
CHAPTER 4

Choosing the best maneuver for vessel separation taking into account the energy efficiency of the trajectory

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Abstract

Traditional ship passing methods are mostly focused on minimizing the risk of collision without considering fuel consumption, which complicates achieving sustainable development goals in maritime transport. At the same time, rising fuel costs, tightening international environmental regulations, and the need to reduce greenhouse gas emissions highlight the importance of integrating energy efficiency principles into the navigation decision-making process.

This work examines the functional capabilities of overlaying radar imagery on the ECDIS display as one of the key tools supporting energy-efficient maneuvering during ship passing. The advantages and limitations of integrating radar information with electronic navigational charts are analyzed, as well as the impact of such integration on improving navigation accuracy, reducing collision risks, and supporting sustainable fuel use. The relevance of integrating radar information with ECDIS to enhance real-time situational awareness is substantiated. It is shown that combining radar data with ECDIS significantly reduces the risks of erroneous decisions in conditions of limited visibility and high traffic density, and also provides better situational interpretation for making energy-efficient maneuvering decisions. It is determined that such integration is a key component of modern navigation decision support systems, as it allows consideration of the real situation and characteristics of target objects while accounting for safe and economically feasible courses.

The implementation process of collision avoidance systems using models aimed at ensuring navigational safety is analyzed, along with revealing their potential for optimizing energy consumption in maritime transport. A conceptual model for selecting the optimal ship passing maneuver is proposed, based on the combination of safety criteria and fuel consumption minimization. Special attention is given to the use of the Open Sea Model (OSM) as a tool for forecasting and evaluating movement trajectories considering various ship interaction scenarios. Particular

focus is placed on the challenges of integrating this system with modern navigation complexes, including ECDIS, Automatic Identification Systems (AIS), and radars, to ensure real-time operation.

Keywords

Energy efficiency, ship passing, collision avoidance, movement trajectory, ECDIS, radar, data integration, Open Sea Model, modeling, maritime navigation, navigational safety, AIS, route optimization, maneuvering.

4.1 Introduction

In the current conditions of intensive development of global maritime trade and increasing traffic on major shipping routes, the issue of safe ship passing becomes particularly relevant. Every year, millions of interactions occur in the World Ocean between vessels that require prompt decisions regarding course or speed changes to avoid collisions. Traditionally, the primary objective of maneuvering has been to comply with the rules of passing according to the International Regulations for Preventing Collisions at Sea (COLREGs-72). However, in the context of modern requirements for energy efficiency in shipping and greenhouse gas emission reduction, a new dimension emerges – the search for maneuver options that not only ensure safety but also minimize the ship's energy consumption.

The introduction of new environmental regulations by the IMO, such as EEDI, EEXI, and CII, poses a challenge for shipping companies to optimize the operational parameters of vessels [1]. In this context, it is important not only to choose optimal navigation routes but also to minimize the impact of non-standard maneuvers, particularly evasive maneuvers, on overall fuel consumption. Since passing maneuvers typically require changes in speed, course, or both simultaneously, they can cause significant deviations from energy-efficient trajectories, leading to fuel overconsumption, increased voyage time, and, consequently, higher operational costs.

Recent scientific research shows growing interest in developing adaptive decision support systems capable of considering not only geometric and navigational parameters of the situation but also energy consumption characteristics, hydrometeorological conditions, engine type, and the behavior of other vessels. In this regard, the development of models that provide multi-criteria evaluation of possible evasive maneuvers, taking into account both safety and energy efficiency, is a topical task in modern maritime navigation.

The problem of selecting the optimal maneuver becomes especially complex in narrow or restricted navigation areas, where the evasion zone is limited, and spatial

and temporal parameters of interaction with other vessels become critical. Under such conditions, precise assessment of mutual vessel dynamics, real-time situation forecasting, and integration of obtained data into navigation systems, including the Electronic Chart Display and Information System (ECDIS), automatic radar plotting aids (ARPA), and machine vision systems, are necessary [2].

This chapter of the monograph considers an integrated approach to selecting the best ship passing maneuver, combining the analysis of the navigational situation, application of formalized safety rules (COLREGs), and energy consumption models of vessel movement. Special attention is paid to methods for evaluating maneuver options based on fuel consumption, time loss, safety, and route deviation criteria. Examples of calculations, objective function models, and decision-making algorithms adapted for real use in ship navigation systems are presented.

