RSTDE
Remote Sensing Technology in Defense and Environment
RSTDE 2(1): 64-80
ISSN 3062-8970

Institute for Advanced Science, Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Geospatial-driven maritime border security: Integrating AIS, remote sensing, and naval response systems for Indonesia's strategic archipelagic sea lanes

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Received Date: January 5, 2025 Revised Date: February 14, 2025 Accepted Date: February 28, 2025

ABSTRACT

Background: As a strategic archipelagic nation with Indonesian Archipelagic Sea Lanes (ALKI) that serve as vital global trade routes while remaining vulnerable to commplex maritime threats (including illegal fishing, smuggling, and maritime terrorisme), Indonesia requires an integrated Geospatial Intelligence (GEOINT)-based maritime surveillance system. This system must combine Automatic Identification System (AIS), satellite imagery (SAR/optical), and rapid response capabilities from the Indonesian Navy to address infrastructure limitations, inter-agency coordination fragmentation, and increasingly sophisticated transnational threat dynamics. **Methods**: This study employs a descriptive qualitative method with a systematic literatur review approach. Data were collected from Scopus-indexed, national policy documents, reports from international organizations, and technology whitepapers through academic databese using keywords related to GEOINT, maritime surveillance, and maritime threat detection. The collected data were then thematically analyzed and synthesized into a conceptual model of an ALKI surveillance system. The analyzes is grounded in GEOINT and Maritime Domain Awareness (MDA) theories, with a specific focus on technology integration and maritime strategies. **Findings:** This study reveals that the integration of AI-based GEOINT through a combination of AIS, SAR/optical, and GIS significantly enhances maritime threat detection and tactical response capabilities in the ALKI. However, its effectiveness depends on cross-agency data interoperability and the strengthening of national satellite infrastructure, necessitating maritime security governance reforms to address challenges such as IAS blind spots, jurisdictional overlaps, and limitations in realistic scenario to achieve a predictive and integrated surveillance system. **Conclusion**: This study introduces a transformational GEOINT-based maritime surveillance system that integrates AI, multi-sensor technologies, and spatiotemporal data fusion to enable real-time anomaly detection while generating rapid and predictive operational decision in the ALKI. **Novelty/Originality of this article:** Integrating AIS, remote sensing, and sea-based rapid-response patrol systems to strengthen surveillance in the ALKI. This study highlights the application of geospatial technology in addressing surveillance blind spots and potential sovereignty violations along strategic national shipping routes.

KEYWORDS: automatic identification system; Indonesian archipelagic sea lanes; integrated maritime surveillance; geospatial intelligence; transnational maritime threats.

1. Introduction

As the world's archipelagic state, Indonesia comprises more than 17,000 islands spanning the equator, constituting a highly strategic geographical entity bertween oceans

Cite This Article:
Wuryantari, B, A, I. (2025). Geospatial-driven maritime border security: Integrating AIS, remote sensing, and naval response systems for Indonesia's strategic archipelagic sea lanes. *Remote Sensing Technology in Defense and Environment*, *2*(1), 64-80. https://doi.org/10.61511/rstde.v2i1.2025.2063

(the Indian and Pacific) and two continents (Asia and Australia). This geographical position not only endows Indonesia with abundant marine resources but also establishes its ivtal role in global maritime trade and security, particularly through the Indonesian Archipelagoc Sea Lanes (ALKI). The ALKI represents internationally Convention on the Law of the Sea, which permits the continuous and peaceful transit of foreign vessels through Indonesian waters. These sea lanes hold critical importance as primary transit point for global commerce, yet simultaneously present complex maritime security challenges, including threats from illegal activities such as smuggling, piracy, and illegal, unreported, and unregulated (IUU) fishing (Tabish & Chaur-Luh, 2024).

As legally recognized international shipping lanes under the UNCLOS framework, the ALKI serve crucial roles not only as global trade corridors but also as strategics zones requiring rigorous maintenance of security, sovereignty, and navigational order. Through the concepts of innocent passage and transit passage, foreign vessels are granted navigation rights provided they do not compromise national security–a provision that makes surveillance in these lanes particularly complex and demands highly precise monitoring systems. ALKI I, II, and III each traverse maritime areas with distinct geographical, social and political characteristics, necessitating sector-specific and spatially-adapted threat management approaches. Failure to effectively manage maritime traffics in the ALKI could not only undermine national sovereignty buat also jeopardize navigational safety and the potential of Indonesia's marine economy. Consequently, robust maritime law enforcement and modern surveillance technologies are essential to ensure compliance with applicable sea lane regulations.

However, maintaining security and order along the ALKI routes presents significant challenges, primarily due to Indonesia's vast maritime territory spanning over 6 milion square kilometers. Effective maritime surveillance acroos such an extensive area requires adequate infrastructure, including maritimee radar systems, marine communication networks, and satellite-based monitoring stations. Unfortunately, the distribution of surveillance infrastructure in Indonesia remains uneven, with the majority concentrated in western region, while eastern areas traversed by ALKI II and III often lack intensive monitoring. Furthermore, the limited integration of information systems among key institutions such as the Indonesian Navy/*Tentara Nasional Indonesia Angkatan Laut* (TNI AL), the Indonesian Sea and Coast Guard/*Badan Keamanan Laut Republik Indonesia* (BAKAMLA), the Ministry Affairs and Fisheries, and Customs has resulted in fragmented and asynchronous intelligence data, hindering rapid responses to maritime threats (Munim et al., 2020). This fragmentation undermines the effectiveness of the national surveillance system and creates vulnerabilities for illegal activities within Indonesia's jurisdictional waters.

