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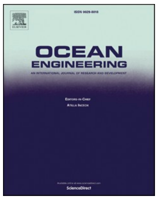

Spatial modeling and analysis approach for ship-encounters dynamic spatial–temporal domain

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ABSTRACT

One of the crucial issues at the forefront of smart ship development that urgently needs solutions is navigational situation safety awareness technology. The development of intelligent navigation safety technology is severely constrained by the issue of challenging mining and accurate measurement of ship encounter dynamic space-time variation law and unknown nonlinear spatial representation information. This work creatively offers a GIS spatial modeling and analysis method based on the dynamic space-time domain of ship encounters, based on the GIS spatial information platform and spatial analysis theory. Based on the ship's approaching rate, encounter hazard identification parameters, relative space-time position distribution, etc., combined with the normal distribution function of the spatial distance adjustment variable, the method successfully constructs a multi-time-space, multi-angle, and multi-state encounter space model. By efficiently reducing the ambiguity of the spatial distribution of hazards, it realizes the in-depth analysis of the spatial distribution features of potential hazards as well as the temporal and spatial trends in the dynamic process of ship navigation. To break through the technical problems of spatial analysis and perception of ship-encountered dangerous area sources. It offers a fresh approach for enhancing intelligent navigation's capacity for safety analysis of ship interactions.

Author contributionsZhichen Liu: Methodology, Experiments, Formal analysis, Validation, Writing – original draft, Visualization, Ying Li: Methodology, Resources, Wenbo Yu: Experiments, Formal analysis, Validation, Bing Han: Resources, Writing – review & editing, YeG Du: Methodology, Writing – review & editing, All authors have read and agreed to the published version of the manuscript.

GIS	Geographic information system
IMO	International Maritime Organization
UNCTAD	United Nations Conference on Trade and Development
IHO	International Hydrographic Organization
ALARP	As low as reasonable practice
MAE	Classic mean absolute error
RMSE	Root mean square error
MRE	Mean relative error
CCS	China Classification Society
EMSA	European Maritime Safety Agency
DFE	Degree of fit error

1. Introduction

1.1. Background

According to the Review of Maritime Transport 2021 and The United Nations Conference on Trade and Development (UNCTAD) official data, the average annual growth rate of maritime trade in the past 20 years is about 2.9%. And the growth rate will not be lower than 2.4% in the next 5 years. Also anticipated for 2023 is a rise in seaborne trade to 12.5 billion tons. As a result, the volume of marine vessel traffic will continue to rise in tandem with the volume of maritime transport trade. According to statistics, the density of ships in sea areas such as the coast of China, Japan and South Korea, the Strait of Malacca, the surrounding waters of the United Kingdom, the northeastern Mediterranean, and the

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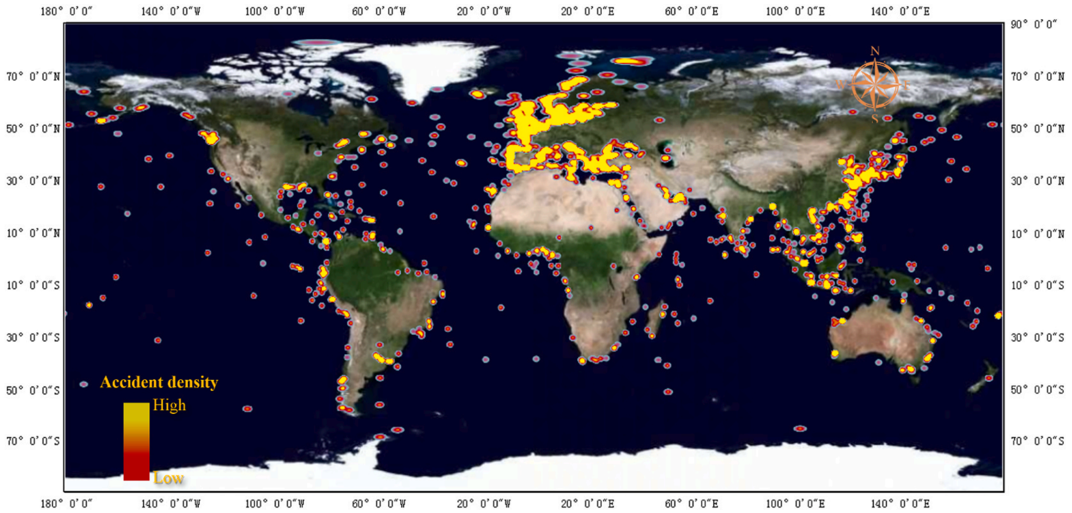
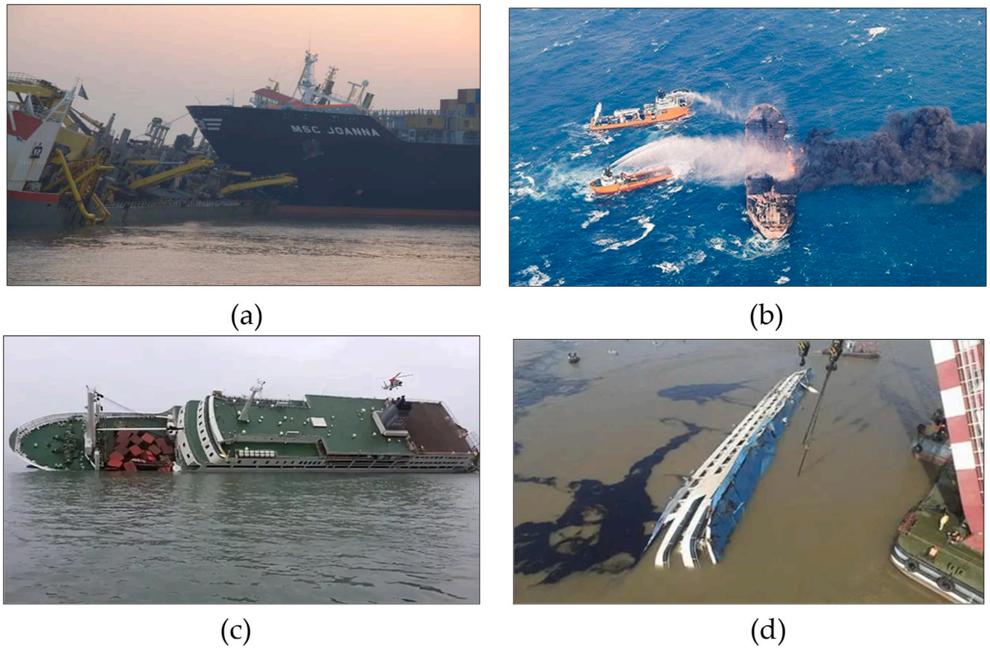


Fig. 1. Spatial distribution map of global maritime accidents.



(a) (b) (c) (d)

Fig. 2. Typical ship collision scenario: (a) Accident scene of the “Fen Wei” (http://news.enorth.com.cn/system/2007/03/12/001572855.shtml) (b) Accident scene of the “SANCHI” (http://psa.cnpowder.com.cn/psa/newsdetail.php) (c) Accident scene of the “SEWOL” (https://www.163.com/dy/article/HF0F1QPO055369F5.html).” (d) Accident scene of the “Eastern Star”(https://baijiahao.baidu.com/s?id=1711047130531248418&wfr=spider&for=pc).

Turkish Strait is very high. There are more than 200,000 vessels in the Pas de Calais and the la Manche channel, which are the strait areas with the largest sea traffic flow in the world. In East Asia, the routes are busy and the number of ships is large. More than 90% of foreign trade goods from China, Japan and South Korea are transported by sea.

Therefore, the marine trade industry and marine economy have risen to the national strategic level. However, marine traffic accidents are unavoidable while marine traffic is active. For example the traffic accident of "Costa Concordia", the sinking accidents of "Sewol" and "Titanic", the subversion of the passenger ship "Oriental Star" in the China Sea, the "SANCHI" collision explosion, and other typical maritime accidents. Fig. 1 visually shows the spatial statistics of global maritime accidents (2011–2021). In addition, the European Maritime Safety Agency (EMSA) database shows that from 2011 to 2021 there were an average of more than 3239 maritime traffic accidents per year. And ship collisions caused up to 51% of maritime accidents. Fig. 2 also visually shows the typical ship collision scenario. Therefore, the problem of ship navigation safety has become more and more important, and it is urgent to tackle the key technologies of ship navigation risk perception and analysis, which is related to life safety, environmental protection and economic development, and has always been a key topic that countries all over the world attach great importance to and study hard. Especially with the advancement of the "e-Navigation" strategy of the International Maritime Organization (IMO) and the "14th Five-Year" Modern Integrated Transportation System Development Plan, “Smart Ship Specifications" and "Smart Ship Development Action Plan (2019–2021)" issued by the International Hydrographic Organization (IHO), China Classification Society (CCS), and the Ministry of Industry and Information Technology, the scientific and technological development requirements of ship navigation situation safety analysis technology has been further stimulated to inspire (see Fig. 3).

Fig. 3. The overall research framework of this article.

1.2. Research goals

Currently, in the field of navigation safety, it is urgent to rely on a robust spatial information platform and a spatial analysis approach that can be used to analyze the safety characteristics of navigation encounters. It can enhance perception, address the issue of a deep analysis of the spatial distribution properties of the encounter danger in the dynamic space-time domain under the multi-time-space sequence and nonlinear space, and handle the problem of the deep analysis of the spatial-temporal trend law. It provides spatial analysis results with the safety characteristics of encounters and spatial–temporal attribute information for the safe navigation of ships, thereby greatly reducing the spatial ambiguity of encounters. The research ideas presented in this paper have the potential to significantly advance the theoretical innovation of a new method system for the safety analysis of ship encounters based on GIS spatial analysis, as well as provide forward-looking theoretical and method support for the development of intelligent navigation safety perception technology.

Therefore, in the face of ship encounter dynamic information, there are challenges such as chaotic spatial characteristics, significant temporal-spatial correlation, low degree of refinement of spatial characteristics, and difficulty in accurately analyzing and extracting nonlinear spatial–temporal distribution characteristics of the encounter space. This work suggests a new approach to GIS spatial modeling and analysis based on the encounter dynamic space-time domain, which is inspired by GIS theory. This method effectively takes into account both spatial and temporal attributes in the course of navigating encounters. To realize the in-depth analysis and extraction of the spatial distribution characteristics and spatial–temporal trends of potential hazards in multi-temporal sequences and nonlinear spaces. It breaks through the problems of spatial analysis and perception of area sources of dangerous ships, and effectively reduces the spatial ambiguity of the ship in danger. It can significantly improve the space safety perception and encounter safety analysis capabilities of future ship intelligent navigation. There are 6 sections in this paper. Section 2 discusses the current situation, advantages and disadvantages of the current navigation risk analysis methods, and draws out the research motivation and contribution of this paper. Section 3 specifically introduces the new method of GIS spatial modeling and analysis of ship encounter dynamic space-time domain. In Sections 4 and 5, we verify the accuracy and superiority of the proposed method on the basis of real SANCHI accident encounter scenario data. Additionally, Section 6 of this paper's novel method is dedicated to a thorough discussion of its innovations and drawbacks. Section 7 presents the results and the next phase of the investigation.

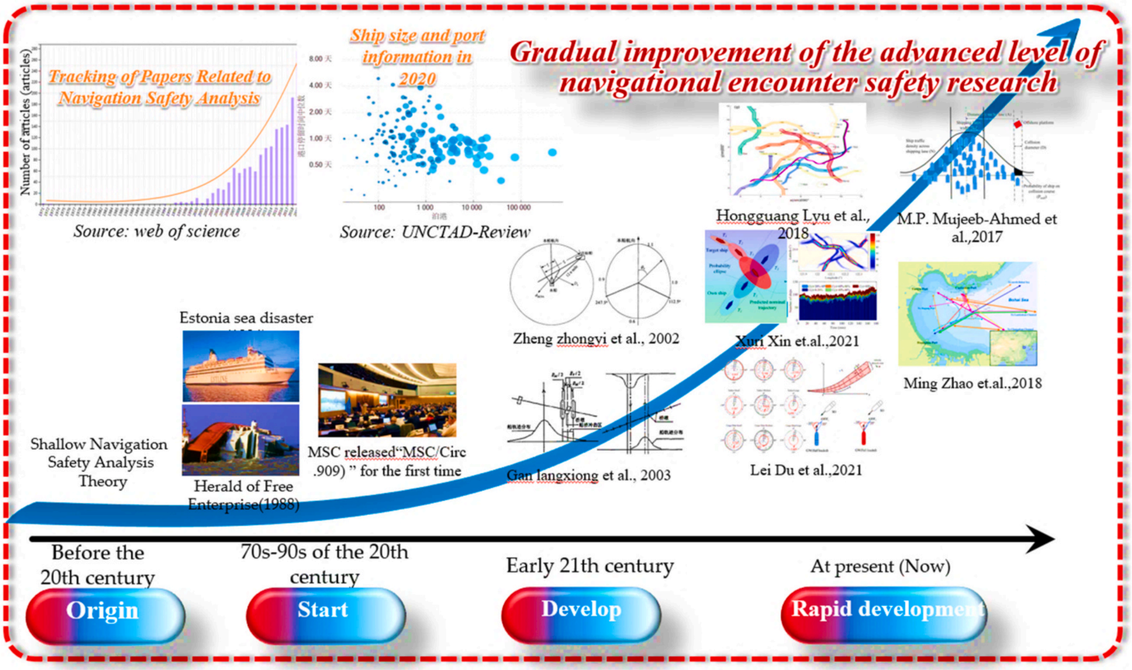


Fig. 4. The typical literature analysis and research progress of ship navigational encounter danger in detail.

2. Related work

2.1. Literature review

Since the 21st century, the International Maritime Organization (IMO) has been consistently enhancing a number of international agreements and rules to raise the bar for ship navigation safety. Almost all coastal nations at the moment have embraced the IMO's (IMO, 2002, 2003) navigation safety assessment program, which has substantially aided the advancement of research into ship navigation risk. Research organizations and academics from many nations have made significant progress in the field of ship collision safety. Using Fig. 4, we conduct a thorough overview and analysis of the direction of development for navigation hazard analysis algorithm research. One of these was the capacity of ships to automatically avoid hazards and impediments, which was selected by the worldwide partner alliance smart ship research project team lead by ProMare as one of the fundamental technologies for the main advancement. The created intelligent ship system makes use of IBM's Power server, Edge computing, and cloud computing technology to create an intelligent navigation data integration and safety analysis module that significantly enhances the ship's capacity to navigate safely. Second, relevant researchers and professionals employ computer and information technology in conjunction with pertinent intelligent algorithms to identify and analyze ships in danger. Gao et al. (2022) built a Seq-CGAN model to learn the navigation behavior during the ship encounter process, and guided the ship's intelligent collision avoidance and decision-making according to the algorithm results. Xu X et al. (2020) proposes a dynamic collision avoidance path planning algorithm based on the A-star algorithm and ship navigation rules, and further obtains the collision relationship between ships and obstacles during the encounter process. Liu J et al. (2022) proposed an intelligent algorithm for multi-ship collision avoidance in complex navigation scenarios, and studied the problems of hazard identification and real-time collision avoidance when multi-ship navigation. Yu Q et al. (2022) proposed a comprehensive assessment framework for ship collision risk and studied Evidential reasoning approach aggregate collision risk. Third, researchers combine numerous cutting-edge mathematical models to study the risks associated with ship sailing. Goerlandt and Kujala (2011) Computing the probability of ship collisions through traffic simulation. Silveira et al. (2013) used computer simulation to predict the relative position relationship of future ships and based on this to calculate the possible collision probability. Debnath and Chin (2009, 2010, 2011, 2016) fitted the relationship curve between collision risk and DCPA and TCPA based on the sequential probit method, obtained the probability result of the ship encountering safety, and then predicted the collision risk in the water area. Zhen R et al. (2017,2021) conducted research on macroscopic maritime collision hazards based on mathematical clustering algorithms. Lu N et al. (2022) established a ship navigation safety field model based on the field theory model in physics, and evaluated the risk of navigation in space by comparing the reference value and fluctuation range of the unstable energy proportional fluctuation curve in waters. Zhen R et al. (2022) quantified the risk of water collision based on the dynamic circle. In addition, some scholars use the calculation of ship density (Wang S et al., 2022; Rong H et al., 2022), ship track (Breithaupt et al., 2017; Rong et al., 2020), close encounter probability (Yoo S L, 2018; Rong H et al., 2021; Fang Z et al., 2018) and other visualizations of marine traffic conditions indices to characterize water collision hazards.

