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Comparative analysis of navigation system maintenance methods on var-ious types of vessels and ships

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Abstract

This study examines approaches to maintaining navigation systems on naval vessels, focusing on practices within the Naval Forces of Kazakhstan. The goal is to enhance operational reliability and combat readiness. Data from public sources were analyzed and compared to derive context-specific recommendations. Maintenance methods ranging from scheduled preventive routines to modernization depend on factors such as vessel type, operating environment, and technical support. The research includes fleets from the U.S., EU (notably France and the Netherlands), and Kazakhstan. Kazakhstan's fleet comprises Bars-MO missile-artillery ships, Bars-class patrol vessels, and various boats such as Sunkar, Burkit, FC-19, and Aybar. Preventive maintenance ensures reliability but is often excessive for low-utilization Kazakh vessels, increasing costs. Condition-based maintenance is more efficient but underutilized due to limited infrastructure. A hybrid strategy is proposed, combining enhanced diagnostics for Bars and Bars-MO vessels, optimized spare part logistics for patrol boats, and inertial navigation systems for special-purpose craft. Additionally, the development of maintenance bases in Aktau and Bautino, local storage facilities, and 3D modeling tools are recommended. These integrated measures aim to improve fleet readiness in the Caspian Sea amid logistical and resource limitations.

Keywords: Diagnostics, Emergency repair, Maintenance bases, Modernization, Naval combat readiness, Scheduled preventive maintenance.

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1. Introduction

The Naval Forces of Kazakhstan play a vital role in maintaining national security and protecting the country's economic interests in the Caspian Sea, an area that contains strategically important oil and gas fields as well as major trade routes. The fleet, which includes missile-artillery ships, patrol vessels, and fast response boats, is tasked with safeguarding maritime borders, countering smuggling activities, and supporting regional stability. At the core of these vessels' combat capabilities are their navigation systems, including satellite, radar, inertial, and cartographic technologies, which provide accurate positioning, safe maneuvering, and coordinated operations within the complex maritime environment of the Caspian Sea. The reliability of these systems is directly tied to the quality of their maintenance, encompassing routine inspections, diagnostics, modernization, and emergency repairs an especially critical for a fleet operating under resource constraints and dependent on externally supplied equipment. The importance of such research is further underscored by the global advancement of maritime technologies and the pressing need to enhance the efficiency of fleets like that of Kazakhstan in addressing contemporary missions amid technological and geopolitical challenges.

Various studies emphasize the critical role of advancing navigation systems and their maintenance in enhancing the safety and effectiveness of maritime operations. In the study by Szelangiewicz et al. [1], a prototype computer system integrating measurement sensors and navigation devices was developed for autonomous control of an unmanned vessel model. The system was successfully tested in open water, confirming the correct functionality of both the software and hardware components. Rivas et al. [2] proposed a comprehensive approach to ensuring safe navigation and network operations of autonomous vessels, with particular emphasis on protection against cyber threats and the integration of robust communication protocols to prevent control system failures. Konstantynov [3] conducted a review of optical navigation systems in maritime applications, highlighting their advantages in improving positioning accuracy and their potential for integration with modern onboard automation systems.

Among recent studies on navigation systems and their role in maritime operations, particular attention should be given to research addressing historical, strategic, and technical dimensions. Unger and McAlister [4] provide a historical and technical perspective on the development of shipborne navigation technologies, tracing the gradual shift from traditional navigational tools to highly automated systems marked by enhanced precision. In a related contribution, Zorri and Kessler [5] examine the increasing dependence of maritime operations on positioning, navigation, and timing (PNT) systems, drawing attention to their susceptibility to cyberattacks, particularly in relation to GPS and arguing for the development of more robust, secure alternatives to ensure operational continuity in military settings. Meanwhile, the experimental work of Felski and Jaskólski [6] investigates the technical behavior of marine compasses under various conditions, with findings that reveal their significant influence on vessel handling and offer practical guidance on improving calibration protocols to enhance directional accuracy during complex maneuvers.

Blackett [7] in his analysis of a Royal Navy research vessel, he examined the deployment of an advanced navigation suite alongside newly developed radar complexes. His observations highlighted the tangible benefits these technologies offer in improving navigational accuracy and reliability, particularly in demanding maritime environments, and reaffirmed the value of field testing in the development of next-generation systems. Building on the technical dimension, Guo et al. [8] proposed a diagnostic method for integrated navigation systems of surface vessels, grounded in $Hi/H\infty$ optimization principles. Their approach proved highly effective in detecting malfunctions in both satellite radionavigation systems (SRNS) and radar systems (RS), thereby emphasizing the pivotal role of real-time fault detection in maintaining operational integrity. In a broader technological context, Olsen [9] reviewed the evolution of digital navigation tools such as Electronic Chart Display and Information Systems (ECDIS) and automated control interfaces, pointing to their growing significance in reducing manual workload and advancing the digital transformation of maritime navigation.

It is worth noting that, despite their valuable contributions to the study of navigation systems, the aforementioned works primarily focus on the development of new technologies, historical overviews, cyber threats, or specific technical aspects such as the characteristics of individual instruments while leaving largely unaddressed the practical issues of organizing, optimizing, and resourcing maintenance processes essential to ensuring combat readiness in real-world maritime operations. Thus, insufficient attention has been given to the comprehensive analysis of maintenance methods for navigational equipment on naval vessels, particularly in the context of their application across different ship types and operational conditions of smaller fleets such as the Naval Forces of Kazakhstan.

This study set out to conduct a nuanced comparative assessment of navigation system maintenance strategies employed on naval vessels, with particular emphasis on the fleet operated by the Kazakh Naval Forces. The overarching aim was to identify ways to improve system reliability and ensure combat readiness, especially in conditions where resources and technical infrastructure are limited. To this end, the research addressed several key tasks: first, it examined the operational features and environmental constraints specific to the Caspian Sea; second, it analyzed the applicability and performance of four primary maintenance approaches scheduled preventive, condition-based, modernization and system integration, and emergency repair across a diverse range of platforms, including aircraft carriers, frigates, submarines, and Kazakhstan's patrol boats. Finally, the study formulated a set of practice-oriented recommendations tailored to the context of Kazakhstan's naval capabilities, with particular attention to strengthening local repair infrastructure and integrating modern technologies.

2. Materials and Methods

The research employed an integrated methodological approach to examine maintenance practices for navigation systems aboard naval vessels, including those in service with the Kazakh Naval Forces. Conducted between March and June 2025, the study drew upon open-source materials and relied on a combination of comparative analysis and structured synthesis of technical data. The methodology encompassed several stages: collection and classification of relevant information, critical evaluation of maintenance strategies, and the formulation of recommendations aligned with the specific operational requirements and environmental conditions encountered in naval contexts.

A key element of the research involved gathering information from publicly available sources, such as official regulations, peer-reviewed studies, technical documentation, and specialized literature in the field of naval operations. The primary source of official information was the materials published by Ministry of Defence | Defensie.nl [10], which include press releases, updates on the development of the Naval Forces, descriptions of fleet structure, and reports on exercises such as “Batyly Toitarys [11] and Association [12]. Additional data were sourced from the website military-kz.ucoz.org [13], which provides a catalog of vessels operated by the Kazakh Naval Forces. To better understand the technical aspects of ship construction, information was also obtained from manufacturer websites, such as JSC "Zenit Uralsk Plant" (Uralsk, Kazakhstan) [14]. The study examined the technical specifications of navigation systems, including satellite radionavigation systems, radar systems, inertial navigation systems (INS), hydroacoustic complexes, and electronic chart display and information systems (ECDIS, WECDIS). Special attention was given to maintenance standards, such as the Class Maintenance Plan used by the U.S. Navy Maintenance Policy for Navy Ships [15].