The limitations in surveillance infrastructur and weak inter-agency coordination futher exacerbate risks from increasingly complex, transnational maritime threats. Phenomena such as illegal fishing, smuggling of contraband, human trafficking, and potential maritime terrorism have become pressing issues, particularly in the heavily trafficked ALKI zones. Indonesia is estimated to lose trillions of rupiah annually due to illegal fishing by foreign vessels exploiting weaknesses in detection and response systems (van der Grient & Drazen, 2021). Moreover, Indonesia waters serve as strategic routes for narcotics and human trafficking, with perpetrators increasingly using small vessels to evade radar and AIS detection (Li et al., 2023). More alarmingly, regional intelligence reports indicate growing potential for exploitation of sea lanes by radical or terrorist groups to transport logistics or conduct sabotage operations, posing direct threats to regional security.

The escalating complexity of contemporary maritime threats, characterized by their dynamic nature and frequent evasion of conventional detection systems, underscores the urgent need to develop adaptive surveillance systems capable of real-time response. Such systems are essential for monitoring, identifying, and responding to suspicious maritime activities with high speed and precision, particularly in strategic areas like the ALKI which serve as primary routes for both international and domestic vessel traffic. An adaptive approach enable risk-based monitoring and machine learning capabilities to detect anomalous shipping patterns or non-cooperative vessel behavior (Zhao et al., 2024). This system must be supported by multi-source data integration including AIS, stellite imagery, marine radar, and field patrol reports to facilitate rapid and targeted decision making. As a maritime nation facing complex geographical and security challenges, Indonesia requires intelligent geospatial-based and automated surveillance strategies as the cornerstone of modern maritime security policy.

Within the framework of developing an adaptive surveillance system capable of real-time response to maritime threats, the Automatic Identification System (AIS) serves as a primary instrument for vessel tracking. AIS automatically transmits information such as geographical position, speed, course, and vessel identity to coastal stations, other ships, or satellites, thereby enabling accurate situational awareness across vast maritime areas (Thombre et al., 2022). Despite its critical role, AIS has fundamental limitations, particularly in dealing with non-cooperative vessels that deliberately disable their transponders to avoid detection. This phenomenon commonly occurs with vessels engaged in illegal activities such as illegal fishing, smuggling, or dark shipping operations. Consequently, relying solely on AIS for maritime surveillance proves insufficient, making the integration of additional sensor data from radar and satellite imagery absolutely imperative.

To address the limitations of AIS in detecting non-cooperative vessels that intentionally disable their transponders, remote sensing technology has become a vital component of modern maritime surveillance systems. The utilization of satellite imagery, indcluding both optical and radar-based systems such as Synthetic Aperture Rada (SAR), enables the detection of surface obejcts independently of active reporting systmes like AIS. SAR technology offers distinct advantages for maritime monitoring, with the capability to observe vast ocean areas during both day and night, and under adverse weather conditions, making it particularly effective for identifying unidentified vessels of ghost ships (Sun et al., 2022). Radar imagery can be automatically processed using artificial intelligence-based vessel detection algorithms, allowing for rapid and efficient anomaly identification (Wang et al., 2024). The integration of remote sensing data with AIS creates a dual-detection system that significantly restricts the operational space of illegal vessels and substantially enhances maritime surveillance effectiveness.

The integration of AIS and remote sensing technologies for detecting illegal or unidentified vessels remain incomplete without the support of rapid response capabilities from maritime security forces, particularly the Indonesian Navy. In the context of safeguarding the ALKI, which holds vital geopolitical and economic significance, the speed of response to intelligence information critically detemines the effectiveness of preventing and addressing maritime threats such as smuggling, piracy, and territorial violations. Through its Fleet Command and Naval Base Command, Indonesian Navy serves as the frontline in maritime emergency response operations, deploying Naval Vessels/*Kapal Republik Indonesia* (KRI) as well as aerial assets including maritime helicopters and reconnaissance aircraft. Rapid response becomes particularly crucial when dealing with dark shipping vessels, which can only be intercepted within a limited timeframe before exiting jurisdictional waters. Therefore, synchronization between surveillance data and operational deployment constitutes the key to maintaining sustainable maritime security (Albotoush & Shau-Hwai, 2023).

The effectiveness of the Indonesian Navy's rapid response to maritime threats in the ALKI would be significantly enhanced when supported by an integrated maritime information system within a unified national geospatial framework. The integration of Automatic Identification System (AIS), remote sensing technologies such as satellite imagery and SAR radar, along with maritime response assets including warships and reconnaissance aircraft, can create a surveillance syngery that is more proactive, precise, and adaptive to evolving threats. Through a Geospatial Intelligence (GEOINT)-based approach, spatial data from multiple sources can be consolidated and visualized on a unified platform to support rapid decision-making in maritime security operations (Sarrau et al., 2024). This system also enables vessel route prediction,anomaly detection, and strategic fleet deployment based on rsik-informed spatial analysis. Indonesia has a significant opportunity to develop a digital maritime defense architecture that consolidate all surveillance elements into a robust and sustainable national system.

Indonesia's strategic role in ASEAN'S regional maritime security framework has become increasingly crucial amid growing security complexities in Southeast Asian waters, particularly along vital sea lanes like the ALKI. As the world's second-longest coastline nation and the primary connector between the Indian and Pacific Oceans, Indonesia bears significant responsibility for maintaining regional stability. The integrated geospatial surveillance system developed in this study holds relevance not only at he national level but could also be adopted as part of regional cooperation frameworks such as ASEAN Our Eyes (AOE) or the ASEAN Information Sharing Centre. This integration fosters data synergy and cross-border interoperability to etablish collective maritime domain awareness. Such an initiative aligns with Indonesia's vision as a global maritime fulcrum and strengthens regional maritime defense diplomacy through spatial information-based technological platforms.

