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Innovations in observational navigation techniques for precise ship positioning

Abstract. The purpose of the study was to enhance methodologies for determining ship position, thereby increasing the accuracy and reliability of navigation. The study involves a comparative analysis of current methods for establishing navigational positions, specifically using bearing and radar data, with an assessment of the accuracy, efficiency, and reliability of each approach. Findings indicated that the precision and effectiveness of each method are heavily influenced by navigational conditions, including weather, geographical location, and vessel type. Although conventional methods remain applicable, they present limitations that may result in substantial positioning errors. In response to these limitations, new approaches are developed and tested, notably through the combined use of direction finders and radar data to improve accuracy. A comparative analysis of these innovative methods against conventional practices demonstrates enhanced accuracy and reliability under variable navigational conditions. These findings inform recommendations for refining ship positioning techniques to enhance navigational safety and optimise maritime transport operations. The recommendations emphasise advancing the use of modern technologies, such as global navigation systems and the integration of multiple data sources, to improve the dependability of navigation solutions. In addition, the adoption of automated systems for analysing and processing navigational data is advised to support timely decision-making in challenging navigational environments.

Keywords: bearings, radar data, transportation, combined use, global systems

Introduction

The field of shipbuilding and navigation has seen significant advancements, presenting professionals with new challenges in improving methods for determining vessel location, a critical component for both safety and effective management. The accuracy of navigational equipment is paramount, not only in ensuring safe passage but also in reducing environmental risks, optimising routes, and enhancing the overall safety of maritime transport. With the growth of maritime traffic and increasingly complex

environmental conditions, refining navigational methods has become a pressing issue. Precise positioning is essential for accident prevention, crew and cargo protection, and minimising environmental impact. Errors in navigational calculations can lead to serious consequences, such as collisions, grounding, or even loss of orientation at sea, posing a threat to crew safety. Consequently, the ongoing improvement of ship location methods is a vital objective for modern science and technology. Research focused on

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enhancing the accuracy and reliability of navigational systems is crucial, as it contributes to improved maritime safety and optimised transportation.

The accuracy of determining a ship's position under varying navigational conditions has been the subject of extensive study. N. Al Bitar & A. Gavrilov (2021) highlighted the importance of integrating data from multiple navigational systems to improve observational accuracy under changing navigational factors. They also noted that combining bearings and radar data could significantly reduce navigation measurement errors. Z. Hong *et al.* (2022) focused on the impact of weather conditions on navigation system accuracy, emphasising the need to adapt methods to atmospheric changes. Their study provides examples that demonstrate how different atmospheric phenomena can affect navigation results. M. Elsanhoury *et al.* (2022) developed new navigation data processing algorithms that can reduce the impact of noise and interference on location accuracy. Their approaches, based on advanced mathematical methods, demonstrated enhanced reliability of results. M.Y. Arafat *et al.* (2023) explored conventional bearing techniques, such as azimuth usage and trigonometric methods, and their limitations in modern conditions. They suggested revising the fundamental principles of navigation, including coordinate systems, compass methods, and celestial observations. Their findings indicate that new technologies could greatly enhance navigational precision and reliability. K. Naus *et al.* (2021) discussed the efficacy of radar systems combined with GPS, which allows for greater accuracy in congested maritime environments. They also noted that integrating these technologies could significantly simplify the navigation process for crews.

A. Comber *et al.* (2023) emphasised the importance of considering the geographical features of the area when choosing navigation methods. Their paper provided specific examples where conventional methods proved ineffective due to unique environmental conditions. X. Zhang *et al.* (2021) noted that modern global navigation systems significantly enhance measurement accuracy, but their use requires specialised crew training. They emphasised the need for training and drills to ensure the proper use of these technologies. C. Liu *et al.* (2022) explored the role of automated location determination in reducing human error in navigation, indicating that automation can substantially improve maritime safety by reducing risks associated with crew mistakes. M. Martelli *et al.* (2021) argued that traffic monitoring and management systems could significantly improve maritime safety. Their study demonstrated that the integration of such systems allows for efficient control of sea traffic, reducing accident risks. A.T. Hoang *et al.* (2022) stated that new technological solutions could revolutionise the conventional approach to navigation observation. They emphasised that developing new methods and tools to enhance maritime safety is an important area in marine navigation.

Despite significant efforts in this field, there are still gaps that require further examination, particularly regarding

the integration of various navigation systems and their adaptation to specific maritime conditions. The purpose of the study was to identify ways and methods to improve the accuracy and reliability of vessel positioning and assess their effectiveness compared with conventional techniques.