The study also included a comparative analysis of navigation system maintenance practices in the Kazakh Naval Forces and those of other countries, including the United States Navy [16], France [17] and the Netherlands [18]. These countries possess advanced naval technologies, diverse approaches to navigation system maintenance, and extensive experience operating fleets across varied geographic and operational environments, making it possible to identify best practices that can be adapted to Kazakhstan’s resource-constrained context. The collected data were classified according to four maintenance approaches: scheduled preventive maintenance, condition-based maintenance, modernization and integration, and emergency maintenance. For each maintenance approach, key parameters were identified: description, applicability across different vessel types, advantages, limitations, frequency, and operational conditions. The data were structured according to vessel classifications, including large ships (aircraft carriers, cruisers, destroyers), medium-sized ships (frigates, corvettes), specialized vessels (submarines, amphibious ships), and small craft (patrol boats of the Kazakh Naval Forces). For Kazakh naval vessels, specific operational factors were taken into account, such as the shallow waters of the Caspian Sea, the intensity of patrol missions, and limited infrastructure. Information on navigation systems, including SRNS, radar, INS, ECDIS, and hydroacoustic equipment, was classified according to their technical specifications, including accuracy, error margins, and operational range.

In the comparative analysis of navigation system maintenance methods, a qualitative approach was employed, based on the comparison of effectiveness, cost, technical requirements, and applicability of each method. For instance, scheduled preventive maintenance was evaluated in terms of inspection frequency, labor intensity, and the cost of spare parts, tools, and accessories (SPTA). Condition-based maintenance was analyzed in terms of the availability of diagnostic systems and the qualification level of personnel. Modernization and integration were examined through the lens of technology adoption and the duration of dockyard operations. Emergency maintenance was evaluated based on repair speed and limitations related to spare parts, tools, and accessories (SPTA). The comparison was conducted within the context of the Kazakh Naval Forces, where resource constraints and reliance on imported supplies present additional challenges. The analysis results were summarized in a comparative table highlighting the advantages and disadvantages of each maintenance method across different vessel types. Additionally, the study employed statistical analysis methods, and all data were validated through cross-referencing of sources to ensure reliability. All materials were translated and standardized for use in a unified format, with careful attention to technical terminology (e.g., SRNS, radar, INS, ECDIS). The study also developed a set of recommendations for the Kazakh Naval Forces, based on the results of the comparative analysis. These recommendations took into account the operational specifics of ships and patrol boats (*Bars-MO*, *Bars*, *Sunkar*, *Burkit*, *FC-19*, *Aybar*, and special-purpose craft) in the Caspian Sea environment, including intensive patrol missions and the protection of economic zones.

It should be noted that any confidential information encountered during the research was excluded from the analysis, in accordance with the Code of Ethics of the American Association for the Advancement of Science (AAAS) [19]. The findings are intended for academic and practical use, without any intent to disclose classified information or compromise national security.

3. Results

Navigation systems form the backbone of combat capability in modern naval vessels, enabling precise positioning, route planning, and operational coordination under complex mission conditions. These systems are critical for executing missions such as missile strikes, aviation operations, covert maneuvering, and the protection of territorial waters. The diversity of naval vessel types, from large aircraft carriers to small patrol boats, dictates specific requirements for navigation equipment, its functional capabilities, and the corresponding maintenance methods. In the case of the Kazakh Naval Forces, which operate primarily in the Caspian Sea, navigation systems are adapted to the conditions of shallow waters, a confined maritime area, and missions focused on safeguarding territorial integrity and economic interests. Modern navigation suites integrate satellite, inertial, radar, and hydroacoustic technologies, ensuring operational reliability in scenarios involving electronic warfare or autonomous navigation.

Satellite radionavigation systems, such as the U.S. GPS and the European Galileo, provide high-precision positioning with an accuracy of 1–5 meters, depending on environmental conditions [20-22]. These systems operate by receiving signals from satellites, enabling the determination of a vessel's latitude, longitude, altitude, and speed. For example, GPS operates on L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies, offering global coverage and resilience through military codes such as the P(Y)-code. On surface vessels, including aircraft carriers, cruisers, destroyers, and frigates, SRNS serve as the primary navigation backbone, providing the precision required for coordination with aviation assets and missile systems. In the Kazakh Naval Forces, SRNS are actively employed on missile-artillery ships of Project 250 *Bars-MO*, such as the flagship *Kazakhstan*, as well as on *Bars*-class patrol vessels (up to 240 tons) equipped with hydroacoustic stations. These ships utilize SRNS for patrolling Kazakhstan's sector of the Caspian Sea and for protecting offshore oil and gas platforms. However, on submarines that are not part of the Kazakh Naval Forces and on special-purpose craft operating under stealth conditions, the use of SRNS is limited due to their vulnerability to jamming and spoofing. To mitigate these risks, protective technologies such as SAASM in GPS are employed. Coastal patrol boats of Project 100 *Sunkar* (13 tons displacement) and high-speed craft of the *FC-19* design (up to 27 tons) are also equipped with simplified SRNS for near-shore operations, where high positional accuracy is essential for maneuvering in shallow waters. An example of such equipment is the U.S.-made WRN-7 receiver.

Inertial navigation systems (INS) use gyroscopes either laser or fiber-optic and accelerometers to autonomously determine a vessel's position, velocity, and orientation without relying on external signals. These systems measure acceleration and angular velocity, integrating the data to compute the vessel's trajectory. Modern INS systems, such as the AN/WSN-7 used by the U.S. Navy, exhibit an error margin of less than 0.01% of the distance traveled, making them a reliable solution in environments where satellite signals are unavailable. INS are indispensable for submarines, such as the U.S. Virginia-class, where access to SRNS is limited. In the Kazakh Naval Forces, the use of INS is limited, as the fleet primarily consists of surface vessels and patrol boats, including *Burkit*-class patrol ships (40–42 tons) of Project 0200 and high-speed patrol boats of Project 0210 *Aybar*. These vessels employ INS as a backup system during operations in contested environments or in cases of temporary satellite signal loss. For example, *Aybar* patrol boats, designed for high-speed missions, are equipped with compact INS units to ensure short-term autonomous navigation capability. On special-purpose boats operated by the Ministry of Defense of Kazakhstan, INS may be used for covert missions where the use of SRNS is undesirable. However, the accuracy of INS degrades over time due to error accumulation, necessitating periodic correction through integration with other navigation systems.

Radar systems provide navigational plotting and collision avoidance by using radio waves to detect objects, shorelines, and other vessels. Modern radar systems, such as the U.S. AN/SPS-73, have an operational range of up to 100–200 nautical miles, depending on the antenna configuration and environmental conditions. Radar systems are critically important for surface vessels operating in low-visibility conditions or along congested maritime routes. In the Kazakh Naval Forces, radar systems are deployed on *Bars*-class patrol ships such as *Sardar* and *Semser* (with a displacement of up to 240 tons), as well as on *Bars-MO* missile-artillery ships equipped with Kh-35 anti-ship missiles. These systems are integrated with ECDIS to enable coordinated operations within the Caspian Flotilla. *Sunkar* and *Burkit* coastal patrol boats utilize simplified radar systems for nearshore patrol missions, where high maneuverability and rapid obstacle response are operational priorities. On *FC-19* and *Aybar* boats, radar systems enhance navigational safety in the shallow waters of the Caspian Sea. While radars are resilient to satellite signal loss, they require regular calibration and are susceptible to interference.