Thus, this chapter represents a logical combination of theoretical principles of maritime navigation, modern energy efficiency concepts, and practical tools of digital ship control. The presented material can form the basis for developing intelligent navigation assistants capable not only of responding to passing situations but also proactively forecasting energy-saving movement strategies in conditions of intensive maritime traffic.

4.2 Radar image overlay on ECDIS: significance for energy-efficient maneuvering in ship passing situations

With the increasing density of maritime traffic and growing demands for reducing greenhouse gas emissions, the need arises not only for safe but also for energy-efficient ship maneuvering. One of the crucial factors influencing collision avoidance decisions is the quality and accuracy of navigational information that ensures situational awareness for the navigator. In this context, the radar image overlay function on the ECDIS display gains special importance, as it combines the advantages of both systems: the tactical detail of radar and the strategic information from the electronic chart. This, in turn, creates conditions for optimal selection of the passing trajectory with minimal energy consumption.

The radar system is a key navigational tool for both collision avoidance and energy-efficient maneuver planning. Thanks to its ability to detect targets and assess the dynamics of surrounding traffic, radar provides the basis for timely decision-making. However, radar displays are generalized and schematic, requiring trade-offs in operation such as:

- choosing between wider coverage and better target resolution;
- balancing noise suppression with the risk of losing weak targets;

- displaying absolute movement versus assessing relative risk;
- selecting display orientation (HEAD UP or NORTH UP);
- stabilization relative to the seabed or the sea;
- integrating data versus avoiding information overload;
- interface convenience versus functional flexibility.

Considering modern requirements for energy-efficient navigation – which entails minimizing maneuvers, fuel consumption, and time loss – high-quality integration of radar information with ECDIS plays a particularly important role. The Radar Overlay mode enables overlaying radar images, ARPA data, and AIS information directly onto the electronic chart, creating a unified information environment for making energy-optimized maneuvering decisions.

A critical aspect is that all relevant navigational data (own ship, targets, coastline, obstacles) are presented in a single scale, orientation, and coordinate system. This allows the navigator to:

- quickly assess the dynamic situation;
- correlate actual target echoes with their positions on the chart;
- choose the most energy-efficient passing option considering safe zones, acceleration, turning angles, and possible hydrometeorological constraints.

Radar and ECDIS integration technologies include "digital NMEA integration" and radar processors [3]. The former allows entering tracked target data into the ECDIS if the radar has ARPA capability; the latter provides analog-to-digital conversion of the radar video signal and input of this signal into the ECDIS, as illustrated in Fig. 4.1.

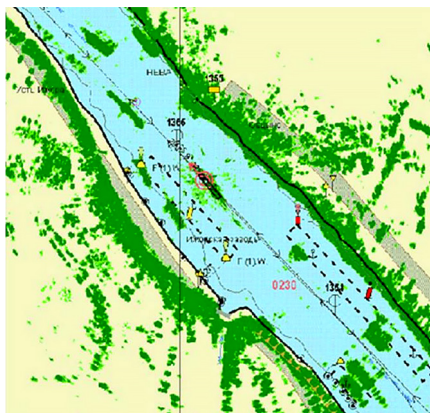


Fig. 4.1 Radar image overlay on ECDIS display

It is important that not only ARPA data but also raw radar data are integrated with chart data. Integration of the electronic chart with radar, or at least providing the user with the ability to overlay selected SENC information, ensures a system that can be used to prevent groundings and avoid collisions. The operator receives the following up-to-date information on a single display: own ship's position, all other vessels in the maritime area, and all charted objects and hazards.

Radar overlay and target correlation have particular value:

- for position fixing, since the overlay provides continuous radar position fixing without requiring manual intervention from the navigator;
- for real-time position monitoring by cross-checking the electronic position fixing system (EPFS), e.g., GPS.

When ECDIS and radar are overlaid on a single display, they create a system that can be used both for navigation and collision avoidance. As specified in IMO performance standards, radar information may be added to the ECDIS display provided it does not degrade the display quality and is clearly distinguishable from the electronic navigation chart. The IMO performance standard also requires that both ECDIS and radar use a common reference system (e.g., WGS 84) and that the chart and radar image correspond in scale and orientation.

Modern navigation suites are based on the integration of systems such as ECDIS, ARPA, AIS, GNSS (GPS/GLONASS/Galileo), gyro and inertial navigation systems, autopilots, power management systems, as well as meteorological modules. Leading manufacturers of marine navigation equipment, such as Transas (Wärtsilä Voyage), Kongsberg, Furuno, Raymarine, and JRC, offer high-tech solutions that support both safe navigation and energy-efficient vessel management.