Materials and Methods

In this study, various vessel positioning methods were meticulously analysed to evaluate their accuracy, effectiveness, reliability, and applicability under different navigational conditions. Initially, a review of scientific literature on vessel positioning was conducted. This review provides a comprehensive overview of the available methods and technologies actively used in navigation, highlighting their advantages and disadvantages. Subsequently, data synthesis was performed to develop a clear understanding of potential ways to improve methods. Methods used include comparison, classification, analysis, modelling, structuring, and evaluation. A comparative analysis was conducted for each method based on criteria such as accuracy, reliability, cost, and applicability in different conditions. Three primary methods were investigated: the directional method, radar data, and Global Navigation Satellite Systems (GNSS).

The study analyses the directional method, which involves measuring angles to navigational landmarks, such as other vessels or coastal objects, to determine location. Observational data gathered under various weather conditions were used to assess the effectiveness of the directional method in low-visibility situations. The effectiveness of radar systems that use radio waves to detect objects on the water surface was also analysed. The accuracy of radar systems was estimated based on experimental data. In addition, the financial aspects of their installation and maintenance were examined. The study further examines global navigation satellite systems (GNSS), including GPS (USA), GLONASS (Russia), Galileo (European Union), and BeiDou (China), with an emphasis on their accuracy under different conditions. This analysis enables identification of the strengths and limitations of each system, and their ability to maintain accuracy in adverse conditions.

The study investigates the root mean square error (RMSE) dependency on the bearing difference to assess the accuracy of navigational measurements. This dependency allows for evaluation of how the angle between directions to navigational landmarks impacts the overall positioning error of a vessel. Examining this relationship contributes to improving positioning methods and enhancing the reliability of navigation procedures. A formula for RMSE was applied to quantitatively assess the accuracy of each method:

$$M_{0(miles)} = \frac{1}{\sin \theta} \cdot \sqrt{\left(\frac{D_{(miles)} \cdot m_{RPS}^0}{57.3^0}\right)^2 + m_{D(miles)}^2} \quad (1)$$

where: $M_{0(miles)}$ - distance adjustment; θ - bearing difference between landmarks; D - distances from the observed position; m_{RPS}^0 - bearing measurement error; m_D^2 - distance measurement error.

This formula facilitates evaluation of how measurement errors impact overall accuracy. Particular attention was given to the combined use of positioning methods. The integration of data from directional methods and radar systems achieves higher accuracy. Combining information from multiple sources reduces errors and improves the reliability of navigational calculations. A comparative analysis of standard navigational practices and new technologies was conducted in the final phase of the study. Field tests performed under different conditions provide a comprehensive assessment of the effectiveness of each method, enabling the formulation of recommendations for improving navigational practices.

Results

Accurate vessel positioning is critical for ensuring the safety and efficiency of maritime transport. Vessel positioning methods continue to evolve, particularly with the use of bearings and radar data. These two approaches offer the required accuracy for navigational calculations, although each has distinct characteristics, advantages, and limitations.

Bearing-based navigation is a method that relies on measuring angles relative to specific landmarks, such as navigational markers or other vessels (Blindheim & Johansen, 2021). This method enables the determination of a vessel's course and relative position. The advantages of bearing-based navigation include ease of implementation and relatively low equipment costs. However, the accuracy of this method is significantly influenced by environmental conditions, such as visibility, weather, and the quality of the landmarks used. For instance, in conditions of poor visibility or during storms, the precision of bearings may decrease, which increases navigational risks. In contrast, radar systems use radio waves to detect objects on the water's surface (Zeng *et al.*, 2023). Radar provides high accuracy and can operate effectively when bearing-based navigation becomes unreliable. This method not only determines a vessel's position but also assesses its speed and direction. However, radar systems require substantial financial investment for installation and maintenance. In addition, their effectiveness can be reduced in complex terrain or when obstacles, such as other vessels, are present.

The combined use of bearing-based methods and radar data can substantially enhance the accuracy of a vessel's location determination. For example, radar data can offer an overall view of the surrounding situation, while bearings can provide precise angular measurements to specific landmarks. This integrated approach helps to reduce the errors associated with each individual method, improving the reliability of navigational calculations. Advances in global navigation satellite systems could further enhance the precision and reliability of vessel positioning, contributing to increased safety in maritime transport and reducing navigation risks. In maritime navigation, the accuracy and efficiency of positioning methods are critical for ensuring the safety of transport and optimising routes. Various methods, including bearing-based navigation, radar,

and GNSS, demonstrate different levels of accuracy and efficiency depending on navigational conditions, such as weather, geographic location, and vessel type. Understanding these factors is crucial when selecting the optimal navigation method for specific situations.