Automatic Identification Systems (AIS) and Automatic Radar Plotting Aids (ARPA) provide situational awareness by enabling the identification of vessels and the exchange of data regarding their position, course, and speed. AIS, which operates via VHF radio communication, transmits vessel information such as name and route an essential feature for ensuring safety in congested waters. ARPA automates the processing of radar data, reducing the workload on operators. In the Kazakh Naval Forces, AIS and ARPA are used on *Bars*-class patrol ships and *Burkit* border patrol boats to facilitate interaction with civilian vessels and prevent collisions within Kazakhstan's sector of the Caspian Sea. High-speed boats such as *Aybar* and *FC-19* utilize these systems for rapid patrol operations and coordination with coastal units. On a special-purpose craft, AIS may be deactivated to maintain stealth, while ARPA remains operational for data analysis. These systems enhance navigational safety but require integration with ECDIS to achieve maximum effectiveness.

Electronic Chart Display and Information Systems (ECDIS) are digital platforms used for displaying and analyzing navigational data, integrating inputs from SRNS, radar, and other sources. These systems provide interactive charts that enable route planning, account for weather conditions, and help avoid collisions. Modern ECDIS platforms, such as WECDIS, comply with International Maritime Organization standards and are used on most surface vessels. In the Kazakh Naval Forces, ECDIS is employed on *Bars-MO* missile-artillery ships such as *Kazakhstan*, *Oral*, *Saryarka*, and *Mangystau* for planning patrol operations and protecting maritime assets. Bars-class patrol ships and *Burkit* border patrol boats use simplified versions of ECDIS adapted for the shallow waters of the Caspian Sea. *Sunkar* and *FC-19* boats are equipped with compact ECDIS units for operations in coastal areas. Although regular updates of charts and software make ECDIS maintenance complex, their contribution to navigational safety and operational efficiency is substantial.

Hydroacoustic systems support navigation and underwater object detection, which is particularly critical for submarines; however, in the Kazakh Naval Forces, they are employed on surface vessels for specific operational tasks. These systems use sound waves to measure depth, detect obstacles, and map seabed topography. *Bars*-class patrol ships are equipped with hydroacoustic stations for mine countermeasures and the detection of underwater threats. *Bars-MO* missile-artillery ships may utilize hydroacoustic systems for navigation in the shallow regions of the Caspian Sea. *Sunkar* and *Burkit* border patrol boats, as well as high-speed vessels such as *FC-19* and *Aybar*, are typically not equipped with advanced hydroacoustic systems but may use basic echo sounders for operations in coastal areas. Special-purpose craft designed for diversionary or reconnaissance missions may be fitted with compact hydroacoustic sensors to support stealth maneuvering. Maintaining these systems requires a high level of technical expertise due to the complexity of their sensors and software. Each navigation system is tailored to the operational roles and environmental conditions of the vessels. In the Kazakh Naval Forces, *Bars-MO* missile-artillery ships and *Bars*-class patrol vessels require the integration of SRNS, radar, and ECDIS to support patrol missions and safeguard national economic interests. *Sunkar* and *Burkit* border patrol boats, along with high-speed *FC-19* and *Aybar* vessels, utilize simplified systems to ensure maneuverability in shallow waters. Special-purpose craft rely on INS and hydroacoustics to maintain stealth. Understanding these operational specifics enables effective organization of maintenance and modernization of navigation equipment, thereby ensuring fleet combat readiness.

A comparative analysis outlining the main types of navigation systems used on naval vessels-their characteristics, advantages, and limitations presented in Table 1.

Table 1.
Comparison of Major Types of Navigation Systems Used on Naval Combat Vessels: Characteristics, Advantages, and Limitations.

System Type	Description	Advantages	Limitations
Automatic Identification Systems (AIS)	Transmit vessel data (name, course, speed) via VHF radio; integrated with ECDIS for situational awareness.	Enhanced safety in congested waters; ease of integration.	Limited utility in stealth operations; reliant on radio communication.
Inertial Navigation Systems (INS)	Autonomous systems using laser or MEMS gyroscopes and accelerometers determine position and orientation with an error margin of 0.01–0.05% over distance.	Independence from external signals; reliable under interference conditions.	Error accumulation over time; high maintenance costs.
Radar Systems (RS)	Use radio waves to detect objects and coastlines at ranges up to 100–200 nautical miles.	Effective in low-visibility conditions; resilient to satellite signal loss.	Susceptible to electronic interference; requires regular calibration.
Electronic Chart Display and Information Systems (ECDIS)	Digital platforms for chart visualization, route planning, and integration of SRNS, RS, and other data sources; compliant with IMO standards.	Interactivity, precise route planning, and incorporation of weather data.	Requires regular software and chart updates; complex maintenance.
Automatic Radar Plotting Aids (ARPA)	Automate radar data processing to reduce operator workload.	Accelerated data analysis; reduced human error.	Dependent on radar quality, requires integration with ECDIS.
Hydroacoustic Systems	Use sound waves for underwater navigation and object detection; operate in active and passive modes.	Effective for underwater operations; accurate depth measurement (up to 6000 m).	High maintenance complexity; limited applicability on surface vessels.

Source: Compiled by the authors based on sources [10–22].

Scheduled preventive maintenance (SPM) plays a critical role in maintaining the reliability and performance of navigation systems on naval vessels, especially in environments characterized by intensive operations, harsh conditions, and the risk of electronic interference. This form of maintenance typically includes regular inspections, system calibrations, and the replacement of components based on predefined intervals, thereby reducing the likelihood of unexpected malfunctions and supporting continuous combat readiness. SPM procedures are guided by formalized protocols that are adjusted according to vessel class, mission profile, and national technical regulations. While large naval forces – such as the United States Navy – apply SPM practices in a more context-specific manner, taking into account the unique operational demands of the Caspian Sea and the structure of their fleet. This includes *Sunkar*-class coastal patrol boats (Project 100), *Burkit*-class patrol ships (Project 0200), high-speed *FC-19* craft, *Bars*-class patrol ships, *Bars-MO*-class missile-artillery vessels (Project 250), *Aybar*-class high-speed patrol boats (Project 0210), and special-purpose craft operated by designated units.

For example, in the U.S. Navy, scheduled preventive maintenance of navigation systems is governed by the standardized Class Maintenance Plan (CMP), which outlines detailed procedures for each ship class. On aircraft carriers such as the *USS Gerald R. Ford* (with a displacement of approximately 100,000 tons), the high operational tempo, including coordination of air sorties and missile strikes, demands strict adherence to the SPM schedule. Satellite radionavigation systems (SRNS), such as GPS with WRN-7 receivers; radar systems (RS), such as the AN/SPS-73; and electronic chart display and information systems (ECDIS) compliant with WECDIS standards undergo inspections every 3 to 6 months. These procedures include antenna testing, receiver calibration, software updates, and the replacement of worn components such as cables or signal processing modules. Inspections are conducted both in-port and at specialized shipyards such as Naval Station Norfolk using diagnostic equipment and certified spare parts, tools, and accessories (SPTA). This approach ensures the navigational accuracy required for complex operations but demands substantial resources, including trained personnel and access to technical infrastructure.