Modern ECDIS platforms, such as Navi-Sailor 4000 or K-Bridge ECDIS, incorporate the following functionalities:

- automatic calculation of CPA/TCPA considering AIS and ARPA data;
- recommendations for course or speed changes taking into account traffic-restricted zones;
- display of radar image layers with position error compensation;
- assessment of traffic trends and likelihood of critical situations.

Let's consider the aforementioned radar integration in Navi-Sailor and the advantages of such integration. Navi-Sailor 3000 ECDIS can be equipped with a special Radar Integrator Board (RIB) from Transas. The RIB converts the radar video signal into digital form, enabling radar image overlay on the electronic chart [4].

The advantages of the radar integrator include:

- unique combination of electronic chart and radar image overlay on a single display;
- ARPA functions with tracking capability of up to 500 targets simultaneously;

- advanced voyage data recording;
- control over brightness, gain, sea and rain clutter on the screen;
- full compatibility with all Navi-Sailor products;
- OEM toolset.

With radar data displayed over the chart background, potentially confusing effects become visible that might otherwise go unnoticed on the radar screen. Three main effects should be taken into account:

1. The first relates to radars with antenna beamwidth – the larger the physical size of the antenna, the narrower the beamwidth, typically around one-degree azimuth. As a result, any object, even a point target such as a buoy, appears enlarged by the same angular extent on the display. For example, a buoy one nautical mile from the radar with a one-degree beamwidth antenna appears about 30 meters wide on the chart, and the farther from the radar, the larger it appears. Moreover, angular enlargement is not the only type of distortion; distance is also increased due to the finite length of radar pulses. For short pulses around 50 nanoseconds, distortion can reach 10 meters; for medium and long pulses, the effect is even stronger (**Fig. 4.2**).

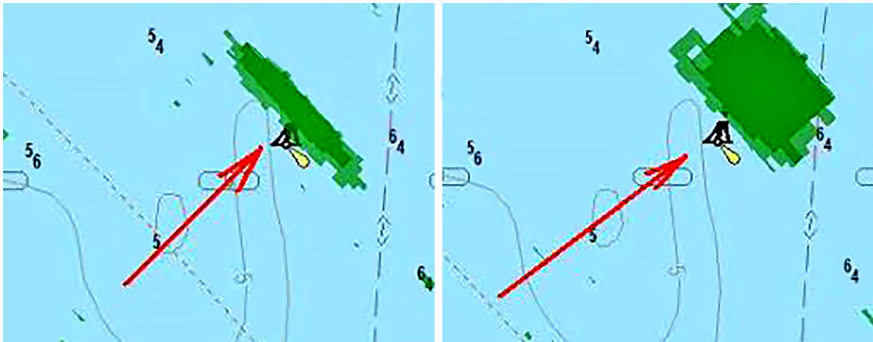


Fig. 4.2 Short-pulse image of the buoy (left) and long-pulse image (right)

2. The same factors lead to another confusing visual effect – the radar returns from the coastline generated at sharp angles appear farther from the shore than they actually are (red sectors in **Fig. 4.3**). Radar returns created at nearly right angles (blue sector in **Fig. 4.3**) do not exhibit such distortion. It is precisely the chart background beneath the radar overlay that helps to reveal this effect.

3. The third effect is that the radar reflection of the coastline does not necessarily coincide with its actual position on the chart. This is because most radar signals are reflected from steep slopes or large coastal structures, while gentle slopes produce

weak reflections and may be practically invisible on the radar image. **Fig. 4.4** shows the actual position of the coastline (red dashed line), which does not correspond to the visible radar echoes.