Bearing-based navigation is one of the oldest and most widely used methods for determining a vessel's position. This method involves measuring the angle to an object (such as another vessel or a navigational marker) from a fixed point. The accuracy of bearing-based navigation heavily depends on visibility and environmental conditions. In favourable weather conditions, such as clear skies and no obstructions, bearings can provide sufficient measurement accuracy. However, in conditions of limited visibility, such as thick fog or heavy rain, the precision of bearings can decrease significantly. In such situations, visually identifying landmarks is challenging, which may lead to measurement errors. Conventional bearing methods become unreliable as reduced visibility complicates the accurate assessment of the angle of an object. Bearing-based navigation can be used in conjunction with other navigation technologies to improve accuracy. For instance, integrating data from radar systems or GNSS allows for more reliable results. This approach helps to mitigate the limitations of bearing-based methods under poor visibility conditions and ensures greater accuracy in determining a vessel's position (Alizadeh *et al.*, 2021).

Radar methods use radio waves to detect objects and exhibit several key characteristics. The operational principle of radar systems involves emitting radio waves that reflect off objects (such as ships, islands, or coastlines) and return to the receiver. By analysing the time taken for the signal to return, the system can determine the distance to the object. Radar remains effective in conditions of poor visibility, such as fog, rain, or nighttime, making it invaluable for maritime safety as it enables the detection of other vessels or obstacles when visual observation is impossible. However, while radar methods are highly useful, their accuracy can be compromised in high radio-noise environments. For instance, in urban or industrial areas, numerous electronic devices emit radio waves that can interfere with the system's correct operation, which is especially relevant for river navigation. In addition, in complex terrains such as coastal zones with numerous natural or artificial obstacles, radar signals may experience reflections and overlaps, complicating measurement accuracy. In such cases, radar systems may provide inaccurate information about object locations. Finally, the operation of radar methods requires specialised equipment, such as radar stations and receivers, which can present a barrier for smaller or older vessels that may lack the capability to install such technology. This limitation reduces their ability for precise navigational control. Consequently, while radar methods are a powerful tool in maritime navigation, they require adequate technical support and suitable conditions to ensure optimal accuracy (Asiyabi *et al.*, 2023).

Global Navigation Satellite Systems (GNSS) are a key tool for determining location and time in modern

navigation, providing a high level of accuracy and reliability due to their complex infrastructure, which includes several satellite networks, each with its own characteristics and advantages. GNSS comprises several key components that contribute to its high accuracy and reliability. The Global Positioning System (GPS) is the most well-known satellite navigation system, developed by the United States. It consists of a network of approximately 30 satellites orbiting Earth, providing positional and time data. The Global Navigation Satellite System (GLONASS), developed by Russia, consists of 24 satellites. GLONASS offers similar functions to GPS, enhancing navigational accuracy, especially in areas where the GPS signal may be weakened. Galileo is a European satellite navigation system under development, aiming to provide more precise and reliable positioning, particularly in urbanised and challenging natural environments. BeiDou, the Chinese satellite navigation system, offers navigation services for China and other countries, comprising 30 satellites that provide global coverage. Through the use of these systems, GNSS can deliver high measurement accuracy; however, their effectiveness can significantly diminish when signals are obstructed. For example, in urban areas, tall buildings may block direct signals, and mountainous regions may present challenges due to the terrain. In remote regions where satellite coverage is limited, accuracy may also decrease. Atmospheric conditions are also important, as they can affect the speed of signals passing through the atmosphere. Achieving maximum accuracy in navigation with GNSS requires consideration of all these factors (Rodriguez-Alvarez *et al.*, 2023).

Thus, the evaluation of the accuracy and efficiency of each method for determining a vessel's position should account for the specific navigation conditions. In each particular case, selecting the optimal method may depend on factors such as weather conditions, geographic characteristics, and the technical capabilities of the vessel. Further analysis in this field could contribute to developing new, more adaptive navigation systems capable of providing high levels of accuracy and safety in constantly changing conditions.

The main methods of vessel positioning observation include bearings taken from two or three points, bearing and distance measurement, radar data, and a cross-bearing method. Two-bearing positioning involves determining the angle to a vessel from two different points. This method requires precise knowledge of both points' coordinates and the bearing measurements. The main advantage of this method is that it provides adequate accuracy if bearings are taken from well-visible landmarks. However, its limitation lies in its dependency on good visibility and accurate bearings (Shajahan *et al.*, 2024). Using three bearings is a more reliable method, as it allows for triangulation techniques to achieve more accurate positioning. This method helps to reduce errors associated with computational deviations, but its effectiveness is limited by the visibility of landmarks. The bearing and distance method combines angle and distance measurements to a vessel, enabling precise

determination of an object's location relative to navigational landmarks. Using bearing alongside distance measurement provides a more accurate location assessment, although the precision of this method can decrease in conditions of poor visibility or when distance measurements are inaccurate (Lu *et al.*, 2023).