In the Kazakh Naval Forces, scheduled preventive maintenance of navigation systems is adapted to the specific conditions of the Caspian Sea, where shallow waters, a limited maritime area, and missions related to the protection of economic interests shape operational requirements. *Bars-MO* missile-artillery ships of Project 250 such as *Kazakhstan*, *Oral*, *Saryarka*, and *Mangystau* (with a displacement of approximately 250 tons) are equipped with SRNS (GPS), radar systems, and ECDIS, all integrated with Kh-35 anti-ship missile systems. SPM for these vessels is conducted every 4 to 6 months at the naval base in Aktau, including inspection of SRNS antennas, calibration of radar systems (e.g., *Monolit-B*), and updating of ECDIS charts to reflect changes in the navigational environment of the Caspian Sea. *Bars*-class patrol ships (up to 240 tons), such as *Sardar* and *Semser*, are additionally equipped with hydroacoustic stations for mine countermeasures. Their SPM includes quarterly inspections of hydroacoustic systems for depth measurement accuracy (up to 200 meters in the shallow zones of the Caspian) and radar calibration for operations under limited visibility conditions. Project 100 *Sunkar* coastal patrol boats (13 tons displacement) and Project 0200 *Burkit* patrol ships (38–42 tons) follow simplified SPM protocols adapted for coastal operations. These vessels are equipped with compact SRNS and radar systems, such as the Furuno FAR-2117, which are inspected every 6–8 months at the ports of Bautino or Aktau. The inspections include antenna testing, ECDIS software updates, and replacement of worn cabling. High-speed boats of the *FC-19* project (up to 27 tons) and *Aybar*-class fast patrol boats of Project 0210 follow similar maintenance schedules, with an emphasis on operational responsiveness and ease of servicing. For example, *Aybar* boats, designed for high-speed patrol missions, undergo SPM every six months, including inspection of compact SRNS and radar systems, ensuring maneuverability in narrow coastal zones. Special-purpose boats operated by the Ministry of Defense of Kazakhstan for reconnaissance and diversionary missions are serviced before each deployment (typically every 3–4 months), with a focus on INS and compact hydroacoustic systems, such as shallow-water echo sounders. These procedures are carried out in field conditions or at small repair facilities, requiring a high level of crew expertise.

The advantages of scheduled preventive maintenance lie in its predictability and its ability to prevent navigation system failures, an especially critical factor for vessels with high operational demands, such as aircraft carriers or Kazakhstan's missile-artillery ships. For instance, on *Bars-MO* ships, regular inspections of SRNS and radar systems ensure the targeting accuracy of Kh-35 missiles. However, the method also has limitations: for vessels with low operational intensity, such as Kazakhstan's *Sunkar* or *FC-19* boats, frequent inspections may be excessive, leading to increased expenditures on SPTA and manpower. Moreover, SPM requires well-developed infrastructure and qualified personnel, which may pose challenges for the Kazakh Naval Forces given their relatively small fleet and dependence on foreign equipment supplies. Overall, scheduled preventive maintenance remains the most widely used method for ensuring the reliability of navigation systems. For large vessels such as aircraft carriers and submarines, it provides strict procedural discipline and high operational readiness. In the Kazakh Naval Forces, SPM is adapted to the conditions of the Caspian Sea, where *Bars-MO* missile-artillery ships and *Bars*-class patrol ships require regular inspections to support strategic tasks, while *Sunkar*, *Burkit*, *FC-19*, and *Aybar* boats follow simplified procedures tailored to coastal operations. Special-purpose craft rely on intensive SPM prior to missions to ensure stealth and reliability. Despite its high cost, this method remains indispensable for maintaining fleet combat readiness.

Another approach aimed at optimizing technical maintenance by conducting repairs or replacing components only when faults or performance degradation are detected is condition-based maintenance (CBM) of navigation systems on naval vessels. This method relies on continuous system monitoring through embedded sensors, diagnostic software, and control systems, enabling reduced downtime and lower costs by avoiding unnecessary servicing. Unlike scheduled preventive maintenance, which follows rigid timelines, CBM is guided by the actual condition of the equipment, making it particularly effective for vessels with variable operational intensity.

On large surface combatants such as *Arleigh Burke*-class destroyers (U.S. Navy, approximately 9,200 tons displacement), condition-based maintenance is actively applied to satellite radionavigation systems (SRNS) and radar systems (RS). For example, the AN/SPY-1 radar part of the Aegis combat system is equipped with integrated diagnostic modules that continuously monitor operational parameters in real time, including signal strength, antenna integrity, and power stability. Diagnostics are performed using onboard control systems such as the Integrated Bridge System (IBS), which analyzes operational data and generates maintenance recommendations. Inspections include testing of power circuits, software, and antenna modules, allowing degradation to be detected before critical failures occur. These procedures are carried out either in port or at sea using SPTA, such as replacement boards and cables certified by the manufacturer (e.g., Raytheon). This approach reduces downtime and optimizes resource utilization but requires highly qualified engineers and access to diagnostic equipment, typically available at bases such as Naval Station San Diego.

In the naval forces of the United Kingdom and European Union countries such as France and Germany, condition-based maintenance of navigation systems is being actively implemented on modern vessels, including French *FREMM*-class frigates (approximately 6,000 tons displacement) and British *Daring*-class destroyers (Type 45, approximately 7,500 tons displacement). Modern naval platforms are typically equipped with advanced systems such as Satellite Radio Navigation Systems (SRNS, e.g., Galileo, GPS), long-range radars like the Thales SMART-L, and Electronic Chart Display and Information Systems (ECDIS), all of which are integrated into diagnostic frameworks such as the Integrated Platform Management System (IPMS). These technologies enable real-time monitoring of critical parameters, including signal integrity, antenna condition, and software functionality, allowing for early detection of anomalies such as diminished radar transmission power or failures in ECDIS data processing. Crew members are notified of such issues through centralized control interfaces. Maintenance operations are usually conducted at well-equipped naval facilities such as Toulon (France) or Portsmouth (UK) and rely on specialized spare parts and tools (SPTA) provided by major defense contractors like Thales and BAE Systems. While this approach significantly enhances operational efficiency by minimizing unnecessary manual inspections, it also demands substantial investment in diagnostic infrastructure and personnel training. As a result, its implementation remains challenging for smaller fleets such as that of Kazakhstan when benchmarked against the capabilities of leading European navies. The advantages of condition-based maintenance lie in its cost-effectiveness and ability to minimize downtime, which is particularly valuable for vessels with variable operational loads, such as Kazakhstan's *Sunkar* and *Aybar* boats. For example, on *Bars-MO* ships, diagnostics help avoid unnecessary radar inspections, thereby reducing expenditures on SPTA. However, the method has limitations: it requires reliable diagnostic systems and highly skilled personnel, which may pose challenges for the Kazakh Naval Forces due to limited technical infrastructure and reliance on foreign supplies. Furthermore, in the absence of accurate diagnostics, there is a risk of overlooking latent faults, potentially leading to failures at critical moments. Condition-based maintenance of navigation systems represents a flexible and efficient approach that complements scheduled preventive maintenance. In the Kazakh Naval Forces, this approach is particularly valuable for *Bars-MO* missile-artillery ships and *Bars*-class patrol vessels, where diagnostics of radar and hydroacoustic systems ensure reliability during strategic operations. Despite the high demands placed on technical infrastructure, condition-based maintenance improves fleet operational efficiency—especially under resource-constrained conditions.