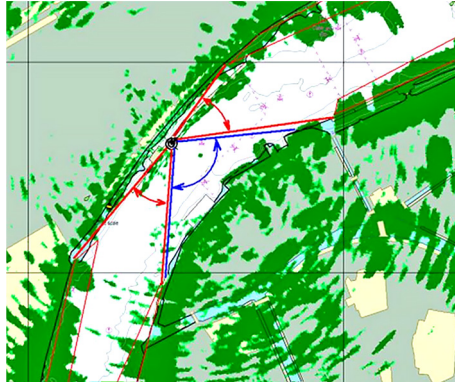


Fig. 4.3 Radar echoes of the coastline at sharp observation angles

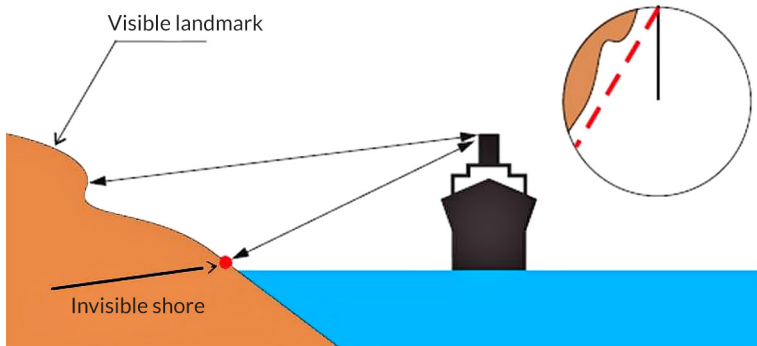


Fig. 4.4 Radar-visible and radar-invisible sections of the coastline

However, such discrepancies between the coastline depicted on radar images and that shown on charts are quite common and well-known (**Fig. 4.5**).

Considering the integration of radar and ECDIS, let's examine how navigation system failures can affect the operation of ECDIS.

The most critical failures are related to cartographic errors. It can only be assumed that such errors do occur, and therefore, nautical charts can never be considered completely reliable (there have been documented cases of islands missing from

navigation charts). The key question is whether the navigator is capable of detecting errors of this kind [5].

Among all ECDIS functions, radar overlay is the most effective in such situations, as acknowledged in IMO Circular No. 255. A discrepancy between the coastline on the chart and the radar image may indicate a cartographic error, although other possible causes of visual distortions of the coastline, as described above, should also be taken into account. Sometimes, cartographic errors on charts arise from inaccuracies in the transformation between local datum and the WGS-84 geodetic coordinate system. Errors of this kind introduce a systematic offset of the actual position of the line or area – the red arrows of approximately equal length and direction in **Fig. 4.6** illustrate this effect.

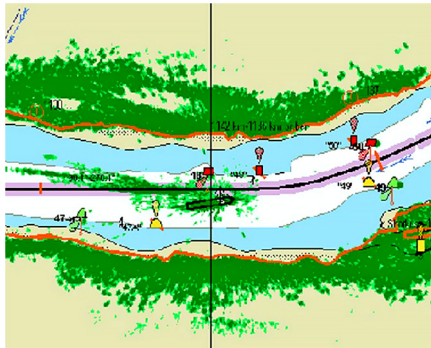


Fig. 4.5 Non-systematic (random) discrepancy between radar imagery and the charted coastline

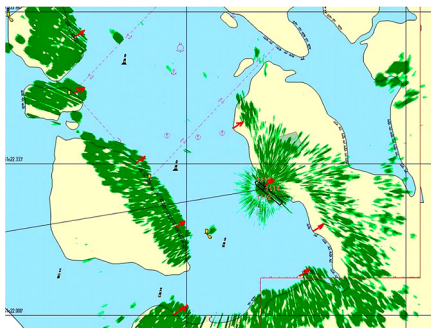


Fig. 4.6 Displacement of radar imagery caused by datum transformation errors

Advantages of Modern Radar Overlay Integration. Monitoring an ECDIS route can be significantly enhanced by adding a radar video layer as an underlying "background". This allows the navigator to compare, at any moment, the actual exposed part of shallow water or isolated hazards revealed at low tide with their positions as shown on the Electronic Navigational Chart (ENC) [6].

On the ECDIS, the ENC layer always has priority over the radar overlay, ensuring that full ECDIS route monitoring capability is not compromised. The radar layer also does not obscure critical ENC elements such as shorelines, submerged rocks, or drying areas during low water conditions.

By combining and integrating radar and ECDIS functions, an Integrated Navigation System (INS) assists the navigator not only in route monitoring and collision avoidance but also in maintaining the integrity of navigation sensors [7].

To avoid excessive clutter on the radar display, careful consideration should be given to the amount of ENC information included in the background layer. However, the navigator is not restricted to the minimal ENC display required for route monitoring, which typically demands at least the standard ENC presentation.

Integrity monitoring of other sensors is a key functionality of the INS. For example, using ENC data as a background for radar displays can help detect any displacement or failure of position and heading sensors.