Radar methods represent modern observation technologies that use radio waves to detect vessels and other objects on the water's surface. This technique relies on transmitting radio signals from a transmitter to a target and analysing the reflected signals that return to the receiver. By measuring the time taken for the signal to travel, the distance to the object can be determined. Radar systems are particularly effective in low-visibility conditions, such as fog, rain, or darkness, as they are not reliant on optical conditions. In addition, these systems can operate in any weather, providing continuous monitoring of the navigational environment. However, the use of radar methods requires specialised equipment, including radars, antennas, and signal processors. Notably, the effectiveness of these systems may decrease in areas with high levels of radio noise or strong electromagnetic interference, which can distort the received data and complicate accurate object detection.

Cross-bearing is a navigation method applied from a moving platform, such as a boat or ship, to determine the angle to a stationary object, like a lighthouse or another vessel. This method allows for real-time location data of a vessel by using a compass or other navigational instruments to measure the bearing. In practice, as the vessel manoeuvres, it can continuously record the angle between its direction of movement and the direction to the stationary object. Based on these data, the location of the vessel can be calculated, although the accuracy of this method may decrease due to the movement of the platform, which introduces additional measurement errors. Cross-bearing is useful in situations where other location methods, such as conventional bearings or GPS, may be hindered by limited visibility or signal loss (Mazurek *et al.*, 2021). Each of these methods requires certain conditions and has its own advantages and limitations. However, they all share an essential factor – the need to consider both distance and angular differences between landmarks in calculations. These parameters are critical for the accuracy of navigational data, as even minor errors in determining them can lead to significant inaccuracies.

To achieve more accurate measurements, values that help reduce the radial root mean square error (RMSE) are typically used. The smaller the RMSE, the more precise the vessel's location determination will be (Liu *et al.*, 2021). Further calculations will allow for a better understanding of how measurement accuracy depends on the distance to landmarks and the angle between them. In situations where the angles between landmarks vary significantly, accuracy may improve considerably. Thus, by analysing these dependencies, the optimal conditions for selecting an observation method can be established, which will enhance the efficiency of maritime navigation. To calculate

the dependence of observed location accuracy on the angle between bearings to a landmark, the following formula (1) for determining RMSE was used. Assuming: $\theta = 30^\circ; 40^\circ; 50^\circ; 60^\circ; 70^\circ; 80^\circ; 90^\circ$; $D = 25$ miles; $m^\circ(D) = 1\%$ of $D = 0.25$;

$m^\circ(\theta) = 1^\circ$. In this case, data presented in Table 1 were obtained, and a graph illustrating the relationship between observational location accuracy and the angle between bearings on a landmark was generated (Fig. 1).

Table 1. Relationship between root mean square error and bearing difference

Bearing difference θ (degrees)	Root mean square error Mo
30	1.02
40	0.80
50	0.67
60	0.59
70	0.54
80	0.52
90	0.50

Source: created by the authors

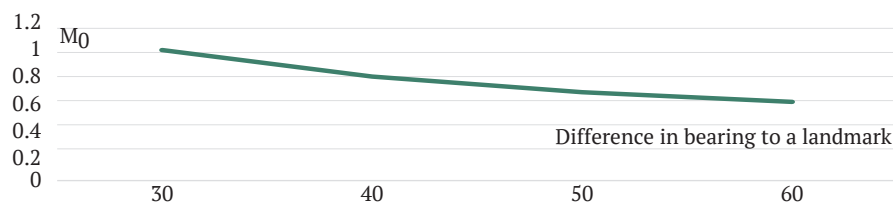


Figure 1. Graph showing the relationship between observational location accuracy and the angle between bearings on a landmark

Source: created by the authors

Based on the data obtained, it was established that an increase in the angular difference between landmarks reduces the root mean square error, thereby enhancing the accuracy of observation. Similar calculations were conducted to determine the relationship between observational accuracy and distance to the landmark.

Assuming: $\theta = 60^\circ$; $D = 1$ mile; 5 miles; 10 miles; 15 miles; 20 miles; 25 miles; 30 miles; 35 miles; 40 miles; $m^\circ(D) = 1\%$ of $D = 0.01; 0.05; 0.1; 0.15; 0.2; 0.25; 0.3; 0.35; 0.4$; $m^\circ(\theta) = 1^\circ$. In this case, the following data was obtained (Table 2). To enhance clarity, a graph illustrating the relationship was created (Fig. 2).