Building upon the urgent need for an integrated maritime surveillance system within a national geospatial framework, this study aims to design a geospatial data-based integrated surveillance system that combines AIS, remote sensing technology, and rapid response capabilities from the Indonesian Navy to enhance the security of strategic ALKI routes. By employing a Geospatial Intelligence (GEOINT) approach, the developed system is expected to process and present maritime data in real-time to detect shipping anomalies, monitor non-cooperative vessel activities, and support rapid and accurate operational decision-making. This research not only provides theoretical contributions to spatial-based maritime security studies but also offers practical contributions in the form of a national system architecture design that can be adopted by relevant institutions such as Indonesian Navy, the Indonesian Sea and Coast Guard, and the Ministry of Marine Affairs and Fisheries. Thus, this system is anticipated to serve as a critical foundation for realizing an intelligent, responsive, and sustainable Indonesian maritime security framework.

2. Methods

The research method employed in this study is descriptive qualitative research, utilizing a systematic literature-based approach. This study aims to examine, analyze, and synthesize relevant scientific literature to develop a comprehensive understanding of the inetgration of geospatial technology in maritime surveillance and security systems, particularly in the strategic area of the Indonesian Archipelagic Sea Lanes (ALKI). The literature review approach was selected because it enables the exploration of diverse theoretical and practical perspectives from academically and policy-validated sources without conducting direct field experiments.

The primary literature sources in this study include Scopus-indexed international journals ranked Q1 and Q2, selected based on their relevance to Geospatial Intelligence (GEOINT), Maritime Domain Awareness (MDA), remote sensing technoogy, and Artificial Intelligence (AI)-based maritime security systems. In addtion to scholarly journals, complementary literature comprises official reports from International Maritime Organization (IMO) and International Hydrographic Organization (IHO), national policy documents from relevant Indonesia agencies including the Ministry of Marine Affairs and Fisheries/*Kementerian Kelautan dan Perikanan* (KKP), Coordinating Ministry for Maritime Affairs and Investement/*Kementerian Koordinator Bidang Kemaritiman dan Investasi* (KEMENKO MARVES), and Indonesian Sea and Coast Guard, as well as technology white papers from global research and space agencies such as the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA).

The literature review process in this study was conducted through several key stages. The first stage involved literature identification and screening using prominent academic databases such as Scopus, ScienceDirect, Springer, IEEE Xplore, and Taylor & Francis. The primary keywords employed included "GEOINT," "maritime surveillance," "AIS integration," "remote sensing for security," and "dark vessel detection." The selected literture was filtered based on specific inclusion criteria; (1) publication within the last five years (2020-2025), (2) focus on geospatial technology-based maritime security issue and (3) relevance to Indonesia's context as an archipelagic nation with strategic interests in the Indonesia Archipelagic Sea Lanes (ALKI).

Upon completing the literature collection, a thematic analysis was conducted to classify the content and research findings according to several central themes; (1) developments and applications of maritime surveillance technologies (AIS, SAR, satellite imagery), (2) military strategies and responses in maritime security, (3) challenges of data integration and inter-agency interoperability, and (4) national and regional policies in maritime domain management. The final stage involved literature synthesis, which entailed summarizing and integrating findings from various sources into a conceptual model of a geospatial technology-based ALKI surveillance system. This model was designed to integrate elements of the Automatic Identification System (AIS), remore sensing technologies, military command and control systems (Naval Response Systems), and artificial intelligence applications for detecting and responding to transnational maritime threats. The synthesis is expected to provide both conceptual and practical contributions to strengthening Indonesia's maritime security architecture, making it more adaptive, responsive, and data-driven.

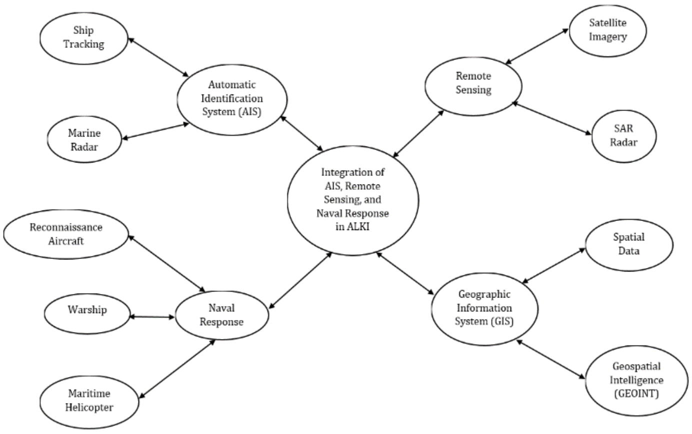

Fig. 1. Brainstorming

3. Results and Discussion

The establishment of the Indonesian Archipelagic Sea Lanes (ALKI) stems from Indonesia's strategic interests in maintaining its maritime territorial sovereignty while upholding principles of international maritime law. The ALKI gained formal recognition following Indonesia's retification of the United Nations Convention on the Law of the Sea (UNCLOS) 1982 through Law No. 17 of 1985, which acknowledged Indonesia as an archipelagic state and granted foreign vessels the right of peaceful passage through archipelagic waters via the archipelagic sea lanes passage mechanism (Beckman, 2013). Within this framework, Indonesia designated three ALKI routes (ALKI I, II, and III), each traversing strategic regions from west to east and connecting the Indian and Pacific Oceans. This Policy seeks to balance international navigation rights with the protection of national interests, including security, environmental concerns, and maritime order in vital domestic waters.