The concept of using the mathematical elliptic domain method to study ship collision avoidance has gradually advanced in recent years. The ship domain is a generalized representation of the ship safety distance, and the safety distance in each direction is different(Fuji and Tanaka, 1971; Goodwin, 1975). It refers to a safe area around the ship to prevent other ships from entering. This domain is a safe encounter distance model that considers factors such as ship scale, motion parameters, and encounter situation. Compared with the circular area constructed by DCPA, the safe encounter distance determined for ships coming from different azimuths in the ship area is different. By establishing a ship domain similar to the elliptic domain, not only can the problem of close-range collision avoidance be solved, but also the accuracy of ship collision avoidance is higher than that of traditional DCPA/TCPA. In addition, the theory of ships' domain continues to receive the focus of attention in the field of collision risk research, and it is one of the most potential and developmental directions in the field of intelligent collision avoidance. Through literature research, a well-known domestic scholar He Y has also conducted more illuminating and reference research based on the concept of elliptical domain in

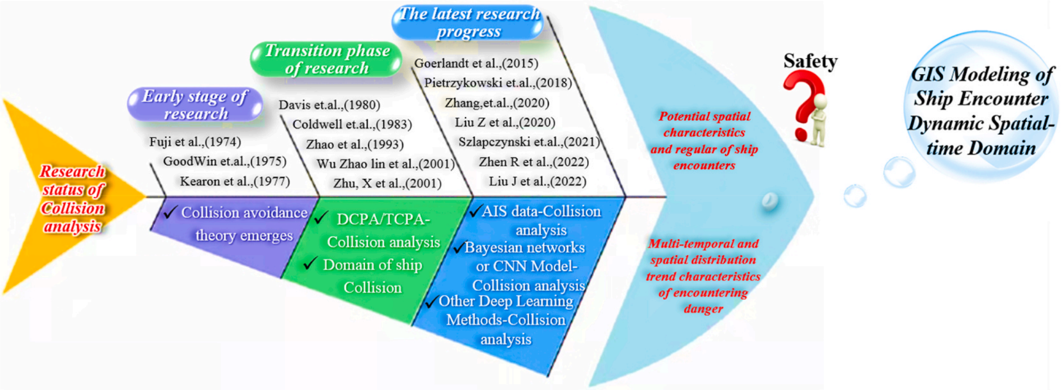


Fig. 5. Research goals and innovations based on the summary analysis of the latest ship encounter danger research overview.

terms of research on ship navigation dangers based on the elliptical domain. Their team proposed three advanced models, it is developed to discriminate encounter situations, stages and actions, and then a new quantitative analysis system is provided based on the International Regulations for Preventing Collisions (COLREG) and navigation technology to generate collision avoidance plans suitable for different encounter situations (He Y et al., 2017). Secondly, their team through real-time sampling, rapid update of the own ship's motion parameters, and traffic situation information, an open-water intelligent navigation decision-making method that can dynamically adapt to the residual error in the system and the target ship's random manipulation is proposed (He Y et al., 2022). Some scholars have also proposed ship domain models that can be used for collision risk identification based on expert knowledge and artificial intelligence (Pietrzykowski et al., 2012; Du L et al., 2021). The methods they proposed are highly feasible and accurate, can significantly improve intelligent navigation safety analysis ability, and provide forward-looking method support and reference value for the development of intelligent navigation situational safety awareness theory. Therefore, this article is also inspired by the elliptical domain idea, and proposes a spatial modeling and analysis method for the ship-encounters dynamic spatial–temporal domain. The method successfully constructs a multi-temporal, multi-angle, multi-state encounter dynamic spatial–temporal domain. It achieves in-depth analysis of the spatial distribution characteristics of potential danger encounters and the spatial-temporal trend laws in the dynamic process of ship navigation, solves the problem of spatial analysis and perception of ship danger surface sources, and effectively reduces the spatial complexity and ambiguity of encounter time. Provides new method support for improving the safety analysis ability of ship-encounters dynamic spatial–temporal domain.

2.2. Motivation and contribution

It is difficult to perceive and analyze the danger of ship navigation in the current context, which has always been one of the core technologies that urgently require breakthroughs in the safety of intelligent

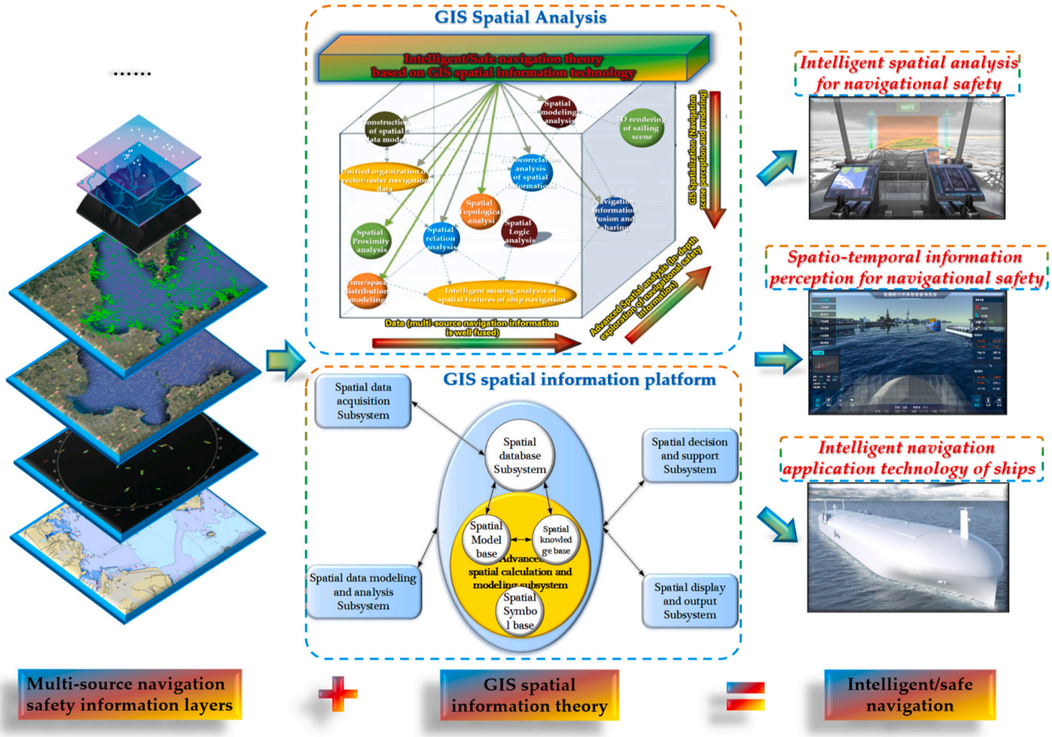


Fig. 6. Research advantages of Spatial analysis of navigation safety and intelligent navigation based on GIS spatial information technology theory.

navigation. Mining the spatiotemporal characteristics and laws of ship encounters has long been a major challenge in navigation safety research. Although the development of ship navigation situation safety analysis technology has received a lot of attention from both domestic and international research institutions. However, most of the existing ship encounter risk algorithm systems focus on the numerical analysis of the collision risk and the single-objective ship risk analysis, without in-depth exploration of the potential heterogeneous and nonlinear space of ship encounter from the perspective of space analysis. In-depth analysis of representational relationships and spatiotemporal trends. In addition, the danger of ship navigation is a spatial–temporal attribute that is closely related to time and space position, resulting in the navigation safety information presenting interlaced and complex spatial–temporal differences and a large number of potential spatial features and regular information. Therefore, there are still many theoretical gaps in the measurement of navigational encounter safety space characteristics, which is also one of the important technical obstacles restricting the research of intelligent navigation safety. Fig. 5 describes in detail the innovations and contributions based on the latest research on ship encounter hazards. Meantime, the Maritime Technology Research Group of Aalto University in Finland, Gdynia Maritime University in Poland, and the domestic navigation safety assurance research team carried out a series of research and conclusions. The results show that it is an efficient and feasible research idea to realize the rapid analysis of navigation situation security from the data layer to the application layer based on the GIS spatial information platform (building a spatial processing and analysis platform that integrates other multi-source navigation information with electronic charts as the bottom layer). GIS spatial information platform belongs to a powerful information platform, which includes spatial data acquisition sub-module, advanced spatial calculation and modeling sub-module, spatial database sub-module, spatial data analysis and query sub-module, decision-making and support sub-module, display and output submodule. The spatial modeling and analysis research framework of ship encounters dynamic space-time domain proposed in this paper is designed and realized based on the support of powerful subsystems in the GIS platform. It can not only improve the utilization rate of ship encounter data, simplify the complexity of space calculation of encounter safety features, but also give full play to play to a great extent the advantages of GIS's advanced spatial data computing capabilities, advanced spatial analysis and modeling methods, and analysis of spatial distribution rules. It provides important spatial information technology support for the new method proposed in this paper. Fig. 6 shows in detail the research advantages of navigation safety spatial analysis and intelligent navigation based on GIS spatial information technology theory.

Second, traditional methods are unable to accurately and efficiently measure and extract the Complicated spatial–temporal feature information, especially when dealing with complex encounter scenarios like those involving obstacles and dense ships. This is because the ship encounter process is a space-time dynamic behavior closely related to the spatial position, and the ship navigation hazard is a spatial–temporal attribute closely related to time and space position. Therefore, in order to conduct in-depth research and exploration, it is necessary to combine the GIS spatial information platform with a spatial analysis approach. However, this research has not been published. GIS technology has the advantages of strong spatial analysis modeling and spatial computation capabilities in the face of complicated and dynamic navigation encounters. It is capable of mining geographical distribution data and trend rules in the encounter process from a time and space perspective in order to thoroughly examine and determine the safety level of every encounter scenario. It is a powerful means to solve the problem of dynamic spatial law analysis of moving targets. Therefore, this paper focuses on proposing a new method based on the GIS spatial information platform for modeling and analyzing the dynamic space-time domain of ship encounters, so as to realize the in-depth analysis of the spatial distribution characteristics of potential hazards and the trends of time and space in the dynamic process of navigation. This method deeply reveals the safety situation of the ship's encounter situation from the perspective of time and space, effectively reduces the spatial complexity and ambiguity of the encounter, and provides a new method support for improving the safety analysis ability of the ship's encounter in the dynamic space-time domain. It also provides forward-looking and innovative method support for the development of intelligent navigation situational security awareness theory.

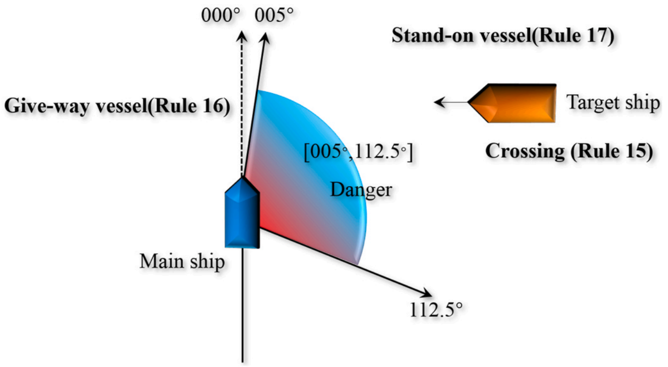


Fig. 7. Graphical expression of vigilance for incoming starboard ships in the COLREG clauses 15–17.

3. Methods

3.1. Construction of a spatial model of the ship encounter hazard domain

In this study, firstly, construct a spatial model of the ship encounter hazard domain is the initial step. This spatial model adds certain spatial constraints to the spatial extent of the encounter during the ship's voyage. The encounter risk characteristics are unique for different spatial locations. The spatial model of the ship encounter hazard domain has its roots in the elliptical domain. This was inspired by the work of Szlapczynski and Szlapczynska (2016). The ship position is placed in the lower left quarter of the center of the offset ellipse, which meets the requirements of strengthening the vigilance on the starboard and head-on situation mentioned in the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) and reflects the perception of the risk of collision by ship drivers. Fig. 7 shows the clauses in COLREGs that require vigilance for ship sailing. The oval space (Fig. 8) indicates the location where other ships are forbidden to invade, and the collision-risk index (CRI) within the space is unity. We studied the spatial distribution of collision risk between our ship and the target ship in dangerous waters. Dangerous waters refer to the area where a ship must be conscious of the target ship. The CRI is 0 at the space boundary of the dangerous water area, also known as the CRI zero boundary. Through numerous investigations and statistics, Zheng and Wu (2001) found that the CRI zero boundary is approximately twice as large as that of the DCPA. Thus, dangerous waters should be twice the size of the oval space. According to the abovementioned safety analysis theory, we established the space range of the waters where ships encounter danger. This water can ensure that the relative position of the ship and the center of the ship domain remain unchanged to facilitate the calculation of the risk degree, which is accurate and meets the rules of the collision avoidance established in the following (Fig. 7, COLREG clauses 15–17). Fig. 8 shows the detailed construction principle of the ship-encounter space domain during ship motion. Its construction process is proposed based on the Szlapczynski ship domain model (Szlapczynski and Szlapczynska, 2016; Szlapczynski et al., 2018). In the Szlapczynski ship domain, the ship's position semi-major axis offset and semi-minor axis offsets are 2.5L and 1.25L. For the convenience of calculation, experienced captains usually think that the distance of the zero boundaries of space hazard of own ship is about twice the minimum

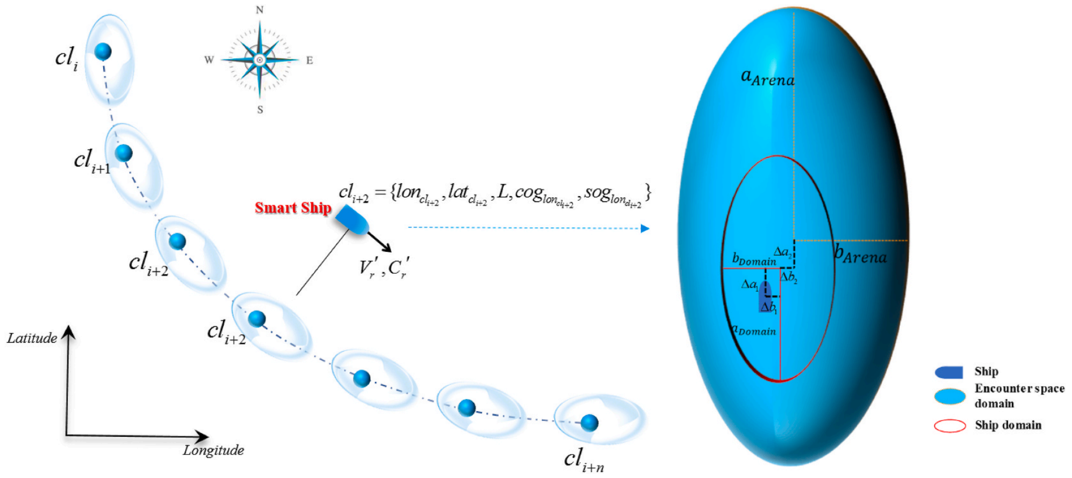


Fig. 8. Detailed construction principle of the ship-encounter space domain during intelligent navigation motion (L is the length of the target ship).

safe encounter distance. Therefore, under the premise that the relative position of the ship and the domain center remains unchanged, the method in this paper is about twice the distance from the ship position to the domain boundary. The displacement of a ship along the semimajor and semi-minor axes can be expressed as $\Delta a = \Delta a_1 + \Delta a_2 = 5\text{L}$ and $\Delta b = \Delta b_1 + \Delta b_2 = 2.5\text{L}$, respectively(the specific meaning of the variable is shown in Fig. 8). In Fig. 8, L is the length of the target ship, Δa is offset of the semi-major axis of the ship's position, Δb is offset of the semi-minor axis of the ship's position, Δa_1, Δa_2, Δb_1, Δb_2 is the geometric auxiliary variable in the offset calculation process. a_{Domain} and b_{Domain} represent the semi-major axis and semi-minor axis of the ship domain respectively, a_{Arena} and b_{Arena} is the semi-major and semi-minor axes of ship-encounter space domain. Simultaneously, the meanings of the formulas and symbols used in the approach have also been summarized, as shown in Table 1. It displays symbol descriptions in the text and method formulations.

3.2. Construction of ship encounters dynamic spatial–temporal domain

In the case of encounter between the main ship and other ships, Based on the spatial model of ship encounter hazard domain proposed in the previous section, this study combines the calculation results of approaching rate, collision hazard identification parameters and relative spatial position distribution to construct the sea space where the target ship poses a threat to the main ship within a certain time gradient, which is the dynamic spatial–temporal domain of the encounter mentioned in this paper. To enhance the accuracy of spatial modeling, this dynamic spatial–temporal domain takes the spatial matrix as the basic unit to normalize the encounter hazard of the domain, which is showing a nonlinear continuous distribution between [0, 1]. The boundary of the dynamic spatial–temporal domain space will be encountered as the edge where the driver perceives the danger of a collision. Secondly, the time range of encounter hazard is constructed by using the moment t_{in} when the ship invades the spatial model of the encounter hazard domain of the target ship and the moment t_{out} when it leaves the spatial model of the encounter hazard domain of the target ship. The constructed dynamic spatial–temporal domain of the encounter can be divided into 3 cases. First, when $t_{in} \geq 0$ and $t_{out} \geq 0$, it means that there is no intrusion into the spatial model of the encounter hazard domain in this space-time, that is, the encounter dynamic spatial–temporal domain has not been formed yet. Second, when $t_{in} < 0$ and $t_{out} < 0$, it means that the behavior of intruding into the spatial model of dangerous domain in this spatial–temporal has ended, that is, the encounter dynamic spatial–temporal domain has been formed. Third, when $t_{in} < 0$ and $t_{out} \geq 0$, it means that the ship is intruding into the spatial model of dangerous domain in this space-time, that is, the formation of the encounter dynamic airspace. Therefore, the time range of [0, t_{out}] should be taken to construct the dynamic time domain. Fig. 9 shows in detail the schematic diagram of the encounter dynamic spatial–temporal domain construction based on spatial matrix cells in a two-ship navigation scenario. This method still works when faced with a multi-ship encounter scenario. Assuming that in the face of a multi-ship encounter scene, the method in this paper divides the multi-ship encounter scene into multiple two-ship encounter scenes in sequence, and establishes the ship encounter dynamic space-time domain in sequence according to the two-ship navigation scenarios, so that the multi-ship analysis problem is transformed into a simple two-ship analysis problem. Then, based on the divided dynamic space-time domains of encounters, the in-depth analysis of the spatial distribution characteristics of potential encounter hazards and the spatial-temporal trends is realized. This method is in the stage of active improvement in the analysis of multi-ship encounter problems. Fig. 10 depicts in detail a schematic diagram of the construction of the encounter dynamic spatial–temporal domain in a multi-ship navigation scenario

3.3. Spatial modeling and analysis method for ship-encounters spatial–temporal domain

3.3.1. Spatial modeling theory

The term "spatial modeling" refers to the abstraction of intricate spatial–temporal dynamic data and phenomena using GIS spatial analytic techniques and sophisticated mathematical models (Molenaar, 1998; Crosetto M et al., 2000). Using the dimensions of spatial–temporal features, geometric states, and spatial relationships, it realizes the accurate description of dynamic goals and dynamic processes and aids in human understanding of prospective spatial–temporal differences and evolving laws of spatial phenomena. According to renowned academic Goodchild, spatial modeling technology has exceptional promise for both the mathematical depiction of dynamic behavior in space and time as well as for the spatiotemporal analysis and mining of data related to dynamic activity. GIS spatial modeling methods can be divided into four categories, including exponential model methods, dynamic model methods, and regression model methods. Spatial modeling is classified as either vector-based or raster-based. In order to accurately analyze and describe the spatial phenomena and the characteristics of space-time, the object model and the field model in the spatial concept information model are used to establish the spatial modeling method for the vector information (He et al., 2017). This method completes the modeling of spatial entities in the form of advanced mathematical functions, the domain of definition is the size of the space occupied, and the value domain is the set of four spatial models. The detailed schematic diagram of spatial modeling based on vector objects is shown in

Table 1
List of symbols in the formulas of method and text.