Table 2. Relationship between root mean square error and distance to landmark

Distance from observational location (miles)	Root Mean Square Error Mo
1	0.02
5	0.23
10	0.21
15	0.32
20	0.45
25	0.58
30	0.7
35	0.84
40	0.99

Source: created by the authors

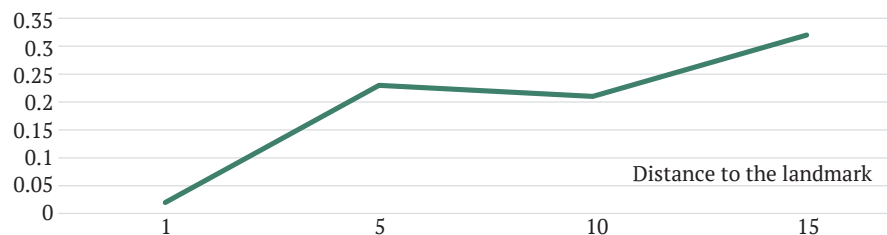


Figure 2. Graph showing the relationship between observed position accuracy and distance to the landmark

Source: created by the authors

The graph clearly demonstrates a trend: as the distance to the observation point increases, the root mean square error also rises, which in turn decreases the accuracy of measurements. Notably, the RMSE remains nearly constant between distances of 5 to 10 miles, indicating that measurement accuracy remains high within this range. This may be due to optimal observation conditions at these distances, where the impact of external factors is minimal. However, beyond this range, the error increases, negatively affecting accuracy. Calculating the RMSE in navigational measurements is crucial for assessing the accuracy of vessel positioning. This analysis helps understand how accuracy varies with increasing distance from the observation object. This is important for optimising navigation systems, as it allows adjusting them to achieve maximum accuracy at certain distances. It also assists in risk assessment and in anticipating potential errors during route planning.

In addition, considering RMSE enhances precision in vessel manoeuvres, contributing to navigational safety.

In modern navigation, the accuracy and reliability of navigational data are critical for ensuring the safety and efficiency of transportation (Melnyk & Onyshchenko, 2021). Standard methods, such as the use of bearings and radar data, have their advantages; however, the development of new approaches can offer higher levels of accuracy. When comparing new methods to conventional ones, several key aspects should be considered. Standard practices may demonstrate satisfactory accuracy in stable navigational conditions, but their effectiveness often decreases under conditions of climate change, reduced visibility, or the presence of obstacles. Meanwhile, new approaches that integrate data from multiple sources, such as global navigation satellite systems (GNSS) and radar technologies, show higher accuracy in challenging conditions, owing to their ability to correct data in real time (Table 3).

Table 3. Comparative table of navigation methods: conventional and new approaches

Method	Advantages	Disadvantages	Impact of geoclimatic and weather conditions	Presence of obstacles	Measurement accuracy
Bearing	◆ Easy to use; ◆ low equipment cost	◆ Requires visibility of landmarks; ◆ accuracy decreases with distance	Poor visibility conditions (fog, rain) reduce accuracy	High sensitivity to obstacles	Moderate to high over short distances, reduced over long distances
Radar systems	◆ High effectiveness in poor weather conditions; ◆ operates at any time of day	◆ High equipment cost; ◆ sensitive to radio interference	Less sensitive to weather conditions	Can be limited by objects blocking radio signals	High, but decreases in the presence of radio noise
GNSS (GPS, GLONASS, Galileo, BeiDou)	◆ High accuracy in open spaces; ◆ global coverage	◆ Vulnerable to signal blockage (mountains, buildings); ◆ high system cost	Accuracy degrades in signal blockage conditions	Sensitive to densely built-up areas and natural obstacles	High, but decreases in challenging conditions
Combined methods (GNSS + radar)	◆ High accuracy due to real-time data correction; ◆ Data compatibility from various sources	◆ Complex data processing; ◆ High system cost	Less sensitive to weather changes, better in geoclimatic conditions	Reduced impact of obstacles due to data correction	Highest, due to integration of multiple technologies

Source: created by the authors based on N. El-Sheimy & Y. Li (2021)

Conventional navigation methods often rely on a single source of information, making them vulnerable to various errors. For example, inaccuracies in determining bearings can lead to significant discrepancies. In contrast, new methods that integrate different types of navigational data reduce the risk of errors and increase the reliability of location determination. Another key factor is adaptability to changing conditions. Conventional methods may require significant adjustments to recalibrate for new conditions, whereas modern technologies

often include built-in adaptive mechanisms. This enables quicker responses to environmental changes, which is critical in the rapidly shifting conditions of the marine environment.