Within the context of ALKI policy that positions Indonesia uniquely as an archipelagic state with legitimate international shipping lanes, the implementation of Geospatial Intelligence (GEOINT) approaches becomes particularly relevant for strengthening maritime surveillance. GEOINT represents an analytical methodology that integrates spatial data, remote sensing imagery, intelligence information, and location-based analysis to generate comprehensive situational awareness of maritime activities (Avtar et al., 2021). In the ALKI framework, GEOINT enables real-time mapping of shipping activities, identification of vessel traffic patterns, detection of anomalies or threats, and strategic deployment of patrol assets. This technology further enhances inter-agency integration by consolidating diverse data sources into a unified spatial platform. Consequently, GEOINT implementation constitutes not merely a technical solution, but rather a strategic approach to enhance national maritime security while complying with international maritime law mandates.

As an integral component of Geospatial Intelligence (GEOINT) methodology, the Automatic Identification System (AIS) plays a crucial role in collecting and disseminating real-time shipping data to support maritime domain awareness. AIS operates through vessel-mounted transponders that transmit information including ship identity, GPS position, speed, heading, and destination port, which can be received by coastal stations or satellites. This system enables highly efficient maritime traffics monitoring by detecting movement patterns and identifying potential risks or violations. However, AIS reliability is fundamentally dependent on vessel compliance. Numerous non-cooperative vessels, including those engaged in illegal fishing or smuggling ectivites, deliberately disable their transponders or falsify data to evade detection (Meyers et al., 2021). These limitations render AIS insufficient as a standalone system, necessitating complementary technologies within an integrated geospatial surveillance framework.

The limitations of AIS in tracking non-cooperative vessels necessitate complementary technologies capable of providing comprehensive maritime surveillance, with remote sensing via satellites being one such solution. These technologies, particularly Synthetic Aperture Radar (SAR) and high-resolution optical imagery, prove highly effective in detecting maritime objects including vessels without AIS signals, coomonly refreed to as dark vessels (Stach et al., 2023). SAR offers distinct advantages in image acquisition during nighttime and adverse weather conditions through its active radar wave operation, while optical imagery provides more detailed visual identification during clear weather conditions. The complementary use of these dual sensors enables more accurate and continuous vessel detection, particularly in remote maritime areas such as rhe ALKI routes. When integrated into a geospatial-based system, remote sensing data serves as a primary resource for overcoming AIS monitoring limitations and supporting advanced, adaptive maritime security operations.

The utilization of remote sensing technologies such as SAR and optical imagery to complement AIS limitations has given rise to various integration models within the Maritime Domain Awareness (MDA) framework, now widely adopted by numerous maritime nations. This integration combines AIS data, remote sensing, coastal radar, and marine sensors into a unified Geospatial Intelligence-based monitoring system to detect, identify, and track vessel activities holistically (Montero et al., 2023). One prominent model is the data fusion framework that integrates temporal, spatial, and vessel characteristics from multiple sensors to reconstruct ship trajectories, including those of vessels with deactivated AIS. This approach has been effectively implemented in international projects such as Blue Hub (EMSA) and I2C (NATO), demonstrating that combining AIS with satellite imagery can significantly enhance maritime surveillance coverage and accuracy (Pallotta et al., 2013). Indonesia has substantial potential to adapt similar models for the strategic protection of ALKI.

The integrated AIS and remote sensing model within the Maritime Domain Awareness system will achieve greater effectiveness when supported by Geographic Information System (GIS) capabilities for spatial analysis. GIS plays a crucial role in dynamically mapping, visualizing, and analyzing maritime data based on geographical locations, enabling the identification of high-risk violation areas such as heavy traffic zones, frequently violated Exclusive Economic Zones (EEZs), and smuggling or illegal fishing hotspots (Rawson et al., 2022). Through its analytical features, GIS can integrate historical vessel movement data, weather patterns, and maritime topography to generate risk predictions and support real-time operational decision-making. In the context of ALKI security, GIS serves not merely as a static mapping tool, but rather as an interactive platform for coordinating naval patrols, developing strategic monitoring routes, and enhancing inter-agency collaboration within a unified geospatial framework.

The capability of GIS in mapping high-risk violation areas will be further optimized when integrated with a tactical response system from organized naval strike forces within a Command, Control, and Communications (C3) structure. This Naval Response System leverages accurate geospatial information and a command network directly connected to decision-making centers and field patrol units. In the context of ALKI security, the C3 system encompasses the integration of patrol vessels, reconnaissance aircraft, coastal radar, and satellites – all interconnected within a single operational network that enables rapid response to therats such as smuggling, border violations, or other illegal activities (Telli et al., 2023). The system's core components are interoperability and communication speed, allowing the Indonesian Navy to efficiently distribute information, mobilize resources, and execute law enforecement at sea within complex geopolitical frameworks.

The integration of maritime command and surveillance systems will be significantly enhanced when augmented with artificial intelligence (AI) to support early threat detection through analysis of anomalous vessel movement patterns. Machine learning-based detection models have demonstrated effectiveness in identifying shipping anomalies by learning from historical AIS, radar, and satellite imagery data to detect deviations from normal vessel routes or behavior (Wolsing et al., 2022). For instance, sudden changes in speed, direction, or anchoring activity in restricted areas may serve as early indicators of potential maritime law violations. This system operates automatically and adaptively, continuously updating its models based on the latest data, making it particularly suitable form implementation within the highly dynamic ALKI security framework. The integration of AI into C3 systems and geospatial paltforms strengthens situational awareness by enabling faster, intelligence-filtered military responses.