Modernization and integration of navigation systems on naval vessels represent a strategically important process aimed at enhancing functionality, adapting to emerging challenges, and extending the service life of equipment. This approach involves the adoption of advanced technologies, such as artificial intelligence for data analysis, cloud-based solutions for chart management, and 3D modeling to optimize maintenance workflows, as well as the integration of next-generation satellite and inertial navigation systems. Unlike scheduled maintenance or condition-based repair, modernization focuses on the long-term enhancement of navigational system capabilities, a priority made increasingly relevant by the rapid advancement of technology and the evolving nature of maritime operations.

In the case of the U.S. Navy, navigation system modernization is carried out under programs such as the Navy's Navigation and Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) Modernization Program, which aims to integrate advanced technologies to enhance operational effectiveness. On aircraft carriers such as the *USS Nimitz* (approximately 100,000 tons displacement), modernization efforts include upgrading satellite radionavigation systems (SRNS) to the GPS Block III version, which offers enhanced jamming resistance and positioning accuracy of up to 1 meter through the use of new L1C signals. Recent upgrades to Electronic Chart Display and Information Systems (ECDIS) have focused on enabling real-time integration with data streams from unmanned aerial vehicles (UAVs), which are increasingly used for reconnaissance and operational coordination. In parallel, cloud-based architectures are being introduced for the storage and processing of navigational information, allowing for seamless connectivity with shore-based command centers, such as the U.S. Naval Air Systems Command (NAVAIR). These modernization efforts are typically undertaken at major shipyards, including Puget Sound Naval Shipyard, and often require extended dry-docking periods ranging from six to twelve months. While this significantly increases maintenance costs, it ensures that vessels, particularly aircraft carriers, remain compatible with next-generation weapon systems, including emerging laser technologies. Such investments are essential for maintaining operational effectiveness amid the growing complexity of multi-domain maritime threats.

In several European Union member states, including France and the Netherlands, efforts to modernize naval navigation systems are increasingly focused on improving system autonomy and strengthening cybersecurity measures. On *Horizon*-class frigates (France, approximately 7,000 tons displacement), radar systems such as the Thales APAR are being upgraded with active phased array antennas (AFAR), enhancing the detection of low-flying targets and increasing navigational accuracy in high-traffic environments. ECDIS systems are being modernized to support the S-100 standard developed by the International Hydrographic Organization, enabling the integration of 3D hydrographic data for precise maneuvering in complex maritime environments such as the Mediterranean Sea. In the Netherlands, *Sigma*-class corvettes (approximately 2,400 tons displacement) are being equipped with artificial intelligence systems for the analysis of navigational data, accelerating real-time decision-making. Modernization is carried out at shipyards such as Naval Group in Brest (France) and includes crew training on the use of new interfaces. This process enhances reliability and adaptability but requires substantial investment, which may limit the frequency of upgrades for smaller fleets.

In the Kazakh Naval Forces, the modernization of navigation systems is tailored to the conditions of the Caspian Sea, where limited depth and the need to protect economic interests such as offshore oil and gas platforms shape operational priorities. On *Bars-MO* missile-artillery ships of Project 250 such as *Kazakhstan* and *Mangystau* (approximately 250 tons displacement), modernization includes upgrading SRNS to support the combined use of GPS with enhanced anti-spoofing algorithms, which is critical for operations near disputed maritime boundaries. ECDIS systems on these ships are being upgraded to integrate with Kh-35 missile guidance systems, incorporating modules for processing data from unmanned surface vessels used in reconnaissance operations. *Bars*-class patrol ships (e.g., *Sardar*, up to 240 tons displacement) are modernizing their hydroacoustic stations to improve the detection of underwater objects at depths of up to 200 meters, which is critical for mine countermeasure operations. Modernization is carried out at the naval base in Aktau, with equipment supplied by enterprises such as JSC Concern Morinformsystem-Agat. The process takes approximately 3 to 6 months and requires the vessel to be withdrawn from active service, which represents a significant operational limitation. Project 100 *Sunkar* coastal patrol boats (13 tons displacement) and Project 0200 *Burkit* patrol ships (40–42 tons) are undergoing modernization with a focus on compact radar systems such as the Furuno DRS4D-NXT, which are being upgraded to support digital signal processing that enhances the detection of small targets in rough sea conditions. ECDIS systems on these boats are receiving software updates to support high-precision charts of the Caspian Sea, enhancing safety in shallow-water zones. High-speed *FC-19* boats (up to 27 tons) and Project 0210 *Aybar* patrol boats are being modernized with the integration of modular SRNS compatible with Galileo, aimed at improving positioning accuracy in coastal waters. Special-purpose craft used for reconnaissance missions are upgrading their compact inertial navigation systems (INS) with integrated MEMS gyroscopes, providing orientation accuracy of up to 0.05% in the absence of satellite signals. Modernization is carried out at small repair facilities in Bautino, which helps minimize costs but limits the scale of upgrades due to the absence of large shipyards.

The advantages of modernization and integration lie in the significant improvement of accuracy, reliability, and adaptability to emerging threats such as cyberattacks and the use of unmanned systems. For example, on U.S. aircraft carriers, upgraded ECDIS platforms enable the coordination of drone operations, while in Kazakhstan, modernized SRNS systems on *Bars-MO* ships enhance missile targeting precision. However, this approach requires substantial financial investment and extended dry-dock periods, which may pose challenges for fleets with limited budgets, such as the Kazakh Naval Forces. In addition, the need to retrain crews to operate new systems further increases both time and cost demands.

Another key method of navigation system maintenance is emergency maintenance, which focuses on the rapid resolution of malfunctions that occur during operation, particularly in situations where access to specialized shipyards is unavailable. This approach relies on onboard spare parts, tools, and accessories (SPTA), as well as crew expertise, to rapidly restore the functionality of systems such as satellite radionavigation systems (SRNS), radar systems (RS), electronic chart display and information systems (ECDIS), or hydroacoustic complexes. Emergency maintenance is especially critical during extended deployments or combat missions in remote maritime areas, where immediate repair may be essential for both safety and mission success.

In major fleets such as the U.S. Navy, emergency maintenance of navigation systems is an integral part of the broader “Damage Control” concept, which ensures rapid response to system failures at sea. On *Ticonderoga*-class cruisers (approximately 9,600 tons displacement), crews employ SPTA to carry out prompt repairs of SRNS components such as AN/WRN-6 GPS receivers in the event of failures caused, for example, by antenna damage during storm conditions. The SPTA inventory includes spare antenna modules, signal processing boards, and software patches, stored in secured compartments onboard. This method enables the maintenance of combat readiness during extended deployments such as operations in the Pacific Ocean, but is constrained by the complexity of repairing advanced systems, such as integrated navigation suites, which may necessitate temporary fixes that require follow-up maintenance at a shipyard. In the United Kingdom and European Union countries such as Germany, emergency maintenance of navigation systems is focused on ensuring autonomy and responsiveness during NATO missions. On British *Type 23*-class frigates (approximately 4,900 tons displacement), radar systems such as the Type 996 and ECDIS are equipped with modular components that enable crews to rapidly replace faulty elements such as processors or power cables using SPTA supplied by BAE Systems. Crews are trained at facilities such as HMS Collingwood to perform at-sea repairs, including reprogramming ECDIS software in the event of chart data processing failures. In Germany, emergency maintenance on *Braunschweig*-class corvettes (approximately 1,840 tons displacement) focuses on SRNS compatible with Galileo, where crews are able to replace antenna units or synchronization modules within 1–2 hours. This approach is effective for operations in the North Sea but is limited by the complexity of repairing hydroacoustic systems, which require specialized equipment available only at shipyards such as Blohm+Voss in Hamburg.