Evaluating the effectiveness of new methods also includes cost analysis. While new technologies may require substantial initial investments, their ability to enhance accuracy and reliability can lead to substantial cost savings by reducing the risk of accidents and losses due to navigational errors (Table 4).

Table 4. Analysis of installation and maintenance costs for radar equipment and global navigation systems

Method	Minimum installation costs (USD)	Minimum maintenance costs (USD/year)	Notes
Radar equipment	15,000-50,000	2,000-5,000	Costs vary depending on the power and type of radar used.
Global navigation systems (GNSS)	10,000-30,000	1,000-3,000	Includes the cost of receivers, antennas, and software.

Source: created by the authors based on B. Bartel (2024)

Although installation costs may vary, investing in such technologies proves advantageous due to improved accuracy, reliability, and functionality in limited-visibility conditions. Radar systems enable rapid object detection and real-time monitoring, reducing accident risks and enhancing navigational safety. In turn, global navigation satellite systems demonstrate effectiveness across a wide range of conditions, offering global coverage. Both methods contribute to optimising maintenance and operational costs, making them economically sound investments in modern navigation systems.

Therefore, the comparative analysis of these methods against standard practices suggests that new approaches can greatly surpass conventional ones in aspects such as accuracy, reliability, and adaptability. Given the growing demands for safety and efficiency in navigation, investment in new navigation technologies can be essential for success in the maritime industry, safeguarding crew, cargo, and the environment. One area for improving vessel positioning methods is the integration of advanced technologies like GNSS, which offer high accuracy and data reliability. For example, the use of Differential GPS (DGPS) systems can significantly reduce errors caused by atmospheric interference or multipath effects, enhancing measurement accuracy to the centimetre level.

A critical aspect is data monitoring and analysis. The implementation of systems for collecting and analysing navigational data, alongside analytical tools capable of processing large data volumes, will help identify patterns that enhance navigational efficiency. The development and implementation of advanced software solutions that use artificial intelligence can allow for timely error detection in data and automatic route adjustments in real time. Attention should also be given to crew training. Modern navigation methods require high qualifications from seafarers. Regular training covering the latest navigation technologies and methods can improve crew competence in using navigation equipment effectively.

All these recommendations aim to mitigate risks associated with navigation errors, enhance the safety of crew and cargo, and optimise transportation processes. The introduction of a comprehensive approach to improving vessel positioning methods, encompassing technological, organisational, and training aspects, can significantly increase the efficiency of maritime transport processes and ensure reliable navigation in the face of modern challenges.

Discussion

The study reveals that innovations in navigational observation techniques have significantly enhanced the accuracy of vessel positioning. Specifically, the use of new technologies, such as automated coordinate determination systems, has markedly improved accuracy under conditions of limited visibility. For instance, integrating data from global navigation satellite systems with conventional navigation methods has substantially reduced positioning errors that previously occurred when relying solely on one method.

This was also explored by B. Wiśnicki *et al.* (2024), where results confirmed that navigation technologies, such as GPS and GLONASS, have greatly increased maritime transport accuracy, enabling vessels to make precise route calculations. The integration of automated ship control systems enables rapid responses to environmental changes, reducing the risk of accidents and delays. These innovations contribute to optimising fuel costs and reducing transit times, which are crucial factors for companies in the logistics sector. Research by J. de Vos *et al.* (2021) further demonstrated that technologies such as real-time monitoring systems and data analysis significantly enhance maritime transport safety. The use of drones to inspect vessel and cargo conditions, along with automated alert systems, has enabled quicker responses to emergencies. These innovations not only reduce the risk of accidents but also enhance the overall efficiency of maritime transport, creating safer conditions for crew and cargo alike.

Notably, the successful integration of innovations in navigation and safety technologies depends not only on technical aspects but also on companies' willingness to adapt to new market conditions. Training and upskilling of personnel are critical for the effective use of new technologies. Furthermore, cooperation between countries and regulatory bodies can promote the development of unified standards, improving the safety and efficiency of international maritime transport.

The study also discovered that cutting-edge technologies, such as radar systems, allow for the detection of objects at long distances, which is crucial for collision avoidance in challenging conditions. The use of radar, combined with directional data, has contributed to creating a more detailed picture of the surrounding environment, helping to reduce navigation risks in low visibility or adverse weather. This approach demonstrates how integrating various technologies can enhance overall maritime safety. L. Huang *et al.* (2022) concluded that radar systems have become a vital tool in modern navigation, providing detailed visualisation of the environment in low-visibility conditions. They not only enable the detection of other vessels but also facilitate weather analysis, contributing to safer route planning. With advancements in digital radar technology, data is processed in real time, enabling crews to make well-informed decisions more quickly and effectively.