While the integration of advanced technologies such as AI and C3 sytems promises significant improvements in maritime surveillance, their implementation in Indonesia faces substantial challenges, particularly regarding limited data interoperability among authorized agencies. Institutions including the Indonesian Sea and Coast Guard, the Indonesian Navy, the Ministry of Marine Affairs and Fisheries, and Meteorolgy, Climatology and Geophysics Agency/*Badan Meteorologi, Klimatologi, dan Geofisika* (BMKG) often operate with disparate systems and data protocols that hinder real-time and effective information exchange (Durlik et al., 2023). The absense of a unified paltform for sharing spatial data, AIS information, weather forecasts, and patrol reports leads to operational redundancies, delayed responses, and surveillance gaps in strategic maritime areas such as the ALKI. Yet, successful maritime monitoring and law enforcement fundamentally depend on interagency synchronization and the integration of multi-score data within a national geospatial framework.

The limited data interoperability among Indonesia's maritime surveillance agencies exacerbates weaknesses in rapid response systems, particularly in vulnerable border areas distant from command centers. Numerous cases of smuggling, illegal fishing, and cross-border violations remain unaddressed due to delayed information flows between institutions and inadequate communication and logistics infrastructure in outer maritime zones (Howson, 2020). The scarcity of standby patrol vessels, coupled with poor integration between and-based and maritime surveillance, frequently results in suboptimal responses to threats in ALKI zones such as the North Natuna Sea and eastern Indonesian waters. This demonstrates that an effcetive rapid response system requires not merely fleet availability, but more crucially, real-time spatial data coordination capable of sumultaneously integrating all surveillance nodes into a unified network.

Response delays in Indonesia's maritime border areas are further exacerbated by the presence of AIS blank spots – marine zones unreachable by Automatic Identification System signals due to limited communication infrastructure or extreme geographical conditions such as narrow straits, deep seas, or remote regions. This surveillance vacuum creates significant gaps in vessel monitoring systems, allowing illegal activities like smuggling, illlegal fishing, or the presence of non-cooperative foreign vessels to go undected. In heavily trafficked ALKI zones, ALKI blind zones pose particular dangers by enabling vessels to disable thei transponders and disappear drom maritime uthorities' radar. This risk underscroes the critical need to integrate AIS with complementary technologies such as satellite-based radar, remote sensing systems, and maritime drones to close monitoring gaps and establish comprehensive situational awareness (Nikolic et al., 2023).

The surveillance gap in AIS blank spot areas is further compounded by the limited capability of national satellites to optimally cover Indonesia's entire maritime territory. Domestic satellites such as LAPAN-A3 and Satria still face constraints in terms of coverage area, spatial resolution, and temporal resolution required for-real-time, high precision maritime monitoring. This situation significantly reduces the effectiveness of detecting non-cooperative vessels with disabled AIS, particularly in remote and border waters distant from land-based monitoring stations. Additionally, limited revisit frequency diminishes detection capabilities for rapid and sporadic illegal activities. Therefore, strengthening the national satellite system is imperative through enhanced remote sensing payload capacity and strategic collaboration with commercial or international satellites to ensure comprehensive maritime domain awareness (Zucchetta et al., 2025).

The limited coverage of national satellites and the existence of AIS blank spots create significant vulnerabilities for the emergence of ghost ships – vessels that remain undetected by either disabling their AIS transponders or deliberately concealing their true identify through ship spoofing techniques. This method enables perpetrators to transmit false data regarding location, vessel identity, or speed, thereby creating confusion within maritime monitoring systems (Beseng & Malcolm, 2021). These vessels are frequently employed for illegal activities such as drug smuggling, human trafficking, and illegal fishing, yet remain ectremely difficult to detect using conventional sutveillance systems. These technical challenges demonstrate the critical need to adopt artificial intelligence-based detection systems and multi-sensor integration to cross-reference AIS data with satellite imagery, maritime radar, and other electromagnetic signals to identify anomalous patterns. Consequently, the ghost ship phenomenon demands a far more sophisticated, cross-platform technological response.

The threats posed by ghost ships and ship spoofing techniques become increasingly challenging to address when compounded by structural issues such as overlapping jurisdictions among Indonesia's maritime agencies. The lack of synergy between institutions including the Indonesian Navy, the Indonesian Sea and Coast Guard (Bakamla), the Ministry of Marine Affairs and Fisheries (KKP), and Customs often leads to operational confusion in field implementation, particularly regarding responsibility allocation and emergency decision-making (Liu et al., 2024). These inefficiencies not only delay threat response times buat also create legal loopholes that maritime criminals may exploit. Without integrated command structures and clear coordination mechanisms supported by unified information systems, even advanced technologies like satellite detection and IAS cannot achieve optimal impact. Therefore, reforming maritime security governance structures is crucial to eliminate such jurisdictional overlaps.

Jurisdictional overlaps in maritime security governance not only create operational inefficiencies but also contribute to sluggish improvements in maritime infrastructure duality, particularly along strategic ALKI routes. Many supporting facilities–including feeder ports, navigation stations, coastal radar systems, and surveillance posts–remain structurally and fuctionally vulnerable. The developmental disiparity between western and eastern Indonesia has resulted in security weak points that not only increase navigational safety risks buat also serve as entry points for illegal activities (Diniz et al., 2024). Ports with limited capacity and navigation systems that lack full digital integration with updated spatial data significantly weaken vessel movement monitoring efficinecy, especially during critical periods. These infrastructure vulnerabilities underscore the necessity for a systemic approach to maritime facility modernization, incorporating interagency integration and advanced geospatial technologies.