At the same time, in the Kazakh Naval Forces, emergency maintenance of navigation systems is adapted to the specific conditions of the Caspian Sea, where short patrol missions and limited infrastructure require a high degree of crew autonomy. On *Bars-MO* missile-artillery ships of Project 250, the SPTA for SRNS and radar systems includes spare antennas, circuit boards, and cables, enabling the resolution of malfunctions such as satellite signal loss caused by antenna damage during storms. Crews can complete repairs within 1 to 3 hours, restoring navigational capability for missions related to the protection of oil and gas infrastructure. *Bars*-class patrol ships utilize SPTA for hydroacoustic stations such as *Rubikon-M* to resolve depth sensor malfunctions, which are critical for mine countermeasure operations in shallow-water zones. Border patrol boats such as *Sunkar* and *Burkit*, along with high-speed *FC-19* and *Aybar* craft, are equipped with compact SPTA kits for radar systems, allowing antenna module replacement or ECDIS software reboot at sea within 30 to 60 minutes. Special-purpose boats used for reconnaissance missions carry minimal SPTA for compact INS and echo sounders, enabling field repairs while maintaining operational stealth. Repairs are carried out by crews trained in Aktau; however, the limited complexity of available SPTA may result in temporary fixes requiring follow-up maintenance at the Bautino base. The primary advantage of emergency maintenance lies in its ability to rapidly restore the functionality of navigation systems, which is critical for maintaining combat readiness at sea. In the United States and the European Union, this method ensures responsiveness during complex operations, while in Kazakhstan, it enables the fleet to remain operational despite limited infrastructure. However, the limited capacity for at-sea repairs, particularly for complex systems such as hydroacoustics, and the risk of relying on temporary fixes that may require additional maintenance remain significant drawbacks. For the Kazakh Naval Forces, an added challenge is the dependence on imported SPTA, which may delay system recovery in the event of supply shortages.

A comparative analysis of navigation system maintenance methods across different types of naval vessels, including those operated by the Kazakh Naval Forces, is presented in Table 2.

Table 2.
Comparative Analysis of Navigation System Maintenance Methods Across Different Types of Naval Vessels.

Vessel Type	Scheduled Preventive Maintenance	Condition-Based Maintenance	Modernization and Integration	Emergency Maintenance
Cruisers (e.g., Ticonderoga-class, USA)	SRNS, RS, and ECDIS inspections every 4–6 months; power circuit testing; chart updates. High reliability, but excessive for low operational load.	Aegis diagnostic modules monitor RS and SRNS; real-time replacement of signal amplifiers. Resource-efficient but requires diagnostic equipment.	RS upgrade; ECDIS integration with S-100 for 3D charts. Enhances accuracy but requires 6–9 months.	SPTA (processors, cables) for RS and SRNS enable 1–3 hour repairs at sea. Complex systems may require dockyard support.
Destroyers (e.g., Arleigh Burke-class, USA)	Quarterly SRNS, RS, and ECDIS checks at base; antenna calibration; software testing. Reliable for missile operations, but costly.	SRNS and RS monitoring via IBS; replacement of boards/antennas based on diagnostics. Reduces cost but requires a skilled crew.	AI integration for ECDIS data analysis; SRNS upgrade for spoofing protection. Improves autonomy, but expensive.	SPTA (spare modules) for RS and SRNS; 2–4 hour repair possible. Complex repairs at sea are limited.
Frigates (e.g., FREMM-class, France)	SRNS, RS, and ECDIS inspections are conducted every 4–6 months; gyroscope testing and chart updates are also performed. These procedures are reliable but may be excessive under low loads.	Self-diagnostics for RS and SRNS; signal noise monitoring. Targeted repairs (e.g., amplifier replacement) save time. Requires software and training.	ECDIS upgrade for 3D data; UAV integration. Improves accuracy but is costly.	SPTA (antennas, boards) for RS and SRNS; repairs in 1–3 hours at sea. Complex repairs require base training.
Corvettes (e.g., Sigma-class, Netherlands)	SRNS, RS, and ECDIS inspections occur every 6–8 months; software	Diagnostics via IPMS for RS and SRNS; module replacement based on monitoring. Cost-effective	AI-enabled ECDIS; RS upgrade. Enhances maneuverability but requires investment.	SPTA (cables, processors) for RS and SRNS; repairs within 1–2 hours.

	updates and antenna calibration are also performed. The process is simple, but SPTA costs are involved.	but requires systems.		Limitations for sonar systems.
Submarines (e.g., Virginia-class, USA)	INS and sonar checks before and after missions; gyroscope testing. High autonomy, but complex procedures.	INS and sonar monitoring via onboard systems; sensor/bearing replacement. Time-saving but demands high qualifications.	INS upgrade with MEMS gyros; sonar enhancements for stealth. Improves autonomy, but expensive.	SPTA (sensors, boards) for INS and sonar; repairs in 2–4 hours at sea. Complex repairs are limited.
Amphibious Ships (e.g., Mistral-class, France)	SRNS and RS inspections every 6–9 months; ECDIS chart updates. Simple, but excessive for low-load vessels.	SRNS and RS diagnostics via basic modules; cable/antenna replacement. Cost-effective, but limited by system complexity.	ECDIS 3D chart upgrade; drone integration. Improves landing operations but is costly.	SPTA (modules, cables) for SRNS and RS; 1–2 hour repair possible. Complex system repairs require shore facilities.
Kazakhstan Navy Ships (*Bars-MO*, *Bars*)	SRNS, RS, ECDIS, and sonar inspections are conducted every 4–6 months in Aktau; calibration for Kh-35 missiles and mine countermeasures are also performed. Reliable but costly SPTA.	Diagnostics for SRNS, RS, and sonar via portable kits; antenna/depth sensor (up to 200m) replacement. Resource-saving, but requires training.	SRNS spoofing protection upgrade; ECDIS for UAVs; sonar upgrades. Conducted in Aktau. Enhances accuracy, but is resource-limited.	SPTA (antennas, boards) for SRNS, RS, and sonar; 1–3 hour repairs at sea. Import dependence limits effectiveness.
Kazakhstan Navy Patrol Boats (*Sunkar*, *Burkit*, *FC-19, Aibar*)	SRNS and RS inspections occur every 6–8 months in Aktau/Bautino; ECDIS software updates are also performed. The process is simple, but SPTA costs are involved.	Basic SRNS and RS diagnostics; antenna/cable replacement. Cost-effective in coastal zones but needs diagnostic modules.	RS digital upgrade; ECDIS for Caspian charts; SRNS with Galileo. Conducted in Bautino (2–4 months). Enhances maneuverability but is yard-limited.	Compact SPTA for SRNS and RS; 30–60 minute repairs at sea. Training in Aktau. Temporary solutions due to SPTA limitations.
Kazakhstan Navy Special-Purpose Boats	INS and echo sounder checks before missions; stealth test procedures. High reliability, but complex tasks.	INS diagnostics (MEMS gyros) and echo sounders; field sensor replacement. Time-saving, but requires qualification.	INS upgrades conducted in Bautino (2–3 months). Enhances stealth but is resource-limited.	Minimal SPTA for INS and echo sounders; 1–2 hour field repairs. Limited capacity for complex fixes.

Source: Compiled by the authors based on sources Ministry of Defence | Defensie.nl [10] and Bian et al. [22].