M. Plaza-Hernández *et al.* (2021) established that integrating various technologies, such as radar systems, automated control systems, and monitoring technologies, provides a comprehensive approach to enhancing maritime transport safety. These technologies interact with one another, allowing for consolidated information on the condition of the vessel and its surroundings, thereby reducing the risk of accidents. In addition, this integration facilitates data exchange between vessels and ports, which is crucial for coordinated responses in emergency situations. These findings confirm that the integration of new technologies into navigation systems not only improves route accuracy but also the overall safety of maritime transport. For

instance, the reduction in accidents attributed to radar and automated control systems demonstrates the effectiveness of these solutions in practical application. Furthermore, the implementation of innovations in this field may enhance the competitiveness of companies in the global market, as safer and more efficient transport is a key factor for clients.

The study also demonstrated that innovative data-processing algorithms used in modern navigation systems contribute to improved accuracy and speed in obtaining location information. Specifically, the use of algorithms for correcting signal errors related to atmospheric conditions or obstacles has proven to be highly effective. This has substantially reduced the time needed to obtain accurate data, which is critical in situations that require prompt decision-making. P. Karagiannidis & N. Themelis (2021) similarly highlight the role of data-processing algorithms in enhancing the speed and accuracy of maritime transport, enabling the analysis of large volumes of information in real time. Through the application of machine learning and artificial intelligence, vessel systems can more quickly adapt to environmental changes, optimising routes and reducing fuel costs. This, in turn, increases the overall efficiency of logistical operations, which is crucial for maintaining competitiveness in the global market.

Conversely, D. Li *et al.* (2021) concluded that signal issues in navigation can significantly impact the safety and efficiency of maritime transport, as even minor disruptions may lead to serious consequences. Modern solutions include the use of multi-constellation navigation systems, which combine signals from various satellite systems to ensure data stability and accuracy. In addition, the implementation of backup communication technologies and signal-boosting antennas in remote areas helps to mitigate risks associated with navigation errors and communication losses. These findings are consistent with this study, as they underscore the importance of implementing modern data-processing algorithms to achieve high accuracy and speed in maritime transport. This suggests that investments in technology can significantly enhance navigation systems by reducing risks and optimising logistical processes. Moreover, the results highlighted the need to address signal issues, as stable communication is critically important for the successful operation of maritime transport in challenging conditions. Meanwhile, there is a need for further development of navigation technologies, since not all innovations can be universal. For example, it has been observed that in densely built or mountainous areas, the effectiveness of satellite systems may decrease, raising the need for alternative solutions for inland waterway navigation. This indicates that combining different navigation methods remains the optimal approach for achieving maximum accuracy.

T.E. Kim *et al.* (2022) also confirmed that navigation technologies face a range of challenges in specific maritime transport conditions, such as adverse weather or remote areas. In such situations, conventional systems may not provide the required accuracy, which could lead to delays or even accidents. In addition, natural obstacles such

as large waves and ice fields complicate navigation and require continuous advancements in technology. B. Wu *et al.* (2022) found that alternative solutions, such as using terrestrial radio-navigation systems or hybrid technologies, can significantly improve the accuracy of maritime transport under challenging conditions. For instance, combining satellite systems with radar and sensors can offer more reliable navigation even when standard signals are unavailable. Moreover, advancements in machine learning technologies enable the development of adaptive algorithms that account for specific environmental conditions, aiding route optimisation and risk reduction.

Comparing the data obtained in these studies makes it clear that adapting navigation technologies to the specific conditions of maritime transport is essential for ensuring their efficiency and safety. The analysis indicates that conventional navigation methods may be insufficient in extreme weather conditions or in the presence of natural obstacles, affirming the need for the development of new solutions. Therewith, alternative technologies such as hybrid systems and adaptive algorithms show significant potential to improve the accuracy and reliability of maritime transport, which could substantially enhance the overall efficiency of logistical operations. When discussing the advantages of new technologies, it is also important to consider the financial and technical aspects of their implementation. While modern systems can offer high precision, their installation and maintenance may require substantial investment. This could be a barrier for smaller companies or countries with limited resources. Therefore, it is essential to find a balance between the costs of new technologies and their effectiveness to ensure these innovations are accessible to a broad range of users.