The vulnerability of maritime infrastructure along the ALKI is further exacerbated by the absence of scenario-based tactical response simulation systems capable of testing and evaluating national maritime security preparedness against real-world threats. To date, relevant agencies such as the Indonesian Navy, the Indonesian Sea and Coast Guard

(Bakamla), and the Ministry of Marine Affairs and Fisheries (KKP) continue to rely on manual or periodically scheduled training exercies without real-time simulation support that could replicate dynamic threat scenarions, including dark vessel infiltration, cyberattacks onvagination systems, or maritime terrorism activities (Akpan et al., 2022). The lack of training systems utilizing actual spatial data and digital scenarios results in diminshed tactical response speed and precision, particularly in vulnerable border zones. Ths is particularly concerning given that technologies such as digital twins and artificial intelligence have proven effective in other nations for enhancing maritime security readiness through multi-dimentional threat scenario training.

The absence of real-time tactical simulation systems in ALKI security operations stems from historical and ongoing limitations in maritime data collection and integration. To enable rapid and precise response, maritime security systems must be equipped with the capability to simultaneously and continuously access both Automatic Identification System (AIS) and satellite imagery. While AIS provides real-time tracking of vessel positions, speeds, and identities, optical and Synthetic Aperture Radar (SAR) satellite imagery offers spatial visualization of maritime objects, including non-cooperative vessels with disabled transponders (Bolbot et al., 2022). However, data acquistion methods frequently ancounter technical challenges such as transmission delays, limited spatial resolution, or restricted access to high-frequency imagery. Consequently, the development of a national maritime data architecture capable of dynamically integrating historical and real-time data becomes imperative.

In developing a robust and adaptive maritime surveillance system for ALKI security threats, the mere collection of AIS data and satellite imagery proves insufficient wihout effective spatiotemporal data fusion. Data fusion refres to the technical process of integrating information from multiple sources–including vessel location data from AIS, SAR or optical satellite imagery, and temporal metadat from each observation–to generate a more comprehensive and reliable representation (Yilmaz et al., 2022). This spatiotemporal integration enables surveillance systems to detect abnormal vessel movements, identify suspicious trajectory patterns, and predict high risk areas for maritime law violations. Wihtout proper data fusion, analyses remain fragmented and vulnerable to misinformation or delayed responses. Within the context of Indonesia's vast and complex maritime territory, data fusion, emerges as a vital component for supporting both real-time tactical decisions and long-term strategic planning (Shi et al., 2024).

Effective spatiotemporal data fusion paves the way for advanced spatial analysis implementation, particularly in detecting vessel movement anomalies as early indicators of potential violations in ALKI waters. By integrating positional, temporal, and navigational behavior data from AIS and satellite imagery sources, the system can establish normalized shipping pattern models to identify deviations from established patterns. Anomalies such as zigzagging vessels, sudden dtops in restricted areas, or unusual route traversals at atypical times may signal illicit activities including illegal fishing or smuggling operations (Shao et al., 2024). This anomlay detection technique employs statistical approaches, machine learning, and rule-based spatial modeling, methodologies that have demonstrated efficacy in advanced maritime security systems. Spatial analysis not only enhances detection accuracy but also significantly reduces response times to maritime incidents.

The outcomes of spatial anomaly detection analysis serve not only as crucial early indicators of violations but also as foundational elements for developing more accurate and threat-based maritime response simulations and evaluations. Operational simulations enable comprehensive testing of maritime surveillance and response systems under dynamic scenarios, such as suspicious vessel movements in high-risk zones or ghost ship intrusions into strategic ALKI areas. This approach facilities measurable improvements in the response capabilities of naval and aerial patrol units – particularly those of the Indonesia Navy (TNI AL) and related agencies – across three critical dimensions: response speed, coordination effectiveness, and operational efficiency. The evaluation of such spatiotmeporal data-driven simulations proves essential for identifying procedural or technical gaps, while thoroughly assessing interagency system interoperability.

Implementation of scenario-based simulation systems has demonstrated significant enhancements in maritime preparedness and supports the development of adaptive Standard Operating Procedures (SOPs) (Yang et al., 2022).

Following developmental and simulating testing, the crucial subsequent phase involves model validation and field testing to verify the actual effectiveness of the integrated maritime surveillance system under real-world conditions. This validation process entails direct system deployment in ALKI regions with actual threat characteristics, including high-traffics zones, smuggling-prone areas, and AIS blank spot regions. Futhermore, the field testing serves as a paltform to assess interagency providing a foundation for future system refinements (Li et al., 2024). This approach aligns with global maritime defense system validation practices that emphasize real-time data-driven proof-of-concept testing under actual operational conditions.