Considering all these points, it can be concluded that operating modern radar systems is vastly easier than it was only a few years ago. Thanks to intelligent software on multifunction displays and multi-core processing power (e.g., four processors in the Raymarine series), the user rarely needs to adjust settings to obtain a high-quality radar image. Apart from selecting the appropriate range, tuning the TUNE and GAIN settings on each radar has the greatest influence on the image quality. In most modern radar systems, these settings are automated, and manual adjustments are only beneficial under special circumstances [8].

By enabling radar overlay, the navigator can effectively verify the operation of the ECDIS in real time. It can be argued that the radar overlay feature is not only a safety tool but also an essential element in ensuring energy-efficient maneuvering, meeting the demands of modern digital navigation. Thanks to automated adjustment algorithms (GAIN, TUNE) and multi-processor data handling, contemporary radar systems allow the navigator to focus on decision-making rather than system tuning, thus increasing operational efficiency during real-time ship handling.

Consequently, ECDIS with radar overlay evolves from a simple monitoring instrument into a decision support tool for rational, safe, and energy-efficient maneuvering. This is particularly critical in congested waters where the choice of evasion angle, speed, or timing of a maneuver has a decisive impact on fuel consumption reduction.

4.3 Ensuring navigational safety through the development of collision avoidance strategies based on the Open Sea Model

Maritime safety remains a paramount concern; however, contemporary trends increasingly emphasize improving the energy efficiency of vessel movements. Optimizing collision avoidance maneuvers with minimal fuel consumption reduces operational costs and mitigates environmental impact [9]. Risks threatening maritime safety pose significant dangers to human life, the environment, and property. Ship collisions constitute one of the most critical threats that, despite classical mitigation methods, require modern systems and technologies for effective resolution.

One promising approach is the development of collision avoidance systems based on modeling, particularly the OSM collision avoidance system [10]. This system not only supports navigators in making safe decisions for vessel passing but also promotes trajectory optimization considering energy efficiency, thereby reducing fuel consumption and ecological burden.

Modeling vessel passing processes and developing corresponding systems serve as vital tools that integrate diverse data and algorithms to assess collision risks and calculate optimal movement trajectories, addressing both safety and energy expenditure minimization. Collision avoidance models are complex analysis and forecasting systems that, using current and predicted data on vessel positions, courses, speeds, weather conditions, and other factors, generate recommendations for avoiding hazardous situations and selecting energy-saving routes.

Collision avoidance models compute parameters such as Closest Point of Approach (CPA), Time to CPA (TCPA), potential collision courses, and other vessel movement characteristics [11]. The use of algorithms and mathematical models enables risk assessment and the development of recommendations for navigators and vessel traffic operators to prevent collisions.

These models typically handle large datasets and employ various algorithms, including route optimization, classification, and prediction methods, to analyze and forecast scenarios that may lead to collisions. However, it is important to remember that collision avoidance models provide recommendations and decision support, while the final responsibility for maritime safety decisions lies with shipowners, vessel operators, and coastal state authorities [12].

These models differ from existing ship collision avoidance systems by their high accuracy in considering geographic voyage conditions, seabed topography, and other factors affecting vessel movement.

They provide a more precise and realistic forecast of vessel movements in the open sea, offer a broader scope of analysis and prediction of possible scenarios,

and enable real-time implementation with data visualization. Such models account for a wide range of potential collision situations, including different vessel types, varying speeds, routes, and other parameters. As a result, by following the recommended actions, these models help enhance maritime safety and efficiency, reduce collision risks, and facilitate decision-making for navigators and vessel traffic system operators [13].

Various methods and technologies are employed to implement ship collision avoidance systems. One approach is the use of the Open Sea Model, which represents a dynamic maritime environment that includes information about vessel locations, courses, and speeds. A general description of building a collision avoidance system based on the OSM includes:

- data collection and acquisition: gathering essential data for the model, including information about target positions, courses, speeds, and other relevant parameters from multiple sources such as AIS (automatic identification system), radar, satellite imagery, or even simulated data;
- data preprocessing: segregation and processing of acquired data, including filtering out noisy or unreliable data, converting data formats if necessary, and ensuring consistency and accuracy;
- development of the OSM model: creating a visual representation of the maritime environment and surroundings. This model must include vessel locations, courses, and speeds as obtained from the data. It should also support real-time updates as new data arrive and are processed;
- collision risk assessment: using the OSM to evaluate collision risk between vessels by calculating parameters such as CPA, TCPA, and potential collision courses based on vessel positions, courses, and speeds. Various algorithms and methods, such as nearest neighbor search or collision risk assessment models, may be applied to identify potential collision scenarios;
- decision making: based on risk assessment, the system makes decisions to avoid possible collisions. This may involve generating collision alerts or warnings for vessel operators, suggesting course or speed adjustments, or even issuing autonomous commands to the ship's navigation control system;
- visualization and operator interface: providing a user-friendly interface that visualizes the model and offers real-time updates on vessel locations, collision risks, and recommended actions. The interface should be intuitive and easy to use, enabling quick and well-informed decisions by vessel operators;
- integration: seamless integration of the collision avoidance system with the ship's navigation system and other bridge equipment to ensure reliable communication and execution of recommended collision avoidance maneuvers (**Fig. 4.7**).

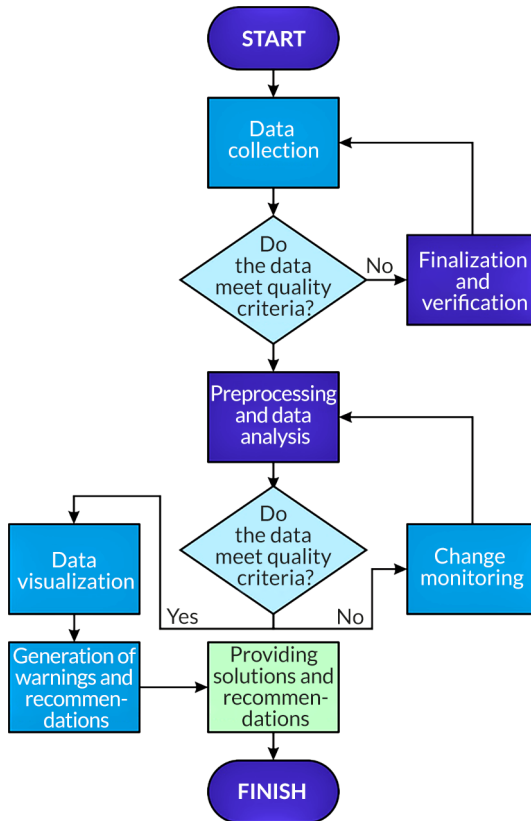


Fig. 4.7 Block diagram of the OSM functionality

It is important to note that the implementation of anticollision systems requires adherence to complex regulations, safety considerations, and integration with existing navigation systems. Continuous collaboration with experts and compliance with industry standards are critical to ensuring system effectiveness. The ability to update the OSM in real time is a key aspect of the proper functioning of collision avoidance systems.

Real-time updates and the adaptability of the OSM to changing open sea conditions enable the collision avoidance system to remain relevant and effective in the continuously evolving maritime environment. This is essential for enhancing maritime safety and preventing accidents.

The risk assessment methodology in the OSM-based collision avoidance system includes calculating important parameters such as CPA and potential collision courses. The following section discusses this methodology and the decision-making process based on collision risk evaluation:

1. Calculation of Closest Point of Approach (CPA). The Closest Point of Approach is the point on the trajectories of two vessels where the distance between them reaches its minimum value. The CPA calculation is based on data about the positions and movements of vessels received by the OSM. The system analyzes the vessels' trajectories and determines the moment when the distance between them is minimal. This allows assessing the closest possible point of approach and the potential risk of collision.

2. Calculation of potential collision courses. Potential collision courses are different directions of vessel movement that may lead to a collision if maintained. The collision avoidance system uses information about the current courses and speeds of the vessels to compute potential collision courses. This enables evaluating the likelihood of collision if vessels continue along their current trajectories.

3. Decision-making process. The results of collision risk assessment, including CPA and potential collision courses, are used to generate warnings and recommendations for the navigators. The system provides information about potential collision threats and suggests corrective actions regarding the vessel's course or speed to reduce collision risk. These alerts and recommendations can be delivered via the ship's navigation system interface or other communication means. It should be noted that the ship's crew can use these collision risk assessment results to make informed decisions and avoid collisions. Additionally, navigators may take actions such as changing course or speed to evade potentially dangerous situations. Automated warning and control systems may also be activated, which can signal collision risks and autonomously take measures to mitigate those risks.

Overall, the collision risk assessment methodology and decision-making process in the collision avoidance system using OSM provide navigators with information and recommendations to manage collision risks and enhance safety in the maritime environment.