Notations	Meaning	Notations	Meaning
Δa	Offset of the semi-major axis of the ship's position	(x_{i1}, y_{i1}), (x_{i2}, y_{i2})	The spatial coordinates of the modeling feature point
Δb	Offset of the semi-minor axis of the ship's position	(A_{sk}, B_{sk})	The mathematical set of unknown spatial points
L	The length of the target ship	N	Total number of unknown spatial points
a_{Domain}	The semi-major axis of the ship domain	$d_{k,\alpha}$	The distance between the spatial modeling feature point and other unknown points to be modeled
b_{Domain}	The semi-minor axis of the ship domain	$d_{\max}$	The maximum distance value between the spatial modeling feature point and other unknown points to be modeled
a_{Arena}	The semi-major axes of ship-encounter space domain	$d'_{k,\alpha}$	The standardized distance value between the spatial modeling feature point and other unknown points to be modeled
b_{Arena}	The semi- minor axes of ship-encounter space domain	$w_{k,\alpha}$	The influence range of spatial modeling feature points
t_{in}	The moment when the own ship invades the space model of the target ship's dangerous domain	$W_{k,\min 1}$	The impact value of the nearest spatial modeling feature point
t_{out}	The moment when the own ship leaves the space model of the target ship's dangerous domain	$d_{k,\min 1}$	The distance between the spatial modeling area and the nearest modeling feature point
CR	The collision risk	WC_{φ}	The influence value of other collection points to be spatially modeled
$T_{\min}$	The arrival time at the nearest meeting point	$w_{\varphi,\min 1}$	The influence coefficient of the nearest known spatial modeling feature point to be modeled
T_S	The time required to avoid a collision	$\mu_i(s_i)$	The value of the spatial modeling feature point
$f(t)$	The scaling factor at time t	$\widehat{\mu}(s_0)$	The calculation result value of the point to be modeled
$f_{\min}$	The minimum scaling factor	$C(l_k)$	The distance adjustment variable on the unknown point of space modeling
φ_1	The heading of own ship	m	normal distribution optimization coefficient
φ_2	The heading of the target ship	$\overline{d}_{k,\min 1}$	The distance adjustment variable between the nearest known spatial modeling feature point and the point to be modeled
x_A, y_A	The position coordinates of the own ship in the original coordinate system	$\overline{d}_{k,\min 2}$	The distance adjustment variable between the point to be modeled and the second closest known spatial modeling feature point
x_B, y_B	The position coordinates of the target ship in the original coordinate system	I_i	The space-time distribution law index
A, B, C	The intermediate variable of the dynamic scaling factor equation	$E(I)$	The expected value
B_T	The relative orientation of the two ships	$V(I)$	The variance value

Fig. 11(a). In the face of spatial raster information, spatial modeling is usually carried out based on grid coverage and pixel array information. Fig. 11 (b) shows the spatial modeling method based on grid information. In order to further realize the spatial quantitative analysis and semantic expression of the dangerous feature information in the dynamic space-time domain of ship encounters, the detailed spatial analysis of the hazard spatial distribution features and the temporal and spatial law information of ship encounter dynamic spatial–temporal domains will be realized next in this chapter based on the spatial modeling and analysis technology.

3.3.2. Spatial modeling and analysis method of ship encounter dynamic spatial–temporal domain

3.3.2.1. Calculation of safety parameters for ship encounters. The algorithm in this chapter is inspired by Coldwell (1983) ship domain model and the research work of Szlapczynski and Szlapczynska (2017). The ship domain with offset value is proposed to quantitatively analyze the ship's encounter danger information. The algorithm comprehensively considers the heading, sailing speed and size of the target ship. At the same time, the scaling factor f introduced by SZLAPCZYNSKI et al. (2018) can improve the ability of hazard identification for targets with similar motion parameters, and the vigilance of ships coming from the right front is higher, which is more in line with the requirements of relevant regulations of COLREGS. Fig. 12 shows the vector diagram calculated based on the hazard information in the ship field. This calculation method of encounter safety information adopts the ship domain proposed by Coldwell, and Combined with the smoothing processing such as Davis to obtain the approximate ellipse graphic ship domain. This improved method uses the scaling factor in the ship domain, and has a higher ability to identify dangerous targets with similar motion parameters. It is more vigilant to ships coming from the right front, and more in line with the requirements of the relevant COLREGS regulations. Fig. 12(a) Schematic diagram of scaling factor calculation. The calculation formula of the corresponding ship risk degree CR is as follows:

$$CR = \left[a_1 f_{\min}^2 + a_2\left(\frac{T_{\min}}{T_S}\right)^2 + a_3 f^2(t)\right]^{-\frac{1}{2}} \tag{1}$$

Where $f(t)$ means the multiplier when the ship domain is enlarged and reduced until the target ship is just at the boundary of the domain at time t; f_{min} indicates that the ship maintains a sailing state, and the zoom factor when the distance is the closest. The target distance is the closest $T_{\min}$ moment is CR represents the risk of ship collision。When the value of CR is larger, it means that the target ship and the own ship do not take any non-yielding measures, and the collision probability and time urgency of the current navigation state are higher. $T_{\min}$ represents the time to reach the nearest encountering point, T_S represents the time to avoid collision, and a_1, a_2, a_3 represents the influence coefficient of different ship main scales, ship types and navigation waters, respectively. Fig. 12 (b) details represents the geometric expression of the ship encounter parameter. Among them, ship A is the own ship, B is the target ship. φ_1 is the heading of own ship. φ_2 is the heading of the target ship. x_A, y_A are the position coordinates of the own ship in the original coordinate system. x_B, y_B are the position coordinates of the target ship in the original coordinate system. x_A, y_A are the position coordinates of the own ship after the original coordinate system is rotated by $-\varphi_1$ (counterclockwise) angle, x_B, y_B are the position coordinates of the target ship after the original coordinate system is rotated by $-\varphi_1$ (counterclockwise) angle. The conversion calculation process is as follows:

$$\begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} \boldsymbol{cos}\ \varphi_1 & -\boldsymbol{sin}\ \varphi_1 \\ \boldsymbol{sin}\ \varphi_1 & \boldsymbol{cos}\ \varphi_1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{2}$$

$$X_{\text{A}} = \cos\varphi_1 x_{\text{A}} - \sin\varphi_1 y_{\text{A}} \quad Y_{\text{A}} = \sin\varphi_1 x_{\text{A}} + \cos\varphi_1 x_{\text{A}} \tag{3}$$

$$X_{\text{B}} = \cos\varphi_1 x_{\text{B}} - \sin\varphi_1 y_{\text{B}} \quad Y_{\text{B}} = \sin\varphi_1 x_{\text{B}} + \cos\varphi_1 x_{\text{B}} \tag{4}$$

When considering the scaling factor f parameter, the dynamic expression for the ship domain is:

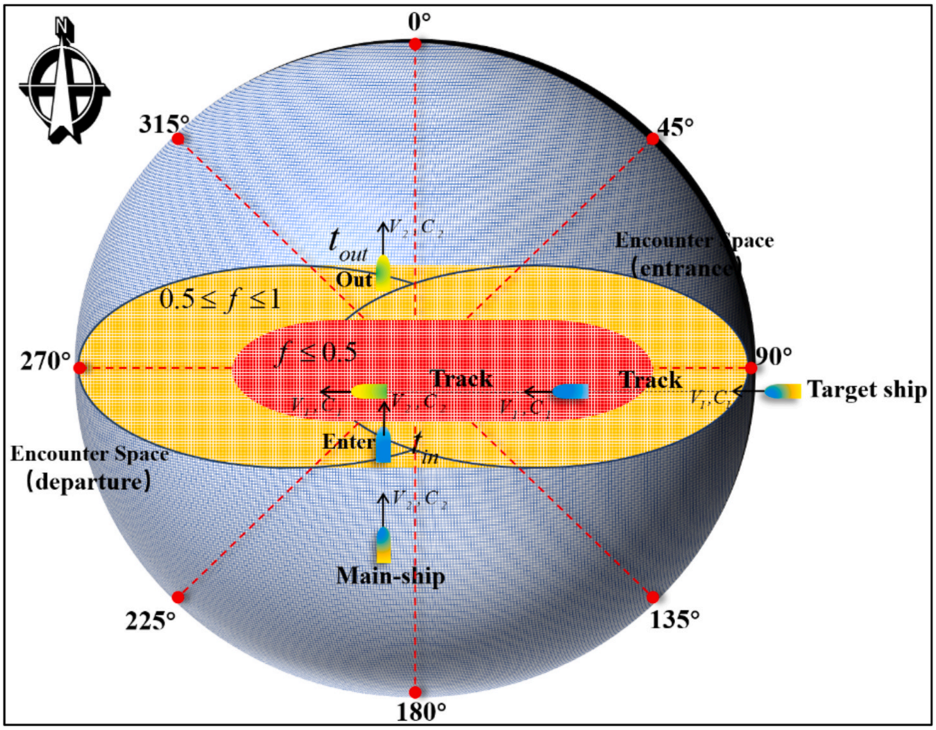


Fig. 9. The principle diagram of the encounter dynamic spatial–temporal domain construction based on spatial matrix cells in a two-ship navigation scenario.

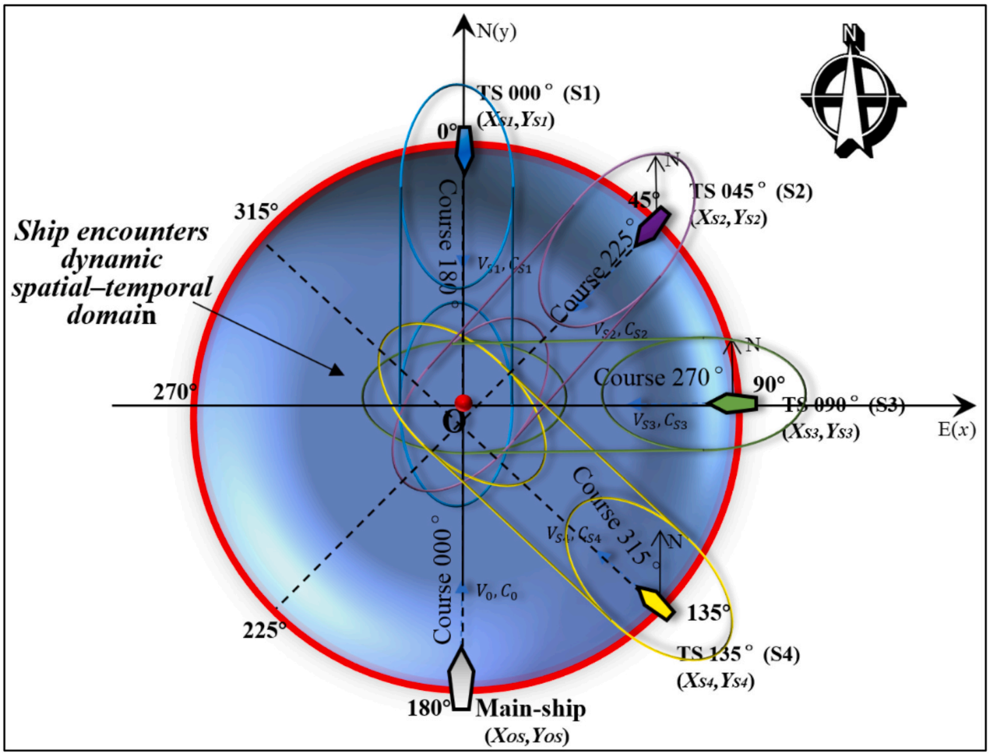


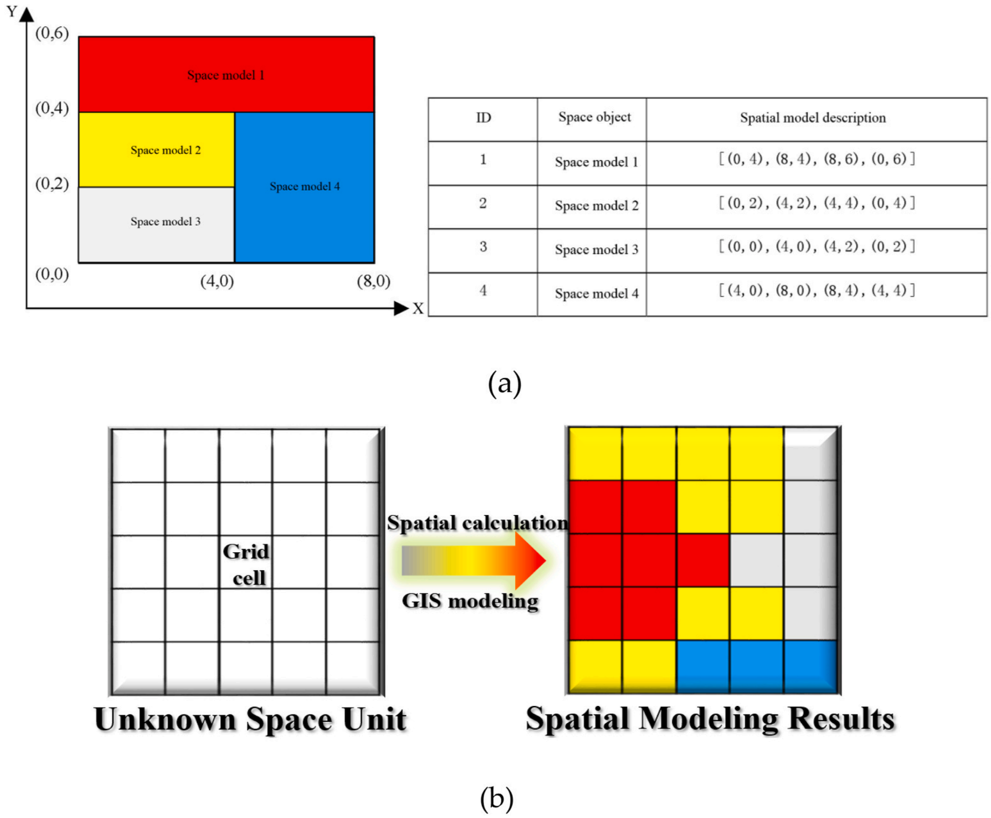
Fig. 10. Schematic diagram of the construction of the encounter dynamic spatial–temporal domain in a multi-ship navigation scenario.

$$\frac{(X_{\mathrm{B}} - X_{\mathrm{A}})^2}{f^2(t)a^2} + \frac{(Y_{\mathrm{B}} - Y_{\mathrm{A}})^2}{f^2(t)b^2} = 1 \tag{5}$$

Assuming that the rotated coordinate system is used to replace the original coordinate system, we can obtain:

$$f^2 = \frac{((x_{\mathrm{B}} - x_{\mathrm{A}})\cos\varphi_1 + (-y_{\mathrm{B}} + y_{\mathrm{A}})\sin\varphi_1)^2}{a^2} + \frac{((x_{\mathrm{B}} - x_{\mathrm{A}})\sin\varphi_1 + (y_{\mathrm{B}} - y_{\mathrm{A}})\cos\varphi_1)^2}{b^2} \tag{6}$$

The mathematical expression of the position change of own ship and



ID	Space object	Spatial model description
1	Space model 1	[(0, 4), (8, 4), (8, 6), (0, 6)]
2	Space model 2	[(0, 2), (4, 2), (4, 4), (0, 4)]
3	Space model 3	[(0, 0), (4, 0), (4, 2), (0, 2)]
4	Space model 4	[(4, 0), (8, 0), (8, 4), (4, 4)]

(a)

(b)

Fig. 11. Schematic diagram of spatial modeling: (a) Schematic of spatial modeling method based on vector objects (b)Schematic of spatial modeling method based on raster objects.

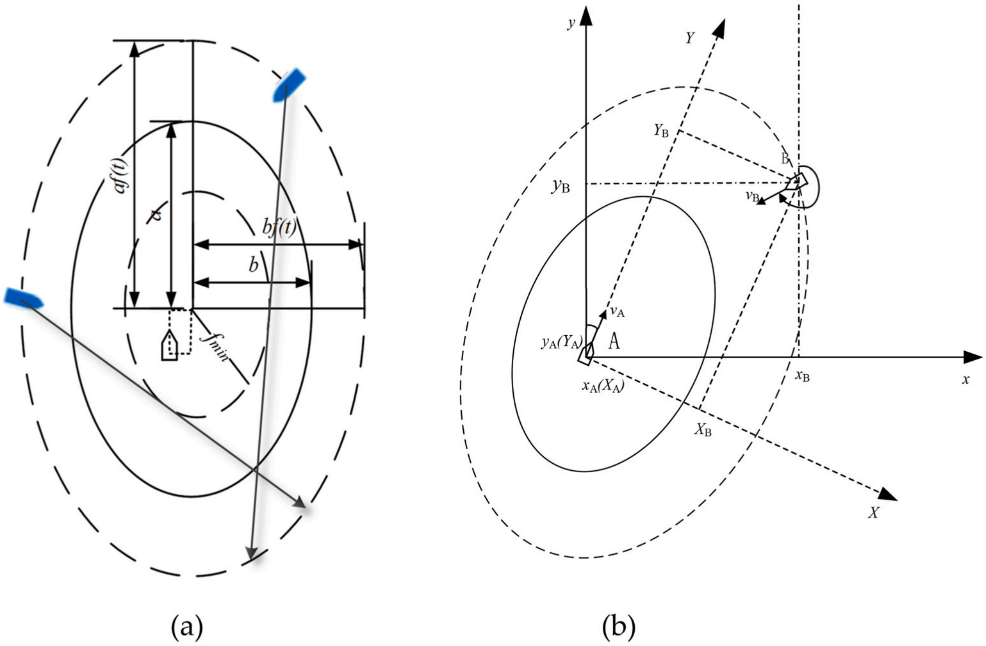
target ship with time t is as follows:

$$\begin{aligned} x_A(t) &= x_A(0) + v_A t \sin \varphi_1, y_A(t) = y_A(0) + v_A t \cos \varphi_1 \\ x_B(t) &= x_B(0) + v_B t \sin \varphi_2, y_B(t) = y_B(0) + v_B t \cos \varphi_2 \end{aligned} \tag{7}$$

Substitute the corresponding parameters into the dynamic scaling factor mathematical equation, to simplify to a mathematical equation with t as a variable, as shown below:

$$f^2(t) = At^2 + Bt + C \tag{8}$$

A, B, C is the intermediate variable of the dynamic scaling factor equation $f(t)$. These variables are closely related to changes in the $f(t)$ value. Among them, assuming $f(t) = 1$, intermediate variable A is $\frac{\cos^2\varphi_2}{\Delta a^2} + \frac{\sin^2\varphi_2}{\Delta b^2}$, intermediate variable B is $2 \sin \varphi_2 \cos \varphi_2 (1/\Delta a^2 - 1/\Delta b^2)$, intermedi-



(a)

(b)

Fig. 12. Vector diagram of collision risk calculation based on ship domain. (a) Schematic diagram of the scaling factor (b) Geometric expression of ship encounter parameters.