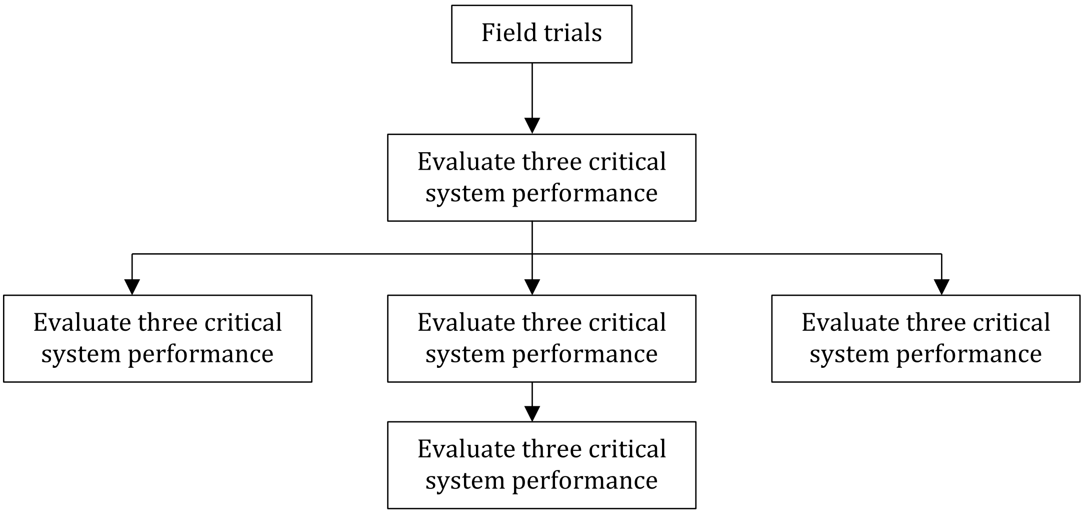

Fig. 2. Field trials performance metrics
(Li et al., 2024)

Based on field validation results, the development of a geospatial surveillance system architecture serves as the foundational framework for establishing an integrated and adaptive maritime security solution. This architecture incorporates multiple tchnological components – including the Automatic Identification System (AIS), remote sensing (RS), Naval Response Systems, and Geographic Information Systems (GIS) – within a unified, geospatially-based interoplerable framework. The integration enables real-time data acquisition, early threat detection, and responsive spatial mapping of security violations in ALKI waters. The system design encompasses; (1) data streams from satellites and IAS transponders, (2) anomaly processing rhtough artificial intelligence algorithms, and (3) direct alert dissemination to naval and aerial patrol units. This structure not only enhances maritime domain awareness but also optimizes naval defense resources through predictive and spatial approaches (Zhao et al., 2022). Such system designs have been successfully implemented in critical maritime zones across Southeast Asia and the Indo-Pacific region.

As a critical component of the geospatial surveillance system architecture, the capability to detect and predict suspicious vessel movements serves as a key feature enhancing technology-based maritime security. By leveraging historical AIS data, satellite imagery, and GIS spatial elements, the system implements machine learning algorithms – including random forest, support vector machines (SVM), and deep neural netwoks – to recognize normal navigation patterns and identify potentially suspicious deviations. This approach enables early detection of vessels performing unusual maneuvers, making sudden stops in strategic waters, or engaging in identify spoofing. Furthermore, predictive models can estimate likely vessel routes based on historical behavior, allowing patrol units to coordinate more efficient and proactive responses (Yang et al., 2024). Recent studies demonstrate that such AI-based prediction enhances surveillance effectiveness by up to 40% in high-risk violation zones.

Once the surveillance system achieves accurate detection and prediction of suspicious vessel movements, the subsequent phase in maritime security architecture involves dynamic patrol route optimization and fleet allocation. By utilizing outputs from spatial and predictive analyses, naval and aerial patrol routes can be designed to maximize coverage of high-risk areas while minimizing response times. Optimization algorithms such as genetic algorithms and vehicle routing problems (VRP) are customized according to threat patterns, vessel speeds, and complex marine topography. Research demonstrates that this approach can improve patrol efficiency by up to 35% in terms of fuel consumption and operational time (Ji et al., 2021). Furthermore, historical data from previous violations facilitates yhat desigin of high-priority zones for warship and reconnaissance aircraft deployment, thereby enhancing military preparedness and presence at critical points along the ALKI waters.

The optimization of patrol routes and fleet allocation based on spatial alaysis and threat prediction requires a reliable and responsive decision support system. In this context, an artifical intelligence-based Real-Time Decision Support System (DSS) serves as a critical component of modern maritime surveillance architecture. This DSS is designed as an interactive dashboard that visually and analytically integrets data froma AIS, satellite imagery, remote sensing, and military command systems. By employing machine learning algorithms, the system provides real-time tactical recommendations, including fleet redirection, early warnings, or response escalation to detected threats (Arifin et al., 2024). The system's key advantage lies in its ability to transform complex spatial data into actionable information with speed and precision, thereby significantly enhancing the effcetiveness of operational decision-making in the field.

The implementation of a Real-Time Decision Support System (DSS) in maritime surveillance yields not only operational impacts buat also establishes a critical foundation for formulating national maritime surveillance policies. The spatial analysis results, technology integration, and threat simulations derived from this system serve as an evidence-based foundation for developing more adaptive, responsive, and data-driven ALKI security regulations and strategies. The Indonesian government, through institutions such as the Coordinating Ministy for Maritime Affairs and Investment, yhe Indonesian Navy, and the Indonesian Sea and Coast Guard, can utilize these research outcomes to develop cross-sectoral policies that enhance interagency interoperability, strategic budget allocation, and maritime technology infrastructure development. This study emohasizes the crucial role of geospatial approaches in formulating risk-based maritime security policies that address actual threats, aligning with international best practices for building comprehensive national domain awareness.

