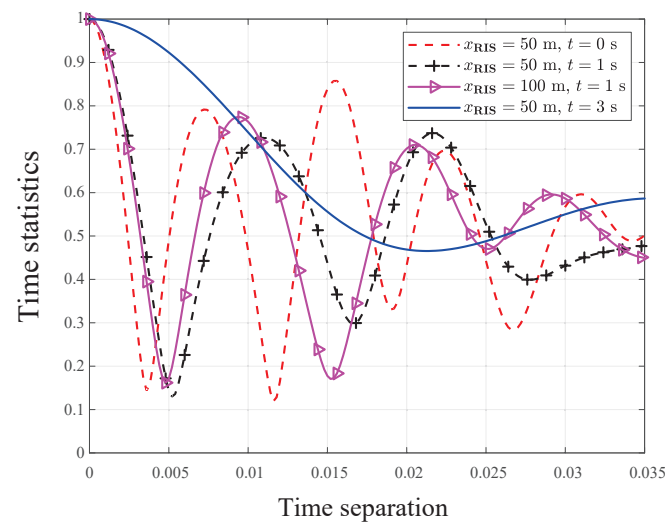


Figure 5. Time-domain autocorrelation characteristics of the RIS-enabled BS-ship communication channel model at different time nodes.

7. Conclusions

This paper proposes a parameterized statistical channel model for RIS-enabled near-field maritime communication. By adjusting the configuration of the channel parameters, the proposed channel model is capable of describing various types of RIS-enabled maritime communication scenarios. The simulation results indicate that the proposed sub-array slicing algorithm can achieve a balance between computational accuracy and complexity when analyzing the transmission characteristics of RIS-enabled wireless communication channels, which has significant theoretical implications for the design of future RIS-enabled wireless communication systems. Furthermore, the simulation results also show that the physical attributes of the RIS array and the influence of sea surface wave effects can impact the signal propagation mechanisms in the spatial, temporal, and frequency domains. These simulation results will provide important technical support for the application of RIS technology in future information networks, aiming to form multiple intellectual property rights and theoretical systems, and to promote the rapid development of the 6G mobile communication industry.

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