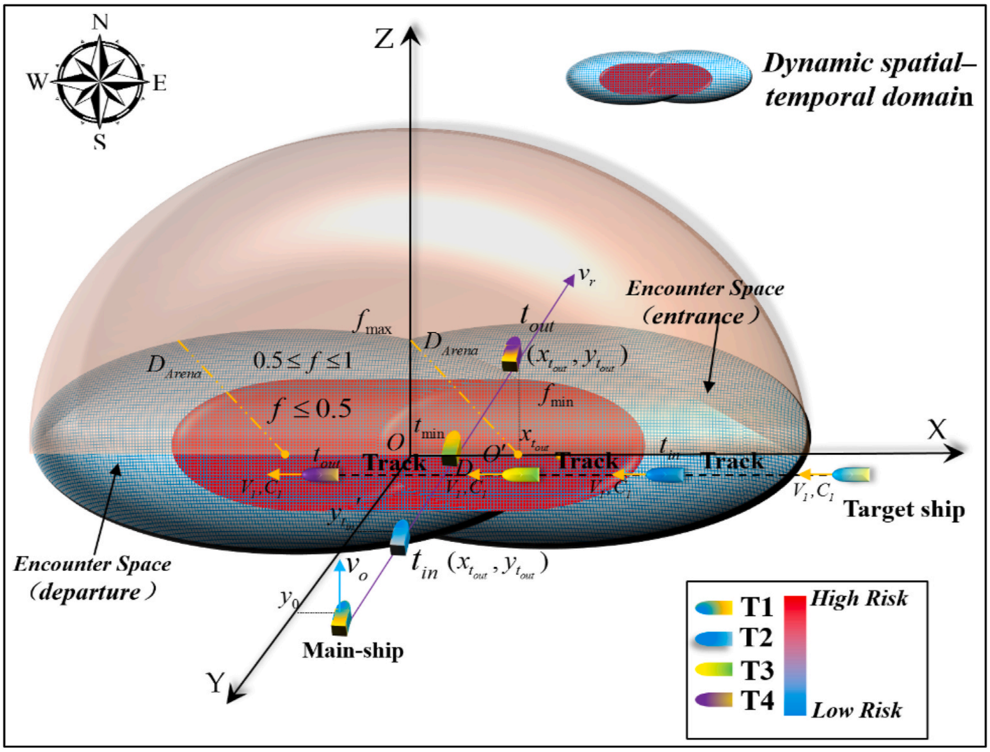


Fig. 13. Construction principle of ship encounter dynamic spatial–temporal domain based on space matrix and encounter danger information.

Table 2
Classification results of ship encounter situations.

Category	Ship encounter situation	Classification basis			
		Collision risk factor	Numeric Interval of Ship Navigation State Parameters	Distance factor	Diagram
01	Overtaking Situation	–	$V_0 > V_t \cos\Delta C$ $C_t + 112.5^\circ \le C_0 + B_T + 180^\circ \le C_t + 247.5^\circ$	≤ 3 *nm*	
02	Head-on Situation	Pose a collision risk	$174^\circ \le \lvert C_t - C_0\rvert \le 186^\circ$ $B_T \le 5^\circ \Vert B_T \le 355^\circ$	Intervisibility distance	
03	Crossing Situation (Crossing of Starboard)	Pose a collision risk	$0^\circ \le \lvert C_t - C_0\rvert \le 180^\circ$ $5^\circ < B_T \le 112.5^\circ$	Intervisibility distance	
04	Crossing Situation (Crossing of portside)	Pose a collision risk	$0^\circ \le \lvert C_t - C_0\rvert \le 180^\circ$ $247.5^\circ \le B_T < 355^\circ$	Intervisibility distance	

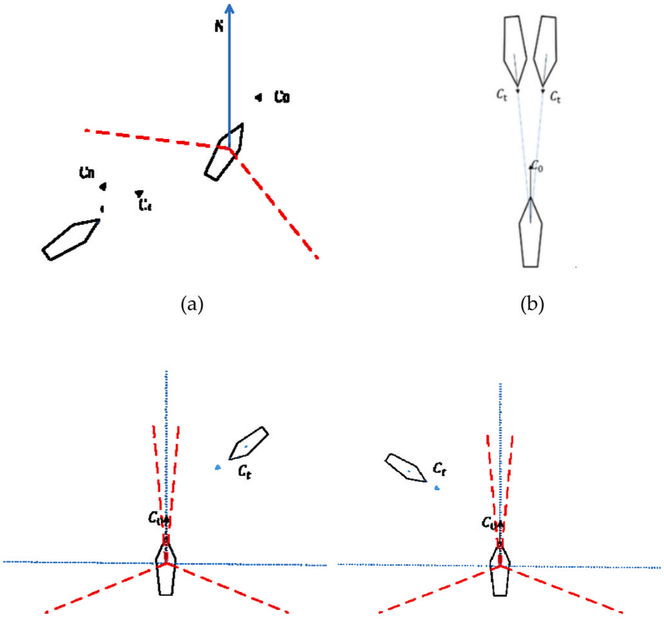
ate variable C is $\frac{\sin^2\varphi_2}{\Delta a^2} + \frac{\cos^2\varphi_2}{\Delta b^2}$.

The above is the detailed process of the ship encounter danger information algorithm. We use Fig. 13 to illustrate in detail the construction principle of the dynamic spatial–temporal domain of ship encounters based on the spatial matrix and the information results of the encounter hazards. Next, this paper will introduce in detail the spatial modeling and analysis methods of the ship encounter dynamic spatial–temporal domain. Then, based on the multi-time-space, multi-angle, and multi-state encounter dynamic spatial–temporal domain, according to the calculation principle of the space matrix in the GIS space modeling method introduced in section 3.3.1, combined with the space modeling of section 3.3.2.2 and section 3.3.2.3 With the analysis algorithm, it further realizes the in-depth analysis of the spatial distribution characteristics of potential hazards and the temporal and spatial trends in the dynamic process of navigation, thereby reducing the spatial ambiguity of hazard information.

3.3.2.2. Spatial modeling method for ship encounter dynamic spatial–temporal domain

3.3.2.2.1. Analysis and clarification of the encounter dynamic mode of ship navigation. Ships in different orientations converge to form different encounter dynamic space-time domains (Jia C et al., 2022; Zhen R et al., 2022). In order to further extract the potential danger and trend characteristics of the ship encountering dynamic space-time domain and simplify the calculation steps of the encounter data, we propose an analysis method for the encounter state of navigation targets in relative space. This method is based on 5 relative spatial physical quantities (relative sailing encounter situation, relative motion direction, relative orientation, relative distance change, and relative speed change), as shown in Table 2, to realize the spatial semantic expression of the movement situation of the navigation target and the dynamic mode of the encounter. Table 2 expresses Classification results of ship encounter situations. It is based on the rules 13–15 of COLREGS to divide the encounter situation. First of all, it is determined to divide the crossing and Head-on situations under the premise of intervisibility distance. Because the compass azimuth of the target ship can only be observed when the two ships see each other. The classification of overtaking situation is based on the distance between two ships is less than or equal to 3 *nm*. Secondly, we also take into account whether there is a risk of collision according to COLREGS rules 13–15. Thirdly, we focus on the sailing motion parameters such as the course speed between the two ships. Thus, the division of encounter situations is completed. Fig. 14 shows the spatial semantic expression and clarification method of the encounter dynamic mode when the ship sails. It contains a total of 12 typical encounter dynamic patterns. Encountering

Fig. 14. Spatial semantic expression and clarification of encountering dynamic mode characteristic situations during ship navigation.



(a) (b) (c) (d)

Fig. 15. Schematic of ship encounter situations: (a) an overtaking encounter, (b) a head-on encounter, (c) a starboard crossing encounter, and (d) a portside crossing encounter.

dynamic patterns is one of the key factors influencing the spatial modeling process in dynamic spatial–temporal domains. This method analyzes and solves the ship's dynamic encounter mode based on the ship's spatial geometric position, navigational motion information, and encounter dynamic information, and realizes the judgment of the encounter dynamic mode before dynamic space-time modeling. This ensure and improve the accuracy of spatial modeling and the ability to adapt to various encounter scenarios (see Fig. 15).

3.3.2.2.2. Elements of modelling characteristics of the encounter dynamic spatial–temporal domain. The spatial analysis of spatial–temporal characteristics and laws in the process of ship encounter has always been the core issue of the encounter risk analysis. The dynamic spatial–temporal spatial modeling method proposed in this chapter. It firstly uses GIS spatial analysis theory and highly matched advanced mathematical functions to abstract and simplify the encountering process and phenomena that are complex, dynamic and static, and finally quantitatively express the internal differences and changing laws of ship dynamic encountering behavior from the perspective of space, according to the situation of encountering dynamic mode. In the ship encounter scenario, there are spatial differences in the ship encounter danger in each space-time state, its spatial location set implies nonlinear spatial characteristics and laws in distribution. The extraction of these spatial features and laws plays an important role in improving the spatial analysis capability of ship navigation hazards.

In order to obtain the distribution state of the risk degree in the encountering dynamic spatial–temporal domain, the key step of the proposed method is to establish the spatial modeling feature points in the encounter dynamic spatial–temporal domain. First, we use the ALARP criterion (As low as reasonable practice) to quantify the navigation risk in the encounter space domain and divide it into four grades. ALARP is a grading evaluation standard that is generally recognized and adopted by the current international risk acceptability level. When the potential danger is in the ALARP area, its distribution law conforms to the mathematical function of system risk. Fig. 16 shows a diagram of the classification and construction method of ship encounter dynamic spatial–temporal domain based on ALARP criterion. Among them, there are three risk levels and four levels in the dynamic spatial–temporal domain of ship encounter. The three types of encounter risk include Areas of high risk, Areas of unpredictable risk, and begin to generate risk. The four levels are composed of 1 value line, median line (high), median line (low) and zero value line of the risk of encountering. Secondly, on the GIS spatial information platform, using C # programming language and GIS components, the vector feature point set of the spatial modeling feature boundary of the encounter dynamic spatial–temporal domain is

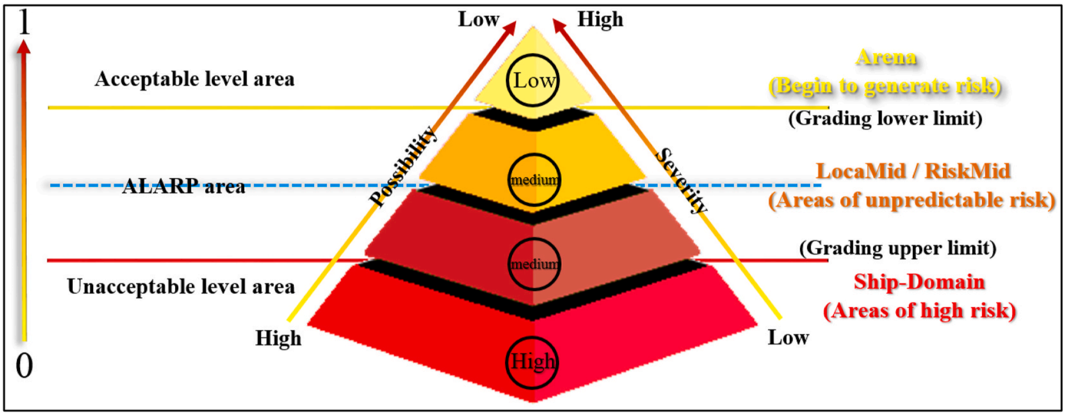


Fig. 16. Diagram of the classification and construction method of ship encounter dynamic spatial–temporal domain based on ALARP criteria.

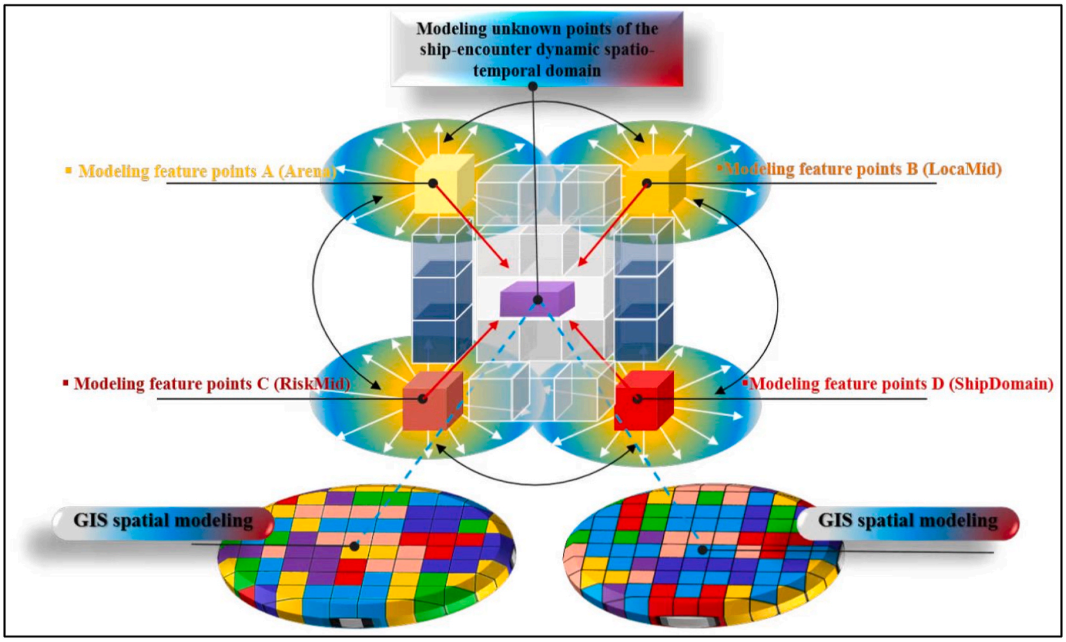


Fig. 17. Schematic diagram of the modeling principle of the ship encounter dynamic space-time domain based on the modeling feature points.

constructed, and the initial space-time attribute expression of the modeling feature point is completed. In addition, when we conduct space modeling in the dynamic spatial–temporal domain of ship encounter, we convert the characteristic points of space modeling into a space matrix as the basic computing unit. Every 1/2 of the dynamic spatial–temporal domain is composed of a space matrix with no less than 400 characteristic points. It can improve the accuracy of spatial modeling results. Fig. 17 vividly describes the schematic diagram of the modeling principle of the ship encounter dynamic space-time domain based on the modeling feature points.

3.3.2.2.3. Modeling algorithm for ship encounter dynamic spatial–temporal domain. Additionally, we use the GIS spatial information platform to spatially construct the potential nonlinear spatial feature differences and laws of the ship encounter dynamic spatial–temporal domain model based on the constructed ship encounter dynamic spatial–temporal domain modeling feature points and the calculation results of the encounter risk degree. The method in this paper explores the mathematical distribution law of the modeling feature points in depth, and then follows the spatial sequence law in the dynamic spatial–temporal domain from the mathematical point of view, in order to achieve the interactive space calculation and analysis between the ship encounter danger feature value and the derived data values. Finally, a space-continuous quantitative expression of the ship encounters dynamic spatial–temporal domain modeling results is possible. The result of the spatial modeling of the dynamic time-space domain of the encounter is an important premise for the next step to infer and mine the potential spatial variation trend and characteristic law of the navigation encounter hazard.

Secondly, due to the fact that the space collection of the ship encounters a dynamic spatial–temporal domain is non-homogeneous. In this paper, when the continuous space-time modeling of ship encounter danger is carried out. Firstly, through the numerical calculation of the spatial feature points in the dangerous sea area, and fitting its spatial distribution law. Then according to the mathematical fitting results, we can find that the encounter dynamic spatial–temporal domain presents a nonlinear law. In addition, the change trend from the vector boundary to the minimum vector boundary in the dynamic spatial–temporal domain is a normal distribution function type with different magnitudes. Therefore, in the continuous space-time modeling of the spatial–temporal domain of ship encounters, the distance adjustment parameters of the normal distribution function will be combined to improve the accuracy of the spatial modeling results of all position sets.