Thus, the comparative table of navigation system maintenance methods illustrates that each approach scheduled preventive maintenance, condition-based maintenance, modernization and integration, and emergency maintenance offers distinct advantages and limitations depending on the vessel type and operational environment. Scheduled preventive maintenance offers high reliability but may be excessive for low-utilization craft such as Kazakhstan's *Sunkar* and *FC-19*. Condition-based maintenance optimizes costs through diagnostics, but it requires advanced monitoring systems posing a challenge for the Kazakh Naval Forces due to limited technical infrastructure. Modernization enhances system functionality but involves high costs and prolonged dry-dock periods, which are particularly burdensome for smaller fleets. Emergency maintenance enables rapid recovery but is limited by system complexity and the availability of SPTA, particularly for Kazakhstan's special-purpose boats. Major fleets, such as those of the U.S. and EU, employ integrated management systems (IMS) and 3D modeling to enhance efficiency, whereas Kazakhstan faces challenges stemming from its reliance on imported SPTA and limited infrastructure.

For the Kazakh Naval Forces, which include *Bars-MO* missile-artillery ships of Project 250 (e.g., *Kazakhstan*, *Oral*, *Saryarka*), *Bars*-class patrol ships (e.g., *Sardar*, *Semser*), *Sunkar*-class border patrol boats (Project 100), *Burkit*-class patrol ships (Project 0200), high-speed *FC-19* boats, *Aybar*-class fast patrol boats (Project 0210), and special-purpose craft a balanced approach to navigation system maintenance is recommended. This approach should integrate elements of scheduled preventive, diagnostic, modernization, and emergency maintenance strategies. For *Bars-MO* and *Bars*-class vessels tasked with strategic missions in the Caspian Sea such as the protection of economic zones and targeting with Kh-35 anti-ship missiles, it is advisable to implement advanced diagnostic modules for satellite radionavigation and radar systems. This would enable an extension of scheduled inspection intervals from 4–6 months to 6–8 months, maintaining reliability while reducing resource expenditure. Diagnostics should include monitoring signal stability and antenna integrity using portable testers available at the Aktau naval base. Additionally, for *Bars*-class ships, regular upgrades of sonar stations are recommended to support mine countermeasure operations, with an emphasis on depth sensor testing (up to 200 meters) in the shallow waters of the Caspian Sea.

For the *Sunkar*, *Burkit*, *FC-19*, and *Aybar* patrol boats, which are primarily engaged in coastal surveillance, it is essential to optimize the onboard spare parts and tool kits. These should include compact modules for radar and echo sounder systems to enable emergency repairs at sea within 30 to 60 minutes.

This is particularly important for operations under storm conditions or limited visibility. Special-purpose boats used for reconnaissance and sabotage missions must be equipped with autonomous inertial navigation systems based on high-precision MEMS gyroscopes, supplemented with minimal SPTA kits to allow for rapid field repairs while maintaining operational stealth.

To enhance fleet autonomy, it is essential to develop local repair capabilities in Aktau and Bautino, including the establishment of spare parts depots and training of crews in the use of diagnostic equipment, thereby minimizing dependence on imported supplies from Russia. The introduction of basic 3D modeling for maintenance planning using software such as AutoCAD-based platforms will help optimize servicing processes, reduce dry dock repair times (from 3–6 months to 2–4 months), and enhance efficiency under constrained budgetary conditions. These measures will ensure the sustained combat readiness of Kazakhstan's fleet in the specific operational environment of the Caspian Sea.

4. Discussion

This study conducted a comprehensive comparative analysis of scheduled preventive maintenance and condition-based maintenance methods for navigation systems on naval combat vessels, including the fleet of the Kazakh Navy. The aim was to develop tailored strategies to enhance reliability and combat readiness under the constraints of limited resources and the unique operational geography of the Caspian Sea.

This study emphasizes the importance of balancing preventive maintenance and real-time diagnostics, offering recommendations relevant to navies with limited infrastructure**.** In contrast, the work of Huang et al. [23] focused on distributed integrated navigation using network-synchronized data from GNSS and radar systems to achieve sub-meter positioning accuracy, opening prospects for automated group operations. However, its orientation toward high-tech fleets overlooks the necessity of scheduled inspections and the constraints of limited storage capacity, making its conclusions less applicable to the operational realities of Kazakhstan. In the study by Zorri and Kessler [5], cyber threats to navigation systems were analyzed, with an emphasis on continuous monitoring as a means of protecting against spoofing. This highlights the global relevance of cybersecurity; however, the approach focused primarily on diagnostics, overlooking the importance of scheduled maintenance, which this study identifies as essential for preventing system failures in the context of limited repair infrastructure. The study by Perera and Mo [24] explored digital models for monitoring vessel performance, optimizing routes, and reducing equipment wear. This demonstrates the potential of digitalization to enhance operational efficiency and highlights the applicability of such technologies in the context of Kazakhstan. The study by Oruc [25] proposed regular software checks of inertial navigation systems (INS) to protect against cyberattacks, emphasizing the importance of preventive measures.

This aligns closely with this research's focus on planned preventive maintenance as the foundation of reliability, particularly under conditions of limited infrastructure. In the work by Fernández Jove et al. [26] A methodology was developed for optimizing the life cycle of ships by combining scheduled inspections with monitoring, which reduces operational costs and confirms the conclusion regarding the necessity of a combined approach; however, the study is oriented toward large fleets, whereas the present research emphasizes solutions tailored to smaller vessels. The study by Hunt [27], which emphasizes the importance of scheduled inspections in extreme Arctic conditions for maintaining navigational accuracy, partially supports the approach of this research, although its narrow focus does not encompass the diagnostic aspects that are critical in the context of the Caspian Sea.

The study by Wang et al. [28] examined the monitoring of ship navigation systems, highlighting the future of autonomous navigation; however, it does not address the challenges of limited infrastructure, unlike the present research, which proposes localized solutions. Thus, this study distinguishes itself by emphasizing the adaptation of maintenance methods to constrained resources and geographical specificities, offering recommendations to enhance fleet resilience.

This study also conducted a detailed comparative analysis of modernization and emergency maintenance methods for navigation systems on naval vessels, with a focus on satellite radio navigation systems, radar systems, inertial navigation systems, electronic chart display and information systems (ECDIS), and hydroacoustic complexes, enabling an assessment of their contribution to enhanced functionality and rapid recovery under resource-constrained conditions, which is particularly relevant for developing fleets. In the study by Liu et al. [29], a method for testing intelligent systems based on artificial intelligence (AI) was developed, achieving Satellite Radio Navigation System (SRNS) accuracy of 1–2 meters, which underscores the potential of automation for improving precision. Although the focus on advanced technologies fails to take into account the limited technical infrastructure, the present study emphasizes practical modernization for fleets operating under budgetary constraints.

The study by Zhang et al. [30] proposed a failure assessment method capable of detecting malfunctions with high accuracy, highlighting the importance of prompt emergency repairs consistent with the goal of minimizing downtime. However, this approach does not encompass modernization, which in the current study is viewed as a long-term strategic objective. In the study by Wang et al. [31], camera-based visual systems enhancing obstacle detection were examined, demonstrating the potential of sensor technologies. However, the disregard for dependence on imported Spare Parts and Tools Allowance (SPTA) contrasts with the present study's emphasis on localized maintenance strategies for developing countries. The study by Parayitam et al. [32] explored the modernization of Satellite Radio Navigation Systems (SRNS) and Inertial Navigation Systems (INS) for operation under interference conditions, highlighting system resilience, which partially aligns with the context of this study, though it does not address emergency repair an issue of critical relevance in the context of the Caspian Sea.