E. Tijan *et al.* (2021) concluded that the cost of new technologies, such as advanced navigation systems and safety solutions, is a crucial factor to consider when planning investments in maritime transport. Although the initial costs of implementing these technologies can be considerable, their effectiveness in reducing accident risks and improving route management often justifies the expenditure. Consequently, investing in new technologies becomes not only an expense but a strategic step to ensure market stability and competitiveness. W. Zhu *et al.* (2021) found that achieving a balance between the costs and efficiency of maritime transport is a complex challenge that requires thorough analysis and strategic planning. Companies should assess not only the initial costs of adopting new technologies but also their impact on overall productivity and safety. Identifying an optimal balance between investment and achieved outcomes can significantly enhance profitability and ensure the successful execution of business strategies in the maritime sector.

An analysis of research findings reveals that investments in new technologies for maritime transport not only increase safety levels but also help reduce overall costs in the long term. Specifically, implementing effective navigation and monitoring solutions allows companies to

minimise delays and accidents, positively influencing financial performance. Thus, strategic investment in new technologies becomes a crucial factor in achieving a balance between costs and efficiency, promoting overall success in maritime transport.

Overall, this study confirms that innovations in navigational observation technology hold immense potential for improving the accuracy of ship location tracking. Given the diversity of conditions in which these technologies may operate, further research should focus on developing adaptive navigation systems capable of considering specific operational conditions. This approach will enable the maximum utilisation of the latest technologies and enhance the safety of maritime transport.

CONCLUSIONS

The research into innovations in navigational observation technology for accurately determining the location of vessels has shown that modern technologies significantly improve the accuracy and reliability of navigation systems. The integration of radar technologies with GNSS has provided more detailed and precise tracking of vessel positions under various conditions. This is particularly crucial in challenging weather situations or areas with limited visibility, where conventional navigation methods may struggle to perform effectively. The study also demonstrated that using intelligent data-processing algorithms enables rapid correction of navigational information, reducing the likelihood of errors. These algorithms can account for multiple factors affecting accuracy, such as atmospheric

conditions, local topography, and obstacles along the route. Furthermore, the incorporation of new technologies, such as differential correction systems for GNSS, has substantially reduced positioning errors, which is critical for the safety of maritime transport.

Thus, the results of the study confirm that innovations in navigational observation technology not only enhance the accuracy of vessel location tracking but also reduce risks at sea. These technologies support more efficient and safer transport, which is a vital factor in developing maritime infrastructure and boosting competitiveness in the global market.

The study was limited to the analysis of certain navigation technologies, such as radar systems and GNSS, without considering other potentially important methods that may impact vessel location accuracy. Further research should cover the effects of new technologies, such as data integration from various sources, the use of drones for environmental monitoring, adaptive signal-processing algorithms, and machine learning technologies, on the effectiveness of navigation systems in specific conditions, such as high levels of electromagnetic noise or challenging terrain. This would further enhance the accuracy of vessel location tracking.

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CONFLICT OF INTEREST

None.

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Інновації в обсерваційній техніці навігації для точного визначення місцезнаходження кораблів

Анотація. Дослідження було проведено для вдосконалення методики визначення місцезнаходження судна, що дозволить підвищити точність та надійність навігаційних процедур. У процесі роботи були проаналізовані наявні методи визначення навігаційного положення корабля, зокрема з використанням пеленгів та радіолокаційних даних, здійснено їх порівняння, а також дана оцінка точності, ефективності та надійності цих методів. Результати показали, що точність і ефективність кожного методу значно залежать від навігаційних умов, таких як погода, географічне положення та тип судна. Виявлено, що традиційні методи, хоча й залишаються актуальними, мають суттєві недоліки, які можуть призводити до значних похибок у визначенні місцезнаходження. На основі виявлених недоліків були розроблені та випробувані нові підходи, що включають комбіноване використання пеленгів та радіолокаційних даних для підвищення точності. Порівняльний аналіз цих методів з традиційними практиками показав, що нові підходи забезпечують більшу точність та надійність в умовах змінних навігаційних обставин. Зроблені висновки стали основою для формулювання рекомендацій щодо покращення методик визначення місцезнаходження судна, що сприятиме підвищенню безпеки судноплавства та оптимізації транспортних процесів у морській галузі. Ці рекомендації включають вдосконалення використання сучасних технологій, таких як глобальні навігаційні системи та інтеграція різних джерел даних для підвищення надійності навігаційних рішень. Додатково було рекомендовано впровадження автоматизованих систем аналізу та обробки отриманих навігаційних даних для оперативного прийняття рішень під час складних навігаційних умов.

Ключові слова: пеленги; радіолокаційні дані; транспортні процеси; комбіноване використання; глобальні системи