Furthermore, the mathematical expectation and variance of spatial point sets that conform to the same mathematical distribution curve are

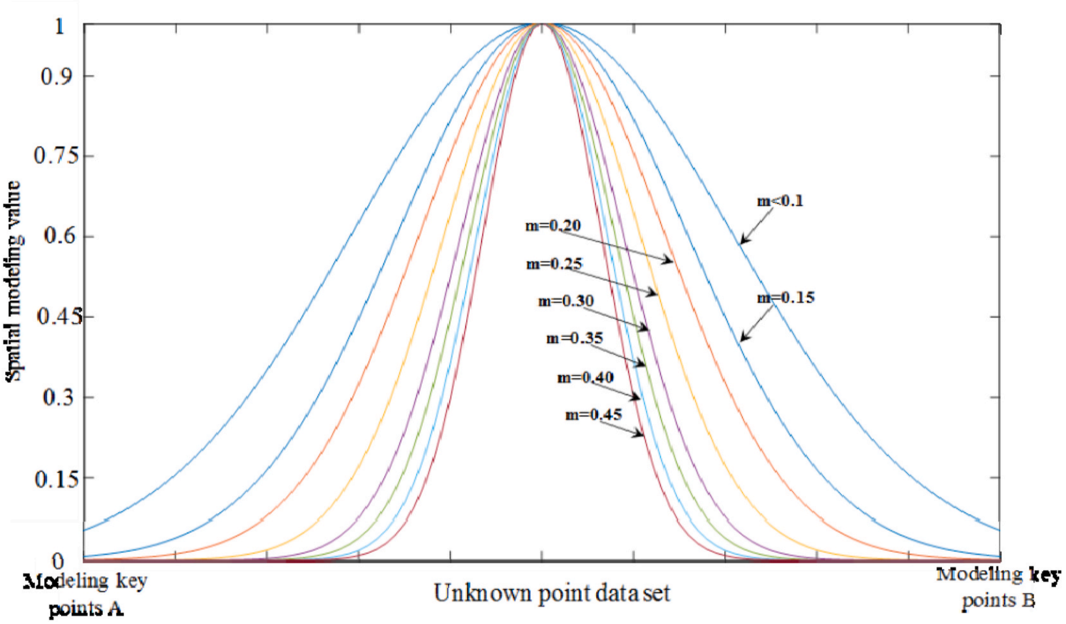


Fig. 18. The principle diagram of the normal function distribution curve of spatial modeling of ship encounter dynamic spatial–temporal domain based on distance adjustment variable.

the same. This method measures the average value of random space points by mathematical expectation and uses the variance to measure the fluctuation range of any random space points around the mean. Thus it can be judged that the Ship encounters a dynamic spatial-temporal domain belonging to the spatial characteristic points of the same mathematical distribution curves. Assuming that the spatial coordinates of the modeling feature points in the dynamic space-time domain are S1 (x_{i1}, y_{i1}) and S2 (x_{i2}, y_{i2}), then the mathematical set of unknown spatial points in the area to be modeled can be expressed as $S_k(A_{sk}, B_{sk}), k \in (1, 2, 3, \ldots, N)$, and the mathematical expression of the set of spatial points to be modeled is as follows:

$$A_{sk} = x_{i1} + \frac{k-1}{N-1}(x_{i2} - x_{i1}), k \in (1, 2, 3, \ldots, N) \tag{9}$$

$$B_{sk} = y_{i1} + \frac{k-1}{N-1}(y_{i2} - y_{i1}), k \in (1, 2, 3, \ldots, N) \tag{10}$$

In order to further solve and obtain the modeling results of all ship encounter dynamic spatial–temporal domain space positions. This method simulates and calculates the values of other unknown points to be modeled in the spatial–temporal domain according to the normal distribution function. The detailed calculation principles of the spatial modeling based on the normal distribution function are shown in (11)-(14). It first calculates the spatial modeling coefficient of any spatial feature point to other unknown points, and the calculation expression is as follows:

$$d'_{k,\alpha} = d_{k,\alpha} \Big/ d_{\max} \tag{11}$$

$$w_{k,\alpha} = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\left(d'_{k,\alpha}\right)^2}{2\sigma^2}} \Bigg/ \sum_{\alpha=1}^{n} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\left(d'_{k,\alpha}\right)^2}{2\sigma^2}}, d_{k,\min 1} \neq 0 \tag{12}$$

$$w_{k,\min 1} = 1, d_{k,\min 1} = 0 \tag{13}$$

$$w_{k,\alpha} = 0, d_{k,\min 1} = 0 \&\& \alpha \neq \min 1 \tag{14}$$

Where $d_{k,\alpha}$ represents the distance between the spatial modeling feature point and other unknown points to be modeled in the dynamic spatial–temporal domain; $d_{\max}$ represents the maximum distance value between the spatial modeling feature point and other unknown points to be modeled in the dynamic spatial–temporal domain; $d'_{k,\alpha}$ represents the standardized distance value between the spatial modeling feature point and other unknown points to be modeled in the dynamic spatial–temporal domain; $w_{k,\alpha}$ represents the influence range of spatial modeling feature points on the encounter dynamic spatial–temporal domain; $W_{k,\min 1}$ represents the impact value of the nearest spatial modeling feature point on the encounter dynamic spatial–temporal domain; $d_{k,\min 1}$ is expressed as the distance between the spatial modeling area and the nearest modeling feature point in the dynamic spatial–temporal domain.

Then further calculate the influence values of other unknown points to be modeled according to the known spatial modeling feature points. k represents any modeling point in the space to be modeled, and the calculation formula is as follows:

$$WC_{\varphi} = \sum_{\alpha=1, \alpha \neq \min 1}^{n} wc_{k,\alpha} \Big/ w_{k,\min 1}, k \in (1, 2, 3, \ldots, N) \tag{15}$$

$$\widehat{\mu}(s_0) = \sum_{i=1}^{n} wc_{\varphi} \mu_i(s_i) \tag{16}$$

Where WC_{φ} is the influence value of other collection points to be spatially modeled. $w_{\varphi,\min 1}$ is the influence coefficient of the nearest known spatial modeling feature point to be modeled. $\mu_i(s_i)$ represents the value of the spatial modeling feature point. $\widehat{\mu}(s_0)$ represents the calculation result value of the point to be modeled.

In summary, the value of any other unknown point to be modeled in space is calculated based on the influence range value $w_{k,\alpha}$ and the influence coefficient WC_{φ}. However, in the process of ship encounter, there are spatial differences in the danger of ship encounter in each space-time state, and the distribution of all spatial positions in the dynamic space-time domain of ship encounter implies nonlinear spatial characteristics and laws. It has a strong correlation with the navigational motion parameters such as the course, speed, azimuth, and distance of the target ship and own ship, and it also has a certain correlation with the dynamic mode of the encounter. Therefore, the navigational motion parameters and the dynamic mode of encounter are the key influencing factors in the process of spatial modeling and analysis in the dynamic

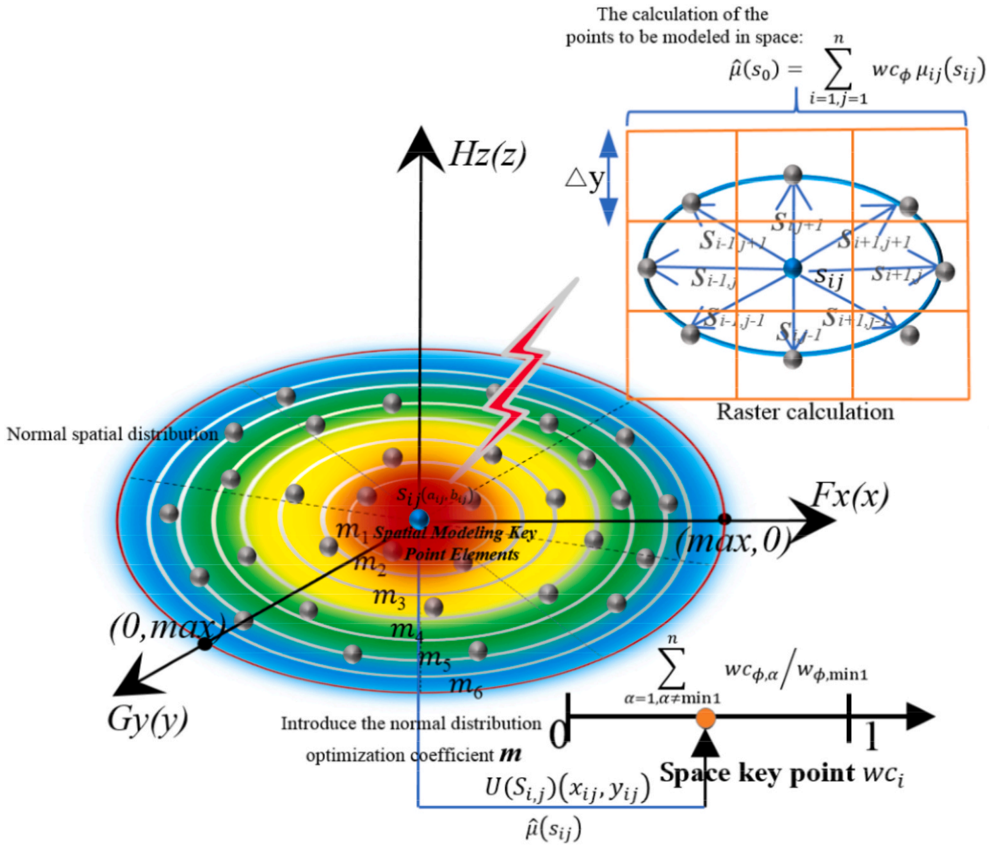


Fig. 19. Schematic diagram of the spatial modeling method of ship encounter dynamic time-space domain based on the normal distribution function.

space-time domain. They make the space unknown points in the ship encounter dynamic space-time domain appear normal distributions with different magnitudes. The distribution curve will generally appear in a mathematical distribution state between flat and steep. This method takes into account the influence of the ship's navigational motion parameters and the dynamic mode of the encounter through the spatial model of the ship encounter hazard domain and the dynamic scaling factor equation. For different normal curve distributions, the corresponding normal function distance values in space modeling are different. Aiming at this situation, we propose a distance adjustment variable and normal distribution optimization coefficient, and introduce it into the spatial modeling calculation of the encounter dynamic spatial–temporal domain. The distance adjustment variable can be used to simulate and calculate the normal distribution of unknown points in the dynamic spatial–temporal domain when the ship encounters in different spatial regions. Fig. 18 shows the distribution of normal function curves of ship encounters dynamic spatial–temporal spatial modeling under different distance adjustment variables. The calculation principle of the spatial modeling of the dangerous area where the ship will encounter danger based on the distance adjustment variable and normal distribution optimization coefficient is as follows:

$$C(l_k) = \frac{1}{l_k} - 1 \tag{17}$$

$$l_k = \frac{d_{k,\min 1}}{d_{k,\min 2}}, k \in (1, 2, 3 \cdots, N) \tag{18}$$

$C(l_k)$ represents the distance adjustment variable on the unknown point of space modeling in the process of space modeling, m is normal distribution optimization coefficient. When $C(l_k) \geq 1$, then the space modeling distance of the ship encountering dynamic time-space domain can be spatially modeled according to the normal distribution function (without introducing the normal distribution optimization coefficient). If the distance adjustment variable $C(l_k) < 1$, the distance calculation formula of the ship encountering dynamic spatial–temporal spatial modeling is as follows:

$$\overline{d}_{k,\min 1} = d_{k,\min 1} + \frac{\left(d_{k,\min 2} - d_{k,\min 1}\right)\left(1 - C(l_k)\right)}{2} \tag{19}$$

$$\overline{d}_{k,\min 2} = d_{k,\min 2} + \frac{\left(d_{k,\min 2} - d_{k,\min 1}\right)\left(1 - C(l_k)\right)}{2} \tag{20}$$

$\overline{d}_{k,\min 1}$ is the distance adjustment variable between the nearest known spatial modeling feature point and the point to be modeled; $\overline{d}_{k,\min 2}$ is the distance adjustment variable between the point to be modeled and the second closest known spatial modeling feature point. This chapter further expresses the detailed calculation steps of the algorithm in the form of pseudo-code. Appendix A specifically shows the detailed process of the spatial modeling and analytical solution method in the dynamic spatial–temporal domain of the ship encounter. Then we execute and implement the proposed method on the GIS platform combined with C# and Python programming languages.

According to the normal function distribution curve of the ship encounter dynamic spatial–temporal domain spatial modeling based on the distance adjustment variable shown in Fig. 18. In the face of modeling feature point elements with different normal distributions, the distance adjustment variable is used to optimize the normal distribution range, which can greatly improve the accuracy and authenticity of spatial modeling. Fig. 19 visually represents the schematic diagram of the spatial modeling method of the ship encounter dynamic spatial–temporal domain based on the normal distribution curve. The red to blue interval in the figure indicates the influence range of the center point (spatial modeling feature point) on the surrounding spatial area, and different colors indicate different magnitudes of influence. It has a strong correlation with the normal function distance moderator variable. The spatial modeling of ship encounters dynamic spatial–temporal domain is described by taking the blue oval in Fig. 19 as an example, and there are eight point elements conforming to the normal function distributed around it. This modeling process is realized under the GIS spatial information platform, using the spatial modeling method based on raster objects. The blue oval in Fig. 19 represents a certain space matrix unit in ship encounter dynamic spatial–temporal domain. It takes the center position of the ship encounter dynamic spatial–temporal space model as the modeling feature point $S_{i,j}(x_{ij}, y_{ij})$, and further calculates the results of other spatial modeling points such as $S_{i-1,j+1}$, $S_{i,j+1}$, $S_{i+1,j+1}$, … in the surrounding neighborhood space. By looping this calculation process, the modeling results of the continuous spatial distribution in the entire encounter dynamic spatial–temporal domain are sequentially obtained. This spatial modeling result can be used to further explain and discover the spatial distribution law and spatial–temporal trend change characteristics of the danger encountered in the dynamic spatial–temporal domain.

In summary, the above content is the detailed steps of the ship encounter dynamic time-space domain space modeling method. Through the spatial modeling of the dynamic spatial–temporal domain of ship encounters, it can further complete the spatial quantitative analysis and expression requirements of the encounter risk in different time and space positions in the actual ship navigation. The proposed new method solves very complex spatial analysis problems such as the precise extraction and quantification of the spatial laws of dynamic and static navigation targets in different time series. It also solves the problem of surface source analysis and calculation of potential spatial features in the process of ship navigation and provides spatial analysis results with encounter safety features and spatial–temporal attribute information for the safe navigation of ships. It can significantly improve the spatial awareness of ship navigation hazards and safety analysis capabilities, and reduce ambiguity and danger during navigation.

3.3.2.3. Spatial analysis method for ship encounter dynamic spatial–temporal domain. In order to further extract the spatial–temporal heterogeneity and spatial homogeneity of dangerous situations in ships encountering dynamic spatial–temporal domain. This paper innovatively proposes a local autocorrelation algorithm in the dynamic spatial–temporal domain, which quickly realizes the potential space-time law and change trend analysis of the encounter danger. This method can accurately calculate the potential interrelationships between encounter hazard values in the same dynamic space-time domain, and express the spatial–temporal heterogeneity of risk value through four coordinate quadrants. This method first needs to calculate the mean value and variance of the point set in the dynamic space-time domain, and obtain the deviation between the modeling value and the mean value of each point element, and the cross-product result is calculated. Then calculate the space-time distribution feature index according to the position number of the modeling feature point in the encounter space domain, and obtain the distribution feature results of it and adjacent spatial–temporal object units. The index I_i of the time-space distribution law is close to zero (that is, the positive cross-product value and the negative cross-product value cancel each other out), indicating that the dynamic spatial–temporal domain conforms to a random distribution function. The calculation expression of the space-time distribution law index I_i in the dynamic spatial–temporal domain is:

$$I_i = \frac{n(x_i - \overline{x})\sum_{j=1}^{n} w_{ij}\left(x_j - \overline{x}\right) - \sum_{i=1}^{n}(x_i - \overline{x})^2 * E(I)}{\sum_{i=1}^{n}(x_i - \overline{x})^2 * \sqrt{V(I)}} \tag{21}$$

In the formula, n is the total amount of feature point sets in the encounter dynamic spatial–temporal domain. x_i and x_j are the modeling values of spatial units i and j in the encounter dynamic spatial–temporal domain, respectively; w_{ij} represents the normalized value of the spatial distance between this point and the surrounding units, and represents the adjacency relationship between spatial units i and j. $E(I)$ is the expected value. $V(I)$ is the variance. Therefore, the proposed local autocorrelation algorithm in the dynamic spatial–temporal domain, greatly improves the ability of spatial analysis and fine perception of the characteristics and laws of dynamic spatial–temporal domain encounter hazards.

Table 3
Basic technical parameter of M/T Sanchi.

		Breadth (B)	50 m
		Moulded depth (D)	23.1 m
		Draft design	16.0m
		Draft in distress	13.4 m
		maximum payload	164 thousand tons
		Actual Load	136 thousand tons
Ship Name	M/T SANCHI	Mean power of the main engine	18860 kW
Length between perpendiculars (L_{pp})	274.18m	Ship speed through water (U)	16knot

4. Applications of the methodology: a case study

4.1. Application examples and data preprocessing

The approach suggested in this study is a novel approach to analyzing and deriving the space-time properties of ship encounter safety. In order to verify the accuracy of the method, we use the actual dangerous situation formed in different time periods as the data input source, and carry out the simulation application research of the spatial modeling and analysis of the dynamic space-time domain of the encounter. The ship encounter data is the sailing movement data and accident scene information of SANCHI and CF CRYSTAL provided by the China Maritime Safety Administration. According to the survey results of the Maritime Safety Administration and the water rescue department, at 20:00 CST (UTC+08) on January 6, 2018, the bulk carrier "CF CRYSTAL" and the oil tanker "SANCHI" crashed in the Yangtze River Estuary in eastern China (approx. 160 nautical miles), which caused the entire hull of the "SANCHI" ship to sink. It was a very large maritime accident. The accident site was in open water, the sea environment information was good visibility, the northwest wind was 4–5, the wave height was 3–4 m, the collision location was 30°51′.1N, and the longitude was 124°57′.6E. The water depth information displayed on the chart is within 55m. Table 3 shows the relevant technical parameter information of M/T Sanchi itself. Fig. 20 shows the details of the navigation accident scenario in detail. In this paper, we first use the navigation radar before the collision of the "SANCHI" as a database, and the GIS spatial information platform is used to carry out GIS processing such as spatial position coding, position registration, and correction of the accident data. In this way, the spatial semantic presentation of the "SANCHI" accident scene information and sea area environmental information is completed, as shown in Fig. 21(a). Fig. 21(b) shows the meeting situation of the surrounding ships before the collision of the "SANCHI". In the case of the CF CRYSTAL and the "SANCHI", the two ships had been in the crossing state before the collision, and the urgency of the meeting situation was constantly escalating. By examining the risky state of ships over time, the proposed method's actual worth is confirmed. Future technology for smart ship navigation, risk intelligent perception, and safety early warning is strongly supported by this strategy.