In the study by Alizada et al. [33] a cognitive route modeling framework for Electronic Chart Display and Information Systems (ECDIS) was proposed to enhance navigational safety, which aligns with the modernization focus of the present study, though it does not take into account emergency maintenance, which has been identified as a key factor for operational responsiveness.

The research conducted by Veitch et al. [34] analyzed crew interaction with automated systems installed on large vessels, yet such an approach remains unadopted for small ships. In contrast to the present study, which offers tailored solutions for operations in shallow-water environments, this study provides a distinct contribution by adapting both modernization and emergency maintenance practices to the specific conditions of Kazakhstan. This includes the localization of Spare Parts and Tools Allowance (SPTA) and the development of supporting infrastructure, thereby enhancing the operational resilience of the fleet.

Additionally, the study develops recommendations for optimizing navigation systems, emphasizing their critical role in ensuring fleet combat readiness, particularly under conditions of limited infrastructure, which renders the findings especially valuable for developing naval forces such as the Navy of Kazakhstan.

Travagnin [35] explored the application of cold atom interferometers in Inertial Navigation Systems (INS), demonstrating exceptionally high orientation accuracy. This work underscores the promise of quantum technologies in enabling autonomous navigation independent of external signals. However, the emphasis on high-cost innovation contrasts with the present study's focus on affordable and scalable solutions tailored to settings with limited financial and technical resources. In a more budget-conscious direction, Grates [36] investigated the use of low-cost Inertial Measurement Units (IMUs) and sensors, achieving navigation accuracy within a 5-meter margin. This finding aligns, at least in part, with the current study's emphasis on practical modernization for resource-constrained fleets. Nonetheless, Grates's analysis does not address the role of emergency maintenance – an omission that overlooks a key component identified in this study as critical for sustaining combat readiness through rapid system recovery.

The study by Zhou et al. [37] developed a calibration method for MEMS-IMU/DVL systems with an orientation accuracy of 0.05°, highlighting the potential for enhancing navigation performance; however, the lack of attention to financial implementation barriers differs from the present study, which focuses on balanced solutions aimed at resource efficiency under the operational conditions of the Navy of Kazakhstan. In another study, Grates [38] examined GPS-independent autonomous navigation based on Inertial Measurement Units (IMUs), emphasizing resilience to interference, which underscores the importance of self-contained systems under conditions of cyber threats; however, the absence of focus on emergency repair contrasts with the present study's approach, which prioritizes operational responsiveness for fleets operating in challenging maritime environments.

The study by De Angelis and Palmerini [39] investigated Galileo services offering spoofing protection, which underscores the global relevance of cybersecurity for modern fleets and fully aligns with the present study's emphasis on enhancing the resilience of Satellite Radio Navigation Systems (SRNS), further highlighting the necessity of safeguarding against emerging threats. The research by Gioia et al. [40] analyzed the implementation of Galileo services for maritime vessels, providing accuracy within 1–2 meters and confirming the importance of modernization for precision-dependent operations; however, the lack of attention to emergency maintenance diverges from the focus of the present study on rapid vessel recovery.

The study by Pandele et al. [41] presented a comparison between Galileo and GPS, highlighting the superior interference resilience of Galileo, which supports the pursuit of system reliability emphasized in the present study; however, the disregard for the need for compact Spare Parts and Tools Allowance (SPTA) for at-sea repairs contrasts with the study's focus on practicality and operational autonomy. The present study distinguishes itself through its unique contribution by offering recommendations tailored to the constrained resources and geographical specificities of the Caspian Sea, thereby providing a comprehensive approach to enhancing the combat readiness of the Navy of Kazakhstan.

Thus, the findings of the referenced studies, in conjunction with the results of the present work, underscore the importance of a comprehensive approach to the maintenance of navigation systems on combat vessels—including scheduled preventive maintenance, condition-based servicing, modernization, and emergency repair—as essential components for ensuring reliability and combat readiness. These studies, encompassing advanced technologies, cybersecurity, and adaptation to diverse operational environments, form a foundation for the further development of maintenance methodologies, particularly for resource-constrained fleets such as the Navy of Kazakhstan, where adaptation to the conditions of the Caspian Sea and the minimization of dependence on external supplies remain key priorities.

5. Conclusions

The study establishes that maintenance methods for navigation systems, including scheduled preventive maintenance, condition-based servicing, modernization and system integration, and emergency repair, collectively contribute to ensuring the reliability and combat readiness of naval vessels. The analysis encompassed a range of platforms, including aircraft carriers, cruisers, destroyers, frigates, corvettes, submarines, landing ships, and the fleet of the Navy of Kazakhstan, covering vessels such as *Bars-MO*, *Bars*, the patrol boats *Sunkar*, *Burkit*, *FC-19*, *Aibar*, and special-purpose craft. Each maintenance method offers distinct advantages and limitations depending on the vessel class and the availability of operational resources.

It was observed that scheduled preventive maintenance of navigation systems on missile-artillery vessels such as *Bars-MO* and patrol ships such as *Bars* is conducted every 4–6 months, ensuring the reliability of Satellite Radio Navigation Systems (SRNS) and Radar Systems (RS), which in turn guarantees the targeting accuracy of Kh-35 missiles.

However, for patrol boats with low operational intensity, such as *Sunkar* and *Aibar*, such frequent inspections prove excessive, leading to increased financial and labor costs. Condition-based maintenance, grounded in diagnostic assessment, enables resource savings; however, on *Bars-MO* and *Bars* class vessels, the use of portable testers for Satellite Radio Navigation Systems (SRNS) and Radar Systems (RS) remains limited due to underdeveloped technical infrastructure. On patrol boats such as *Sunkar* and *Aibar*, basic radar diagnostics require improvement in both equipment and personnel training. Modernization of navigation systems on *Bars-MO* includes upgrading SRNS to provide protection against spoofing, while on patrol boats, the enhancement focuses on Radar Systems and Electronic Chart Display and Information Systems (ECDIS), thereby improving overall functionality.

Nevertheless, the modernization process, typically requiring 3 to 6 months, is constrained by limited resources and continued reliance on external supply chains. Emergency maintenance enables the rapid restoration of Satellite Radio Navigation Systems (SRNS) within 1–3 hours on larger vessels and within 30–60 minutes on patrol boats; however, reliance on imported spare parts and tools introduces risks of delay.

To enhance the operational efficiency of the Navy of Kazakhstan, a combined approach is recommended: strengthening diagnostic capabilities on *Bars-MO* and *Bars* to reduce the frequency of scheduled inspections; optimizing Spare Parts and Tools Allowance (SPTA) kits for patrol boats; equipping special-purpose vessels with autonomous Inertial Navigation Systems (INS); expanding repair facilities in Aktau and Bautino; and implementing basic 3D modeling for maintenance planning under resource-constrained conditions.

It should be noted that this study presents a limitation related to the insufficient depth of analysis concerning the economic aspects of implementing the recommended maintenance methods, including the costs of modernization and personnel training, which warrants further investigation to assess their financial viability within the constrained budget of the Navy of Kazakhstan. Future research should focus on developing localized solutions for the production of Spare Parts and Tools Allowance (SPTA) to reduce import dependency, as well as on the implementation of automated diagnostic systems adapted to the operational conditions of the Caspian Sea, in order to improve the efficiency of navigation system maintenance on both patrol boats and larger vessels.

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