The use of an interface that visualizes the OSM plays an important role in the collision avoidance system. This interface delivers real-time information to navigators about vessel positions, collision risks, and recommended actions, increasing situational awareness and facilitating timely decisions. Key features of the OSM visualization interface include:

1. Vessel visualization: the interface displays the positions of vessels on the maritime chart in real time. Vessels are marked on the map with symbols indicating their

type and status. This allows navigators to clearly see the current positions of vessels and their interactions.

2. Collision risk indication: the interface may use different colors or markers to indicate potential collision risks between vessels. For example, vessels near the CPA can be highlighted with bright colors or markers. This enables navigators to quickly identify potentially hazardous situations.

3. Warnings and recommendations: the interface provides warnings and recommendations based on the collision risk assessment results. This may include alert messages, audible signals, or visual indicators. Additionally, the interface can suggest course or speed adjustments to reduce the risk of collision.

4. Additional information: the interface can provide supplementary information about each vessel, such as its identification data, characteristics, and planned route. This helps navigators to better assess the situation and make informed decisions.

Using an interface that visualizes OSM data enables navigators to have a clear understanding of the current situation, detect potential collision risks, and apply recommended actions. This increases their situational awareness and supports timely decision-making to ensure navigation safety.

Since OSM is one of the most widely used collision avoidance models, its core idea is that each vessel moves in its own direction and at its own speed and can change course or speed to avoid collisions with other vessels. Therefore, the model uses a method to calculate the expected position of each vessel based on its current position, speed, and course, as well as the movement parameters of other vessels.

The model calculates the distance between every pair of vessels and determines whether a collision threat exists. If a threat is detected, the model provides recommendations to adjust the speed and course of each vessel to avoid the collision.

There are many variations and improvements of collision avoidance models, and numerous companies and organizations develop their own models and software for collision avoidance at sea. However, all of them are based on mathematical formulas and algorithms to determine optimal decisions.

One of the most common and accurate methods is the Vincenty formula, which allows precise calculation of the distance between two points on the Earth's surface by using the length and azimuth of the geodesic line between them. It is more accurate than simpler formulas that assume the Earth is a perfect sphere and can be expressed in various forms [14].

Let:

- a - major axis of the Earth;
- b - minor axis of the earth;
- $f = 1 - b/a$ - approximate amount of Earth's compression;

- $L = \lambda_2 - \lambda_1$ - longitude difference;
- $U_1 = \arctan((1-f) \times \tan(\varphi_1))$ - given latitude for the point 1;
- $U_2 = \arctan((1-f) \times \tan(\varphi_2))$ - given latitude for the point 2;
- $\lambda = L$ - initial approximation for longitude;
- $\lambda_{i+1} = \lambda + \Delta\lambda$ - new longitude, calculated iteratively.

Then

$$\sin\sigma = \sqrt{((\cos U_2 \times \sin \lambda_{i+1})^2 + (\cos U_1 \times \sin U_2 - \sin U_1 \times \cos U_2 \times \cos \lambda_{i+1})^2)}; \quad (4.1)$$

$$\cos\sigma = \sin U_1 \times \sin U_2 + \cos U_1 \times \cos U_2 \times \cos \lambda_{i+1}; \quad (4.2)$$

$$\sin\alpha = \cos U_1 \times \cos U_2 \times \sin \lambda_{i+1} / \sin\sigma; \quad (4.3)$$

$$\cos^2\alpha = 1 - \sin^2\alpha; \quad (4.4)$$

$$\cos 2\sigma_m = \cos\sigma - 2 \times \sin U_1 \times \sin U_2 / \cos^2\alpha; \quad (4.5)$$

$$C = f/16 \times \cos^2\alpha \times (4 + f \times (4 - 3 \times \cos^2\alpha)); \quad (4.6)$$

$$\Delta\lambda = L + (1-C) \times f \times \sin\alpha \times \left(\sigma + C \times \sin\sigma \times \left(\frac{\cos 2\sigma_m + C \times \cos\sigma}{-1 + 2 \times \cos^2 2\sigma_m} \right) \right), \quad (4.7)$$

where φ_1 and λ_1 - latitude and longitude of the first point; φ_2 and λ_2 - latitude and longitude of the second point; $\Delta\lambda$ - change in longitude; $s = b \times (1-f) \times A$ - distance between points; A - azimuth (direction of travel) from the first point to the second point; σ - central angle between two points on the Earth's surface; α - initial azimuth (direction).