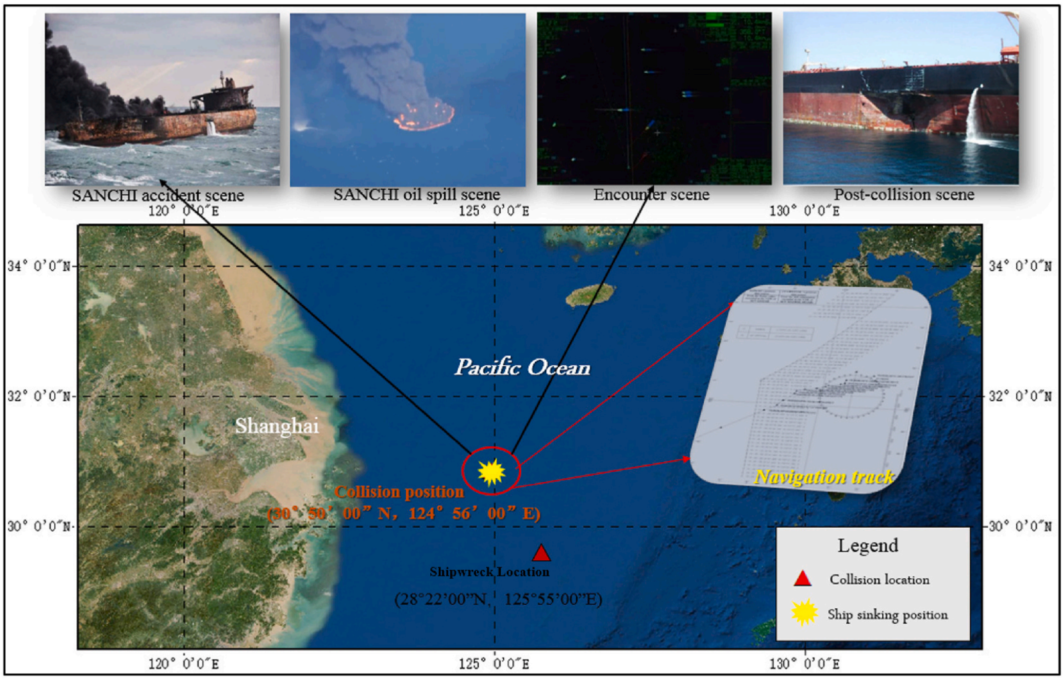
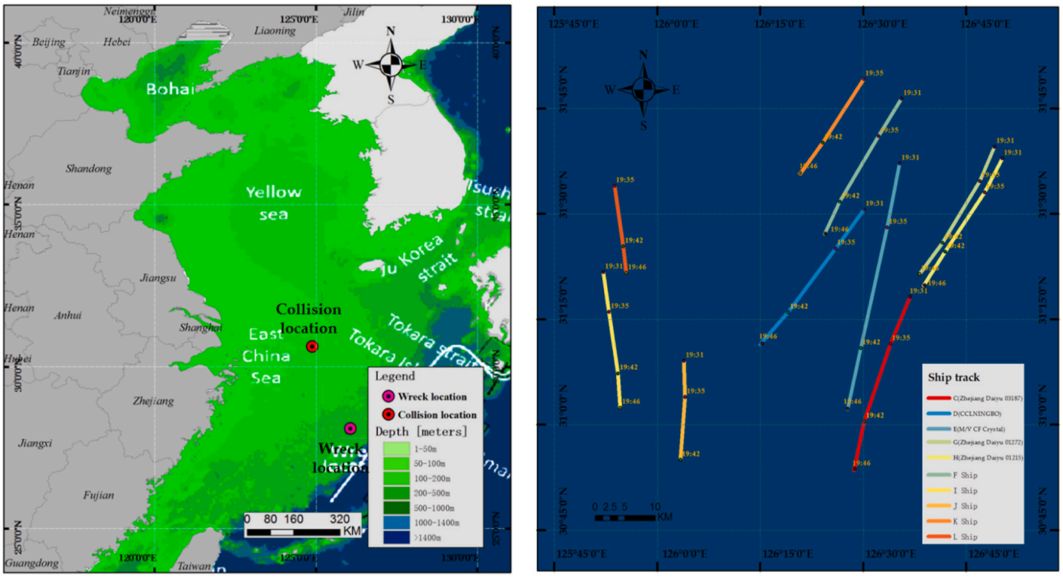


Fig. 20. Detailed information of navigation accident scenario.



(a) (b)

Fig. 21. Incident information of M/T Sanchi after data processing: (a) Diagram of incident information and marine geography (b) Relative track information of other ships around M/T Sanchi (19:31–19:46).

5. Results analysis

5.1. Spatial modeling of ship encounter dynamic spatial–temporal domain

Through the spatial modeling method of ship encountering dynamic spatial–temporal domain introduced in the third chapter, we use the normal function of the spatial distance adjustment variable to construct a multi-time-space, multi-angle encounter hazard space model, and then realize the high-precision area source analysis of the distribution law of potential encounter safety space. The figure above shows the meeting trajectories of the two ships before the collision. Six minutes before the collision, CF Crystal's position was 30°52′.1N/124°58′.8E, heading 225°, speed 13.3 knots. SANCHI's position was 26°42′.73N/123°39 ′.43E, heading 21°, speed 9.2 knots. We selected the time-space data of SANCHI's encounter at 19:42 for spatial modeling. The heading of SANCHI was 358°, the speed was 10.4kn, and the space coordinates were (30°49′37″N, 124°57′39″E). At this time, there were 10 sailing targets in the radar detection area of the SANCHI, among which target E represented the CF Crystal Ship, with a course of about 225°, a speed of about 13.2kn, and a space coordinate of (30°52′28″N, 124°59′ 10″E).

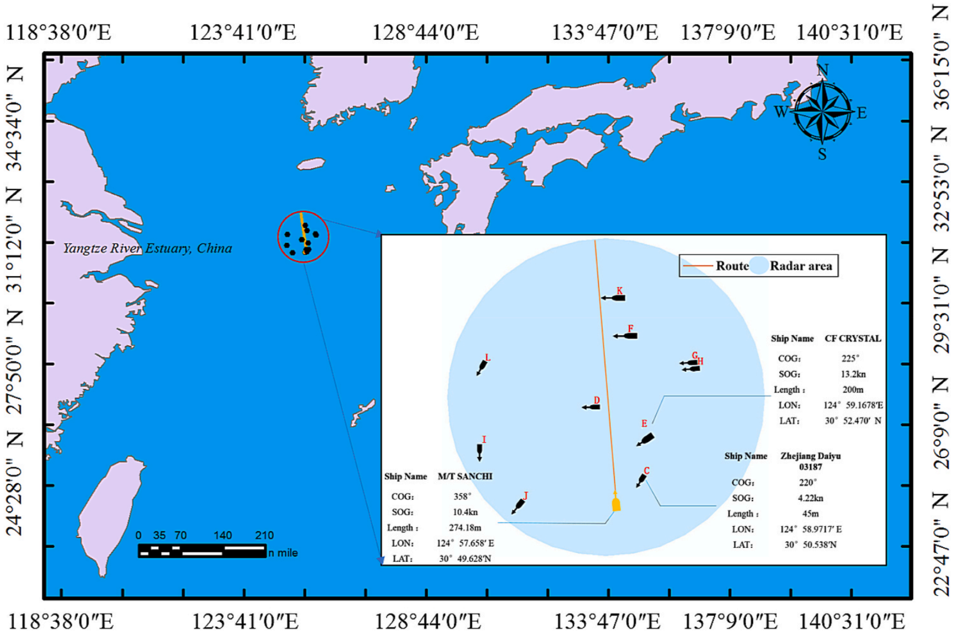


Fig. 22. Spatial distribution of ship encounters before the collision between SANCHI and CF CRYSTAL at 19:42 CST (UTC+08) on the GIS spatial information platform.

Fig. 22 shows the spatial distribution of ship encounters before the Sanchi wheel collided with the CF crystal wheel.

In order to excavate and obtain the spatial modeling results and spatial trend analysis results of the Sanchi ship and CF CRYSTAL's ships encountering dynamic spatial–temporal domain from the micro-spatial scale. This chapter further analyze the spatial–temporal heterogeneity based on the spatial modeling results of the dynamic spatial–temporal domain. First of all, we conducted a dynamic fluctuation trend analysis on the sailing situation when the formation of the Sanchi encountering dynamic space-time domain. Among them, the heading presents a mathematical trend of y = 0.0019*x^{2} - 0.036*x + 3.6e+02, and the residual modulus is about 0.658. The speed presents a mathematical trend of y = 0.00047*x^{2} - 0.009*x + 10, and the residual modulus is about 0.211. It shows that the dynamic mode of the encounter situation of the two ships remains unchanged, and the navigation situation is generally stable. Fig. 23 shows the dynamic fluctuation trend analysis results of the navigation situation when the formation of the Sanchi encountering dynamic space-time domain. Fig. 24 shows the calculation results of the encounter danger parameters of ships C, D, and E and the Sanchi at four period. It is obtained based on the proposed calculation method of encounter danger information.

In this paper, based on the GIS spatial information platform, according to the relatively stable encounter dynamic mode of the ship in relative space, combined with the calculation results of the scale factor of the danger encountered and the Euclidean parameter, the spatial modeling of the dynamic space-time domain of the ship can be quickly realized. First, based on the space modeling method mentioned above, we construct a space model of the ship encounter dynamic spatial–temporal domain. At present, the modeling of spatial entities is mainly divided into vector-based or raster-based spatial modeling methods. Since the space model of the dynamic spatial–temporal domain where the ship encounters not only contain curve elements, but also needs to calculate the continuous coding of grid points. Therefore, according to the ship navigation data and spatial distribution in the Sanchi ship encounter scene, based on the method of combining vector and raster objects, this paper constructs a spatial model of the encounter dynamic spatial–temporal domain in compliance with the ALARP criterion. Fig. 25 shows the construction result of the spatial model of the encounter dynamic spatial–temporal domain established before the SANCHI collided with the CF CRYSTAL. Finally, the modeling feature points in the established space model are converted into a space matrix and used as the basic calculation unit, and each 1/2 of the dynamic space-time domain is guaranteed to be composed of a space matrix with no less than 400 modeling feature points. Each modeling feature point has a dangerous feature value in the dynamic encounter process of the ship object, so as to complete the mining and expression of the distribution law of the dynamic space-time domain of the encounter and the change of the space-time trend from the micro-spatial scale. Fig. 26 shows the spatial modeling results of the encounter dynamic spatial–temporal domain by the SANCHI and CF CRYSTAL at 19:42 CST (UTC+08).

5.2. *Characteristic analysis and study of ship encounter dynamic spatial–temporal domain modeling results*

Using the spatial analysis algorithm in the dynamic space-time domain of ship encounters proposed in section 3, according to the modeling results of the encounter space domain, combined with the space-time distribution characteristic index, to obtain the distribution feature information of the space matrix and adjacent space-time object units, and finally to complete the spatial–temporal distribution analysis of the modeling results of the encounter dynamic spatial–temporal domain. Fig. 27 shows in detail the spatial–temporal distribution characteristics (spatial aggregation, heterogeneity, and association) of the spatial modeling results in the four quadrants of the encounter dynamic spatial–temporal domain. Among them, the abscissa is the encounter time value, and the ordinate is the encounter dynamic space domain, which is divided into 11 sub-segments evenly according to the Euclidean distance. The first quadrant, the second quadrant, the third quadrant, and the fourth quadrant represent four types of spatiotemporal associations between the encounter space matrix unit and its adjacent matrix units, respectively. Fig. 27 shows that the number of point sets (red points) in the first quadrant increases continuously after 19:42. It demonstrates that after 19:42, SANCHI and CF Crystal's encounter forms a dynamic space-time domain that exhibits the traits of high aggregation, strong correlation, and low outlier degree. The other quadrants show the characteristics of high discreteness and insignificant spatial correlation.

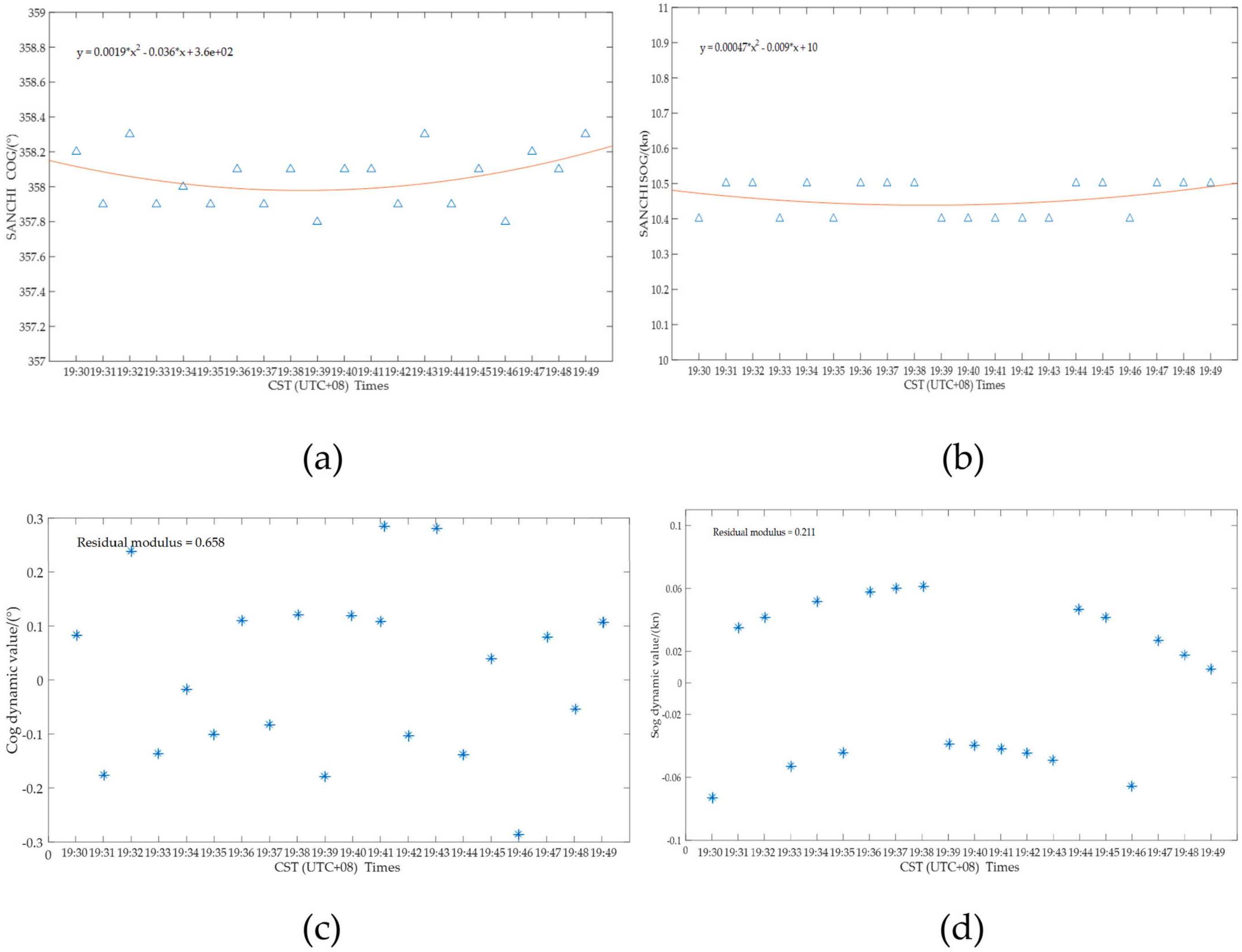


Fig. 23. The dynamic fluctuation trend analysis results of the navigation situation when the formation of the Sanchi encountering dynamic space-time domain: (a) Analysis result of ship COG change trend (b) Ship SOG change trend analysis result (c) Ship COG dynamic fluctuation trend analysis result (d) Ship SOG dynamic fluctuation trend analysis result.

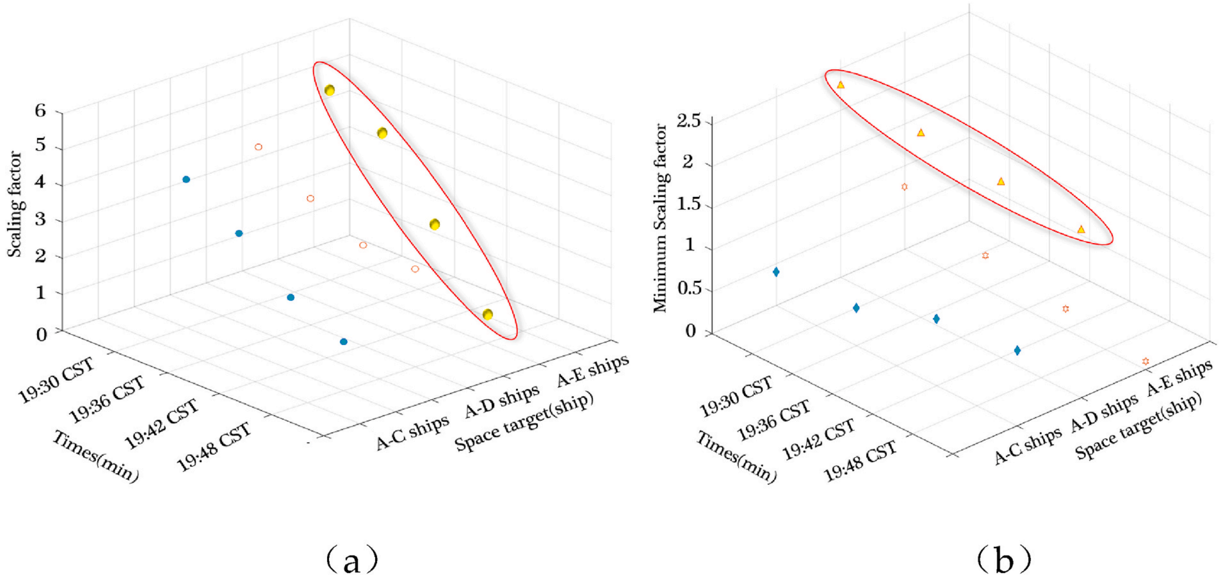


Fig. 24. Results of collision risk calculation of ships in the encounter dynamic spatial–temporal domain using (a) scaling factor and (b) minimum scaling factor.

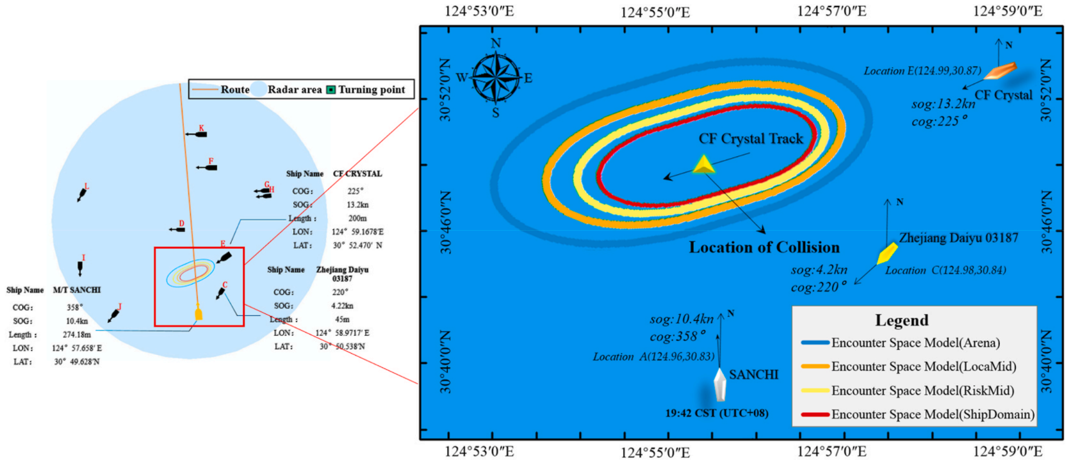


Fig. 25. 19:42 CST (UTC+08) The spatial model construction of the encounter dynamic spatial–temporal domain before the SANCHI collided with the CF CRYSTAL.

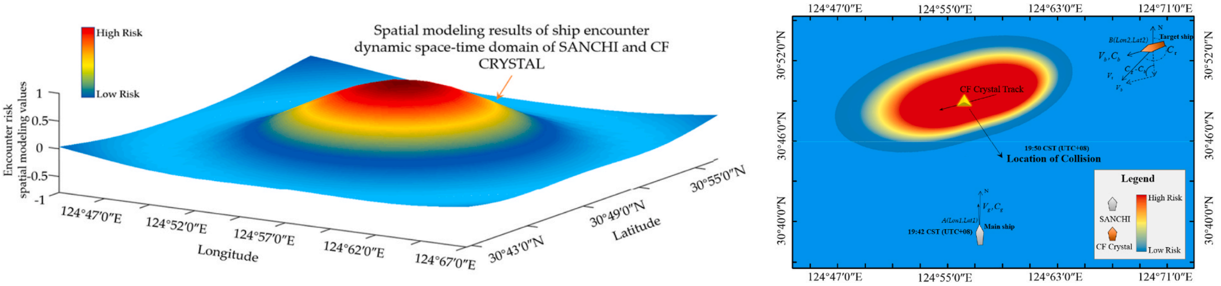
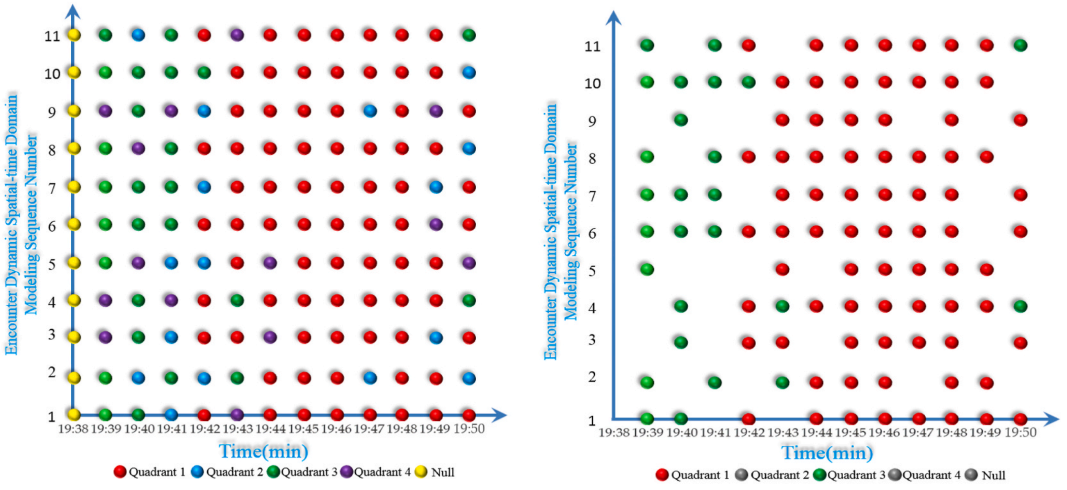


Fig. 26. Spatial modeling results of ship encounter dynamic space-time domain at 19:42 CST (UTC+08): (a) Three-dimensional modeling results of the dynamic space-time domain of the ship encounter between SANCHI and CF CRYSTAL (b) Two-dimensional modeling results of the dynamic space-time domain of the ship encounter between SANCHI and CF CRYSTAL.



(a) (b)

Fig. 27. Spatial–temporal distribution characteristics of the space-time modeling results of ship encounter dynamic space-time domain: (a) Features in the four quadrants (b) Features in the first quadrant and the fourth quadrant.

Furthermore, we conducted spatial variation characteristics and mathematical trend analysis on the characteristic elements and modeling result values of the dynamic time-space domain modeling of the encounter formed by SANCHI and CF Crystal. Through the semi-variation/covariance function cloud, the characteristics and rules of the variation with space distance in various directions in the dynamic space-time domain of ship encounters are further exposed. To select 0°, 30°, 60° and 90° to represent the north-south direction, northeast-southwest direction, east-west direction and southeast-northwest direction respectively, to obtain four spatial variation function clouds in the dynamic space-time domain, as shown in Fig. 28. The horizontal axis in the figure represents the spatial distance in the direction of the

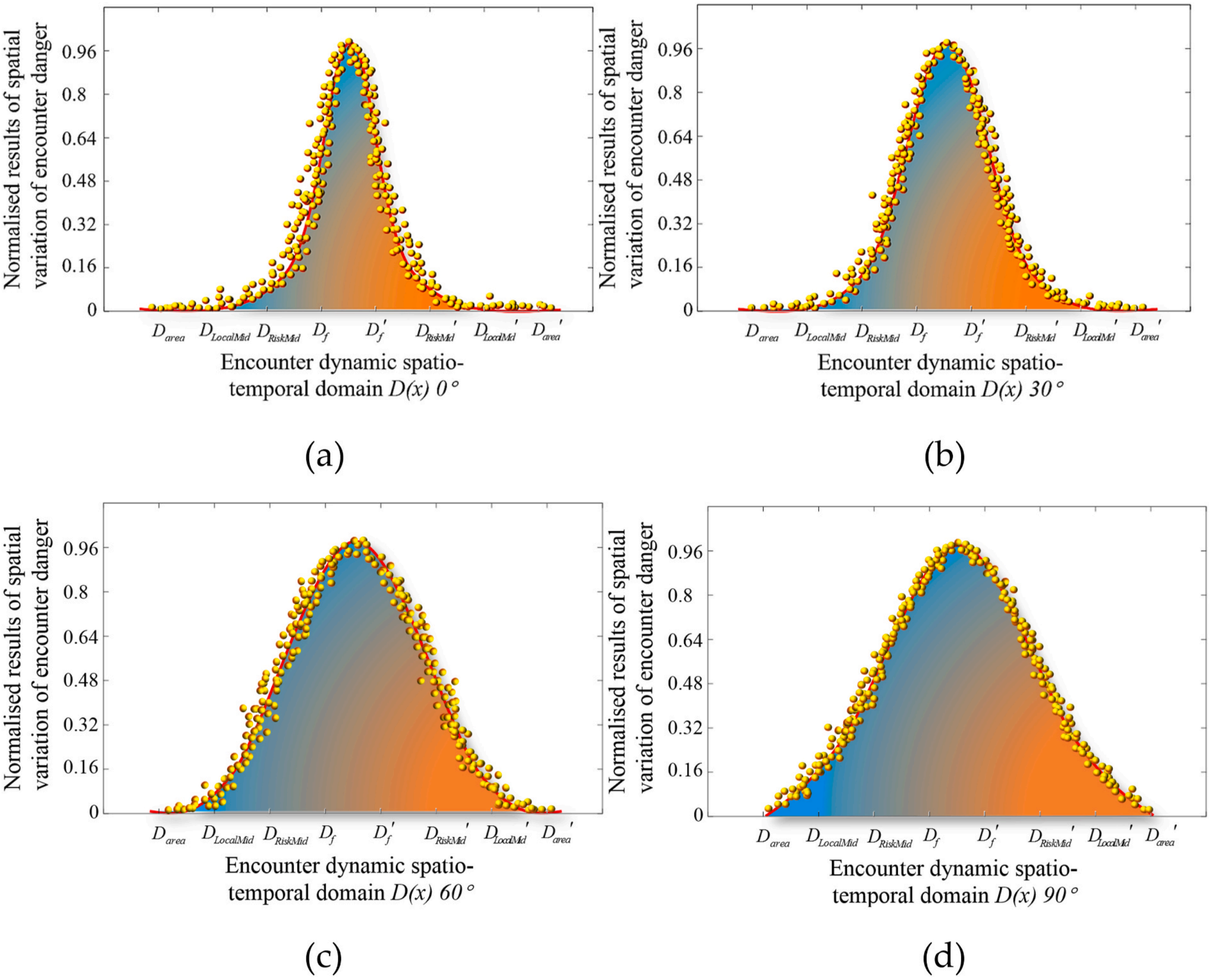


Fig. 28. Spatial variation function and distribution results of encounter dynamic space-time domain at four angles: (a) 0° (b) 30° (c) 60° (d) 90°.

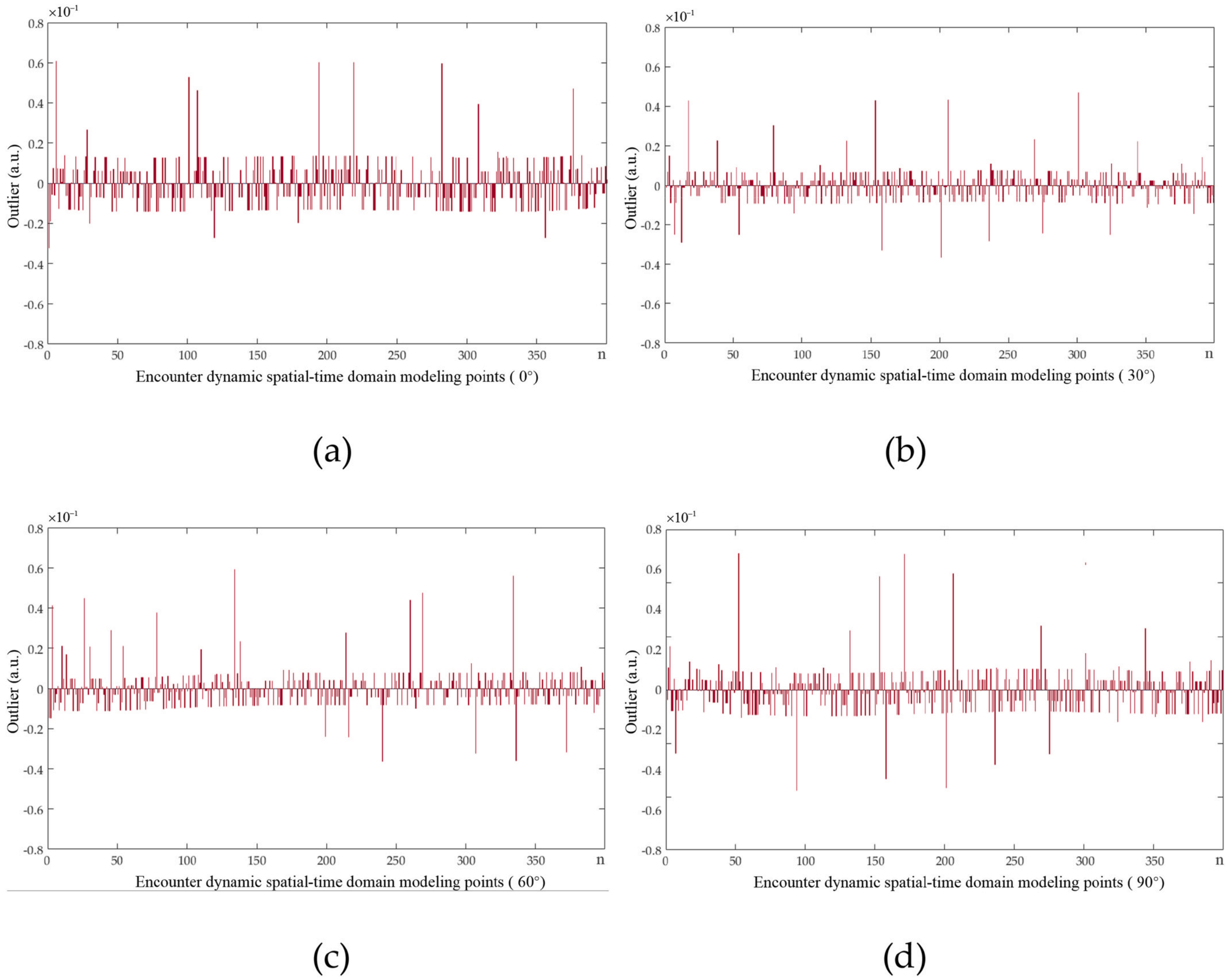


Fig. 29. The outlier analysis results of the modeling results in the dynamic spatial–temporal domain: (a)0°direction (b)30°direction (c)60° direction (d)90°direction.

Table 4
Error analysis index of Spatial modeling and analysis method of ship-encounters dynamic spatial–temporal domain.

Error Analysis Index	Result of error analysis index			
	The accuracy of the proposed method(0°)	The accuracy of the proposed method(30°)	The accuracy of the proposed method(60°)	The accuracy of the proposed method(90°)
MAE	1.58%	2.65%	2.07%	3.08%
RMSE	1.96%	3.31%	1.58%	2.04%
MRE	3.31%	2.39%	2.19%	2.42%
DFE	2.39%	1.82%	2.58%	1.35%
Average	2.31%	2.54%	2.11%	2.22%

encounter dynamic space-time domain, and the vertical axis represents the spatial variation degree of the ship encounter danger value. According to an examination of the results in the figure, the greater the Euclidean distance into the encounter dynamic space-time domain, the law of the encounter danger value first increases and then decreases, and experiences a peak. To sum up, the risk values in the dynamic space-time domain generally present normal distribution curves with different mathematical laws (distance adjustment variables).

5.3. *Analysis of method precision and dependability*

In addition, based on the results of the four semi-variogram clouds in the dynamic spatial–temporal domain of ship encounters obtained in Fig. 28, we analyze the encounter points above the y-axis in the outlier state in the figure. If the outlier degree of the encounter points is smaller, it means that the modeling and analysis effect of the dynamic spatial–temporal domain is better, and it can more accurately reflect the spatial distribution characteristics and changing trends of the encountering danger in the space. Fig. 29 shows the outlier calculation results of the modeling results of encountering dynamic spatial–temporal domain. The overall deviation of the modeling results ranged from 1.86% to 6.71%, with an average outlier value of 3.32%. It shows that the situation of normal distribution in the dynamic spatial–temporal domain of the meeting is relatively significant, and there is no obvious spatial variability, which further shows that the modeling results of the proposed method have good accuracy and reliability.

Furthermore, we use the encounter risk value of the modeling result unit and the normal distribution curve to compare and analyze the error. The classic mean absolute error (MAE), root mean square error (RMSE), mean relative error (MRE) and degree of fit error (DFE) is used as an error analysis index for the dynamic spatial–temporal domain modeling results of ship encounters. Generally speaking, the closer the MAE, RMSE, MRE, and DFE values are to 0, the smaller the error of the

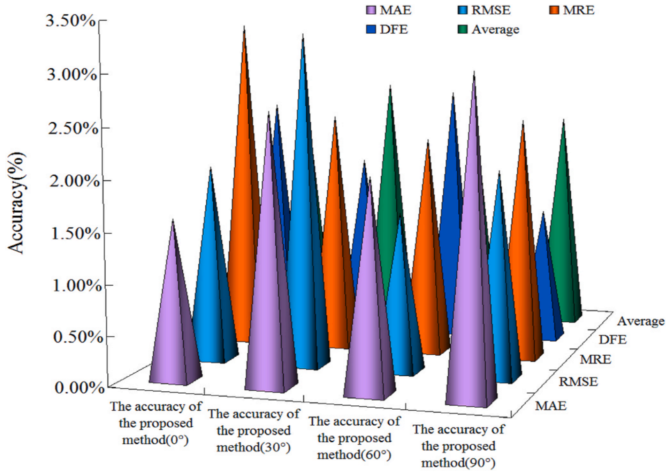


Fig. 30. Numerical comparison of Error analysis results of Spatial modeling and analysis method of ship-encounters dynamic spatial–temporal domain.

modeling result of the ship encountering dynamic spatial–temporal domain, and the higher the accuracy of the spatial modeling method. Table 4 and Fig. 30 describe in detail the error analysis results of the spatial modeling and analysis method for encountering dynamic spatial–temporal domains. The results show that the proposed method can accurately realize the analysis and extraction of the spatial distribution law of the ship's encounter space danger and the characteristic information of the space-time trend change in each space-time of the encountering dynamic spatial–temporal domains. It effectively solves the problem that it is difficult to analyze and extract the dynamic time-space domain characteristics and distribution rules of heterogeneous encounters., thereby improving the spatial perception and analysis capabilities of future ship intelligent navigation for danger.

6. Discussion

At the moment, scholars are currently conducting research work on the analysis of ship encounter danger in the study of intelligent navigation safety. For example: in the study of ship intelligence/safety navigation, scholars proposed Neural finite time formation intelligent navigation algorithm (Huang et al., 2021), A real-time ship collision risk perception model (Wang et al., 2022), Safe and autonomous navigation system (Gao et al., 2022). It makes a certain contribution to the improvement of ship navigation risk analysis ability. Liu, J et al. (2022) defined the maximum separation (MISD) of two ship domains and the violation degree (VDSD) of two ship areas, and established a ship collision risk assessment model based on the ship collision risk probability and two parameters. Zhang et al. (2018) proposed a navigation path planning algorithm that can intelligently avoid obstacles, which improves the intelligence level of ships. Ni et al. (2019) proposed a ship navigation collision risk calculation and automatic trajectory planning method, and graphically expressed the encounter risk in typical encounter situations. These studies have made some progress in calculating navigational risk, and the methods they use are comparable to those proposed in this paper.