For example, in order to calculate the distance between two points on the Earth's surface using Vincent's formulas, it is necessary to sequentially solve the system of equations using the iteration method:

- 1) calculate the given latitude U_1 and U_2 for each point;
- 2) using an initial approximation for longitude λ , calculate the new longitude λ_{i+1} ;
- 3) calculate the central angle σ , and also the initial azimuth α ;
- 4) using σ and α , calculate the distance s between the points.

If the resulting value of s is close enough to the distance given for the search, it is considered the final result. If not, s is used to calculate a new approximation for the longitude λ and the steps are repeated 2-4, until the desired accuracy is achieved.

The Vincenty formula is an accurate method for calculating the distance between two points on the Earth's surface, taking into account the planet's ellipsoidal shape, unlike simplified spherical models. This is crucial for developing modern models and algorithms used in ship collision avoidance systems, especially in conditions of heavy traffic, narrow channels, straits, and approaches to ports.

The application of the Vincenty formula ensures a more precise determination of distances between vessels, which in turn allows for more accurate trajectory prediction and the development of optimal routes for avoiding conflict situations from the perspectives of both safety and energy efficiency. This is critically important for navigation in complex conditions where even minor positioning errors can lead to increased fuel consumption or heightened collision risk.

The advantages of using the Vincenty formula in navigational support and collision avoidance systems include:

1. Increased calculation accuracy and improved energy-efficient route planning. Precise distance calculations enable decision-making systems to build more rational vessel routes that minimize unnecessary deviations, maneuvers, and course changes. This directly reduces fuel consumption and lowers greenhouse gas emissions.

2. Consideration of real geographic and navigational conditions. By accounting for geodetic features of the Earth, such as its ellipsoidal shape, actual seabed topography, and marine currents, the system can model optimal routes that avoid zones of increased resistance or unnecessary delays. This improves fuel management and enables selection of the most energy-saving trajectories.

3. Enhanced safety combined with reduced costs. Accurate information on potential conflict situations allows for minimizing the need for emergency maneuvers, which are usually accompanied by inefficient energy use (sudden speed changes, course alterations, braking). Predictable collision avoidance with minimal energy expenditure becomes possible only under conditions of high accuracy in navigational models.

4. Optimization of logistics and operational efficiency. Rational route management and avoidance of inefficient vessel divergences contribute to reducing time spent at sea, which lowers operational costs, improves adherence to delivery schedules, and ensures stability in logistics chains.

Collision avoidance systems integrated with high-precision distance calculation algorithms, such as the Vincenty formula, are an important tool not only for ensuring maritime safety but also for optimizing energy consumption. They enable timely and accurate assessment of potential threats, formulation of predictable and energy-efficient avoidance scenarios, and support decision-making aimed at the rational use of resources.

At the same time, the implementation of such systems requires a careful approach:

- compliance with standards;
- consultation with experts;
- adaptation to existing infrastructure;
- technical integration with navigation equipment.

Only under these conditions can their full potential be realized to reduce fuel consumption, lower environmental impact, and ensure sustainable and safe maritime logistics.

By combining high-precision geodesy, real-time data, and intelligent forecasting, collision avoidance systems using the Vincenty formula become a powerful tool for enhancing the energy efficiency of shipping and the sustainable development of the maritime industry as a whole.

4.4 Conclusion

The function of overlaying radar imagery onto ECDIS is a key tool not only for ensuring navigational safety but also for energy-efficient management of vessel maneuvering during passing or crossing situations. The integration of radar, ARPA, AIS data, and electronic charts provides an objective and timely assessment of the surrounding environment, enabling decisions that minimize fuel consumption, risks, and delays.

Further development of automatic maneuver optimization algorithms based on integrated ECDIS and radar data is advisable, allowing adaptive real-time support for the navigator.

Collision avoidance systems are important tools for enhancing maritime safety, as they help reduce collision risks and create conditions for making effective decisions to prevent accidents.

However, it is important to note that the implementation of model-based collision avoidance systems requires complex measures, adherence to regulations and standards, expert consultations, and integration with existing navigation equipment to ensure their effectiveness and compliance with industry requirements.

By utilizing advanced technologies and real-time data, model-based collision avoidance systems represent a promising solution for improving maritime safety, ensuring high accuracy in predicting vessel routes, and assessing collision risks. This enables operators and system developers to take appropriate actions to maintain safety, respond promptly to potential conflict situations, and improve the efficiency of decision support systems, thereby contributing to safer navigation and the protection of the marine environment.

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