However, these research works are insufficient for the extraction and analysis of the spatial–temporal variation law and unknown nonlinear spatial features in the ship encounter spatial–temporal domain. These studies have not deeply explored a large number of potential unknown nonlinear hazard spatial characteristics and trend law information in the process of ship encounters. It ignores the latent spatial representation relationship of dangerous information in multi-temporal and spatial domains, which happens to be one of the important problems in the research of intelligent navigation safety technology. In addition, if the traditional algorithm is to be further promoted and applied to actual ship navigation, it needs to rely on a real and powerful navigation environment spatial information platform. The main reason for this is that in the real navigation environment, ship safety information typically presents problems such as huge data volume, multidimensional and multi-source data, complex heterogeneity, and so on, and a large number of ships present navigation spatial relationships that are intertwined, dynamic and static, and discretely distributed during navigation. There are many potential and complex encounter space elements and regular information, which leads to hazy, complex, and imprecise challenges in the navigation process, particularly in the face of complex encounter circumstances like many barriers and dense ships. As a result, it is impossible to accurately extract the hidden navigation risk information and other potential navigation encounter spatial feature information. Therefore, the GIS spatial information platform and the scientific theory of spatial analysis demonstrate enormous benefits and potentials in resolving the aforementioned issues. It will be essential to implement a novel approach to GIS spatial modeling and analysis that is based on the dynamic spatial–temporal domain of ship encounters that we have proposed. GIS is an analysis technology that is good at spatial–temporal dynamic location information. It has powerful spatial data computing capabilities, advanced spatial analysis and modeling, spatial semantic analysis, and spatial feature and law extraction. It solves extremely complex spatial analysis problems, such as the precise extraction and quantification of the spatial laws of dynamic and static objects in various time series, using geographical information data with spatial position, temporal and spatial distribution, and orientation relationship as objects. Since 2020, Dalian Maritime University, Waterborne Transport Research Institute, and Offshore and Marine (LOOM) Research Institute of Liverpool John Moores University have carried out a series of research and conclusions (Zhao et al., 2018; Wang et al., 2022). Their research results indicate that a powerful spatial information platform and a spatial analysis method that can be used to analyze the safety characteristics of navigation encounters are urgently needed in the field of navigation safety. The development of future intelligent navigation safety perception technology is innovatively theoretically supported by the most efficient application of GIS spatial information analysis technology's benefits in navigation safety.

Table 5
Algorithm performance compared to previous studies.

Ref	Year	Models and methods	Error
CHEN et al.	2008	Fuzzy neural network	15.8%
Liu R and Hu Q	2012	Subjective evaluation	–
Wu et al.	2013	Fuzzy clustering	12.1%
Chen D et al.	2015	Fuzzy Comprehensive Evaluation	–
Xu et al.	2017	Fuzzy logic theory and fuzzy comprehensive evaluation	9.7%
Liu Z et al.	2020	Ship encounter space topological model	6.8%
This paper	–	This proposes a novel approach	2.30%

Therefore, relying on the GIS spatial information platform and spatial analysis technology, this research proposes a new method of GIS spatial modeling and analysis based on the dynamic spatial–temporal domain of ship encounters, which innovatively solves the problem of in-depth analysis of the spatial distribution characteristics of potential dangers and the trend of time and space in the dynamic spatial–temporal domain of ship navigation encounters. It provides spatial analysis results with accurate spatial features and spatiotemporal attribute feature information for intelligent and safe navigation of ships in complex waters such as turning sections, multiple obstacles, and dense waters. Moreover, the new method effectively lowers the ambiguity of the encounter space and offers a fresh way to enhance the capability of ship encounter safety analysis in dynamic spatial–temporal domain. These issues are related to spatial analysis and perception of ship encounter risks. This paper enhances the theoretical innovation of GIS spatial analysis in the field of navigation safety assurance. This analysis idea provides a forward-looking method support for the development of intelligent

Fig. 31. Dalian Maritime University Teaching Practice M/V YU KUN schematic.

Table 6
Basic technical parameter of Main-ship (M/V YU KUN).

Serial number	Ship Parameters	Information
01	Overall Length	116 m
02	Moulded depth	8.3 m
03	Draft design	5.4 m
04	Breadth	18 m
05	Rudder area	11.8 m^2
06	Service speed	15 kn
07	Rudder height	4.8 m
08	Ship speed through water (U)	16 knot
09	Mean power of the main engine	18860 kw

navigation situation safety awareness theory. In addition, the model results are compared with the overall accuracy of previous ship collision risk calculation methods based on correlation calculation methods, as shown in Table 5. Through the content of Section 5.3, it is found that the error of the proposed method is between 1.35% and 3.31%, and the average error can reach about 2.30%, which further verifies the superiority and reliability of the proposed method. This method has been successfully applied to the navigation hazard analysis of the collision between the "SANCHI" and the "CF CRYSTAL", which further shows that the method can meet the needs of ship navigation safety assessment. It is of great value to improve the spatial awareness of ship navigation hazards. Currently, this method has been incorporated into the "Dexu" engineering test ship's intelligent navigation platform, and from November 15 to November 19, a real ship navigation test was conducted nearby the Taiwan Strait of China. The trial's length is approximately 369.9 miles. It further shows that this method can effectively perceive and extract rich and comprehensive encounter safety space information. The core algorithm module of this method has passed the official testing and certification of China CNAS. In the next research work, we will further combine the conclusions of this actual sailing test to optimize and perfect this method, especially in the face of shortcomings in complex and multi-vessel sailing scenarios, so as to enhance the stability and dependability of the algorithm.

7. Conclusions and future work

Because each space-time state's navigation safety information is intertwined and complex, as well as because movement and static coexist, space-time difference characteristics are discretely distributed, and there are many potential spatial characteristics and trend law data. The issue of ambiguity and complexity of ship navigation encounter information is significant, particularly in the face of complicated encounter scenarios like those including numerous obstacles and dense ships. In order to improve the ability to extract the safe spatial features of dangerous navigation targets and the ability to analyze the space-time trend of navigation hazards, this study suggests a new approach to spatial modeling and analysis based on the dynamic space-time domain of ship encounters, which is based on the GIS spatial information platform and spatial analysis technology. This method builds a multi-time-space, multi-angle, and multi-state encounter dynamic time-space domain model, and solves the issue of in-depth analysis of the changing trend and characteristic law of the encounter danger for all location sets in multi-time-space sequences and nonlinear spaces. It breaks through the technical problems of spatial analysis and perception of ship-encountered dangerous area sources, and effectively reduces the ambiguity of the encounter space. This research extracts and analyzes the probable spatial characteristics of the dynamic space-time domain of the ship encounter before the collision based on the simulation

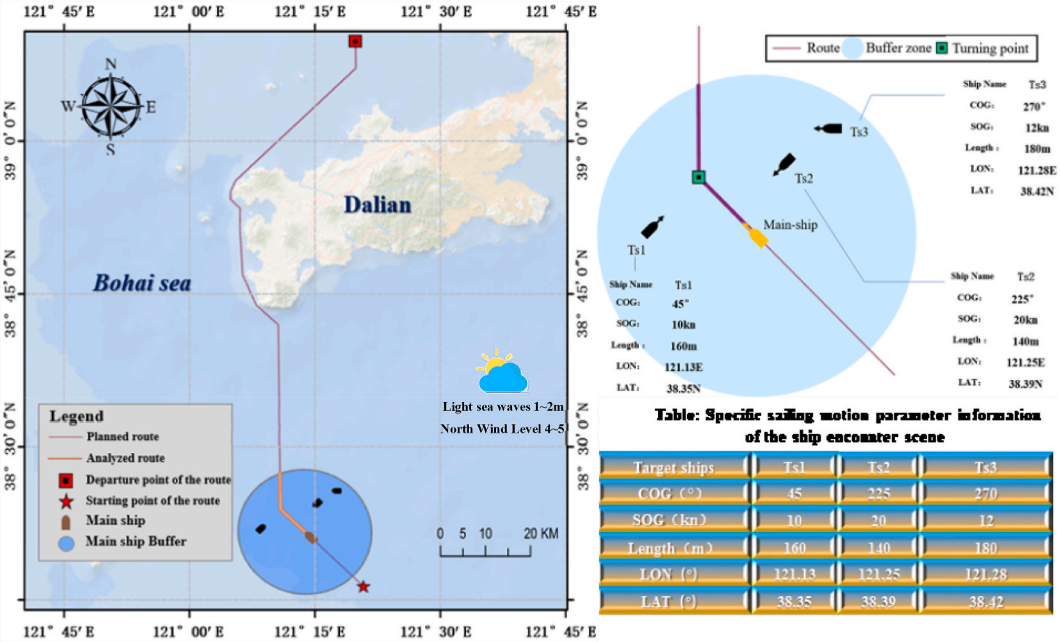


Table: Specific sailing motion parameter information of the ship encounter scene

Target ships	Ts1	Ts2	Ts3
COG (°)	45	225	270
SOG (kn)	10	20	12
Length (m)	160	140	180
LON (°)	121.13	121.25	121.28
LAT (°)	38.35	38.39	38.42

Fig. 32. The navigation motion parameter information of the ship under the selected part of the real sea area during the simulation verification of the multi-ship encounter scene.

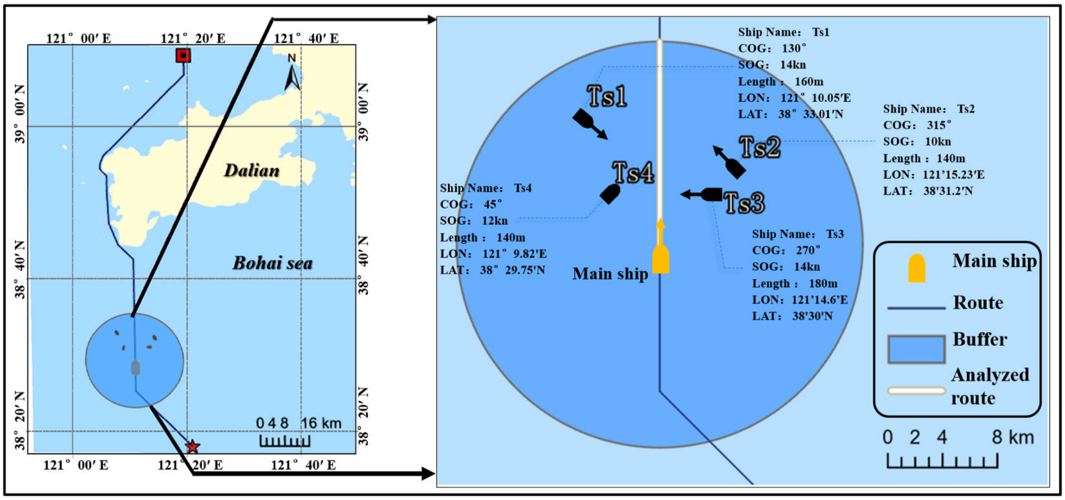


Fig. 33. Description of the encounter scene and navigation information of multi-ship.

verification of the actual encounter scene between M/T Sanchi and M/V CF Crystal. The outcomes demonstrate how precise and cutting-edge the suggested strategy is. For the sensing and analysis of the spatial properties of meet hazards in intelligent navigation, the proposed technique can offer a futuristic and unique theoretical method.

First and foremost, because this article is a preliminary attempt to explore the theoretical innovation of GIS spatial analysis in the field of navigation safety assurance, there are deficiencies in the algorithm design of the emergency encounter scene of multiple ships. We will continue to improve and perfect the method of this paper in the next research stage. Based on the basis of this research work, the focus is to deeply explore and solve problems such as the time-space superposition of multi-ship intersection information in the multi-ship encounter scene, and the calculation of the danger correlation between multiple ships, so as to a highly accurate, applicable and computationally simple method for constructing and spatially resolving the dynamic spatial and temporal domains of multi-ship encounter processes is investigated. In order to better match the realism of encounter scenarios, we conducted simulation experiments based on multi-ship urgent encounter scenarios using our experimental vessel "M/V YU KUN", and further optimized the spatial modeling method of encounter dynamic space-time domain. Fig. 31 and Table 6 describe the basic information of M/V YU KUN in detail. Figs. 32 and 33 are detailed descriptions of the basic information of the simulation case for carrying out the multi-vessel encounter test. Secondly, In the real ship navigation environment, ship navigation information presents problems such as multiple data sources, difficulty in data fusion, redundancy and inconsistency between information, etc. It has an impact on the findings of the analysis of navigational risks, causing ambiguity, complexity, and inaccuracy in the analysis of navigational information. In the next research work, we will conduct in-depth research and build an integrated spatial information platform that integrates other multi-source navigation information (such as radar, AIS, etc.) with the electronic chart as the bottom layer. The figure provided below is a special electronic navigation chart (part of the coastal waters of Dalian) that we initially produced based on the spatial information platform. The constructed platform not only integrates multi-dimensional high-precision navigation data fusion algorithms (including the fusion algorithm of AIS and radar data), but also has a powerful library of navigation safety spatial analysis models and visual graphics, so that navigation can quickly understand the current navigation safety situation. And then realize the rapid fusion, analysis and decision-making of navigation situation security from the data layer to the application layer. It can significantly improve the spatial perception and analysis capabilities of future ships' intelligent navigation and provide technical support for developing intelligent navigational danger perception technology for intelligent ships in the future. At last, by combining the real navigation situation with the method described in this paper, we will continue to improve and optimize it, and further combine the GIS spatial analysis method with the field of intelligent navigation situation security, and innovatively solve the problem of accurate extraction and measurement of spatial law information and spatial security features of dynamic and static targets during navigation from a spatial perspective, and extract more abundant potential navigation space security information. This research work is only a preliminary methodological attempt, from the industrial application needs to do further expansion and improvement work research in the actual navigation scenario. It supplies more space safety information for safe and intelligent ship navigation. This will be a more compelling research topic in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix

Appendix A. Detailed pseudocode flow of spatial modeling and analytical algorithm of ship encounter dynamic spatial–temporal domain (Supplement to Section 3)

```
Initialize ship's navigational motion data
Input ship domain parameters $a_{\text{Domain}}$, $b_{\text{Domain}}$, $\Delta a$, $\Delta b$
Input $a_{\text{Arena}}$, $b_{\text{Arena}}$, $D_f$, $D_{Arena}$ % ship encounter dynamic spatial–temporal domain parameters
Judging the dynamic patterns of encounters between ships
For t = 1, T do
  Input the relative coordinates $X_e(t)$, $Y_e(t)$ of the target ship
    Execute hazard identification function $f(t)$
      Output and store the result of $f(t)$
    While $f(t) \in$ minimum value
  Output $f_{\min}$、$t_{\min}$, store $t_{in}$、$t_{out}$
    Judging the size of $f(t)$
    If $f(t)=1$, % Arena
            Definition spatial modeling feature point elements that encounter dynamic spatial–temporal domains
    Else If $f(t)=0.75$, % Local-Mid
            Definition spatial modeling feature point elements that encounter dynamic spatial–temporal domains
    Else If $f(t)=0.6$, % Risk-Mid
            Definition spatial modeling feature point elements that encounter dynamic spatial–temporal domains
    Else $f(t)=0.5$, % Ship-Domain
            Definition spatial modeling feature point elements that encounter dynamic spatial–temporal domains
    Output all spatial modeling feature points: $S_1\left(x_{i1}, y_{i1}\right)$, $S_2\left(x_{i2}, y_{i2}\right)$, ..., $S_i\left(x_{ii}, y_{ii}\right)$
    End for
    Initialize mathematical collection of unknown points for spatial modeling $S_k\left(A_{sk}, B_{sk}\right)$, $k \in (1,2,3,\ldots,N)$
    For i = 1, k do
    Set the set of unknown points for spatial modeling：
$\left(x_{i1}+\frac{k-1}{N-1}\left(x_{i2}-x_{i1}\right),\ y_{i1}+\frac{k-1}{N-1}\left(y_{i2}-y_{i1}\right)\right)$ $k \in (1,2,3,\ldots,N)$
      Execute $d_{k,\alpha}^{'} = d_{k,\alpha} / d_{\max}$, % The normalized distance value between spatial modeling feature points and other spatial modeling unknown points
    Judging the size of the $d_{k,\min 1}$
      If $d_{k,\min 1} \neq 0$,
```

```
        Execute $w_{k,\alpha} = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-\left(d'_{k,\alpha}\right)^2}{2\sigma^2}} / \sum_{\alpha=1}^{n} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-\left(d'_{k,\alpha}\right)^2}{2\sigma^2}}$ %Influence value of spatial modeling feature points on ship encounter danger space domain
        Else $w_{k,\min 1} = 1 \,||\, w_{k,\alpha} = 0$
    Compute the influence value of spatial modeling feature points $WC_\phi$
    Output the value of $WC_\phi$
    Execute $\hat{\mu}(s_0) = \sum_{i=1}^{n} wc_\phi \mu_i(s_i)$
    Output the result value of to be modeled points $\hat{\mu}(s_0)$
    end for
    Judging the magnitude of the normal distribution curve in the dynamic spatial–temporal domain of ship encounters
    For j = 1, k do
    Set the distance adjustment variable $C(l_k)$ and the normal distribution optimization coefficient $m$
        Execute $C(l_k) = \frac{1}{l_k^m} - 1$ % Obtain the distance adjustment variable between the feature point and other points in the modeling process;
    Judging the value of $C(l_k)$
      While $C(l_k) \geq 1$
          According to steps 19-23 for loop calculation;
      While $C(l_k) < 1$
              Compute $\overline{d}_{k,\min 1}$ , $\overline{d}_{k,\min 2}$ % The distance adjustment variable between spatial modeling feature points and the nearest, the second closest modeling unknown point;
          According to steps 19-23 for loop calculation;
          Output the value of $WC_\phi$
          Execute $\hat{\mu}(s_0) = \sum_{i=1}^{n} wc_\phi \mu_i(s_i)$
          Output result values for modeled points $\hat{\mu}(s_0)$
    End for
```

. (*continued*).

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