Regional and multilateral collaboration contitutes a crucial element in enhancing the effectiveness of cross-border maritime surveillance, particularly in strategic areas such as the ALKI which are traversed by vessels from various nations. In the context, real-time data sharing between Indonesia and neighboring countris including Singapore, Malaysia, and Australia is essential for establishing shared situational awareness and accelerating responses to maritime threats. A proven mechanism in this regard is the Information Fusion Centre (IFC) based in Changi, Singapre, which facilitates multilateral exchange of AIS data, intelligence, and suspicious activity reports. Indonesia's active participation in the IFC and other regional forums such as ReCAAP and IORA enables the integration of national systems into broader international cooperation frameworks, thereby expanding collective maritime security (Puspitawati, 2018). Consquently, national geospatial surveillance systems must be designed with cross-border collaborative compability to ensure maximum operational effectiveness.

The successful implementation of an integrated maritime surveillance system deoends not only on advanced technology but equally on human resource preparedness. In this context, technical training and capacity building for geospatial operators and analysts at key institutions such as the Indonesian Navy, the Indoensian Sea and Coast Guard, and the Geospatial Information Agency/*Badan Informasi Geospasial* (BIG) are critically important.

Give the systems's complexity–encompassing AIS data fusion, remote sensing, rapid response systems, and spatial analysis – personnel msut demonstrate cimpetencies in geospatial data interpretation, GIS-based system management, and data-driven decision making. The lack or standardized training and competency frameworks in the maritime sector often hinders system optimization (Liu et al., 2020). Therefore, sustainable caapcity building and certified training programs must become integral components of intelligent technology-based maritime security policies.

Robust geospatial-based maritime security holds significance not only for defense and sovereignty but also generates substantial socio-economic benefits for coastal communities and traditional fishers. Enhanced maritime stability and legal certainty achieved throughadvanced, precision surveillance systems provide greater protection for coastal economic activities against disruptions such as illegal fishing, piracy, and smuggling. This directly contributes to increased fisher incomes, marine resource sustainability, and more favorable investment climates in the maritime sector. Effective maritime security creates a safe marine space for blue economy development, encompassing fisheries, maritime transport, and ecotourism (Chen & Shih, 2021). The integration of technology into maritime security systems serves as a catalyst for inclusive and sustainable maritime economic development.

In the implementation of geospatial-based maritime surveillance systems, ethical considerations and privacy concerns emerge as a critical issues that cannot be overlooked, particularly regarding data collection and utilization from the Automatic IdentificationSystem (AIS) and remote sensing technologies. While both technologies are crucial for enhancing domain awareness and maritime security, their data usage raises legal and ethical questions concerning merchant vessel privacy rights and the risk of strategic data breaches. Under international law, the IMO SOLAS Convention mandates vessels to activate AIS for navigational safety, yet does not explicity regulate third-party data usage limitations, furthermore, real-time collected data carries potential for misuse by non-state actors, including cybercriminals or parties seeking to exploit sensitive sea lanes. Consequently, system development must incorporate stringent data protection policies and transparent information usage audit mechanisms.

4. Conclusions

As a strategic archipelagic state, Indonesia plays a vital role in the global maritime trade and security system through its Indonesian Archipelagic Sea Lanes (ALKI). However, this position also renders the country vulnerable to various transnational maritime threats, including illegal fishing, smuggling, human trafficking, and potential maritime terrorism. These complex security challenges are further exacerbated by inadequate surveillance infrastructure, uneven technological distribution, and poor inter-agency coordination among maritime law enforcement institutions. The ALKI framework itself represents Indonesia;s strategic policy to maintain its maritime sovereign while fulfilling its obligation as an archipelagic state under UNCLOS 1982. Consequently, there is an urgent need for an adaptive, integrated, and technology-driven maritime surveillance system as a priority measure to address these increasingly complex maritime security challenges.

This study underscores the critical importance of developing a Geospatial Intelligence (GEOINT)-based maritime surveillance system to enhance monitoring effectiveness and law enforecement in strategic sea lanes such as the Indonesian Archipelagic Sea Lanes (ALKI). The system integrates multiple resources including the Automatic Identification System (AIS), remote sensing technologies (satellite imagery and SAR radar), and Geographic Information Systems (GIS), combined with rapid response elements such as naval vessels and reconnaissance aircraft operated by the Indonesian Navy. This technological integration enables real-time detection of shipping anomalies, monitoring of non-cooperative or dark vessels, and facilities swift, precise operational decision-making. Furthermore, the enhancement of artificial intelligence-based Command, Control, and Communications (C3) systems accelerates responses to maritime threats with high efficiency. However, significant challenges persist, including low inter-agency interoperability, overlapping jurisdictions, and infrastructure limitations such as insufficient coastal radar systems and border surveillance posts.

Issues such as AIS blind spots, inadequate cross-sensor data integration, and suboptimal utilization of AI for detecting and predicting suspicious shipping patterns create vulnerabilities that enable illegal activities, including spoofing techniques employed by ghost vessels. Consequently, a comprehensive approach is required through: (1) AI-based multi-sensor technology integration, (2) spatiotemporal data fusion, (3) enhancement of national satellite capabilities, and (4) governance reform to clarifiy inter-agency command and coordination systems. This strategy must be further supported by developing scenario-based tactical response simulation systems and equitable infrastructure modernization, particularly in high-risk areas.

The integrated system design not only enhances maritime domain awareness but also establishes the foundation for a predictive and responsive maritime security framework. This surveillance system architecture encompasses; (1) data streams froma AIS and satellite sources, (2) processing through machine learning algorithms including random forest and deep neural networks, and (3) tactical laert dissemination to patrol units. The optimization of patrol routes and fleet allocation based on spatial analysis outputs and predictive models further enhances operational efficiency. The implementation of an IA-powered Real-Time Decision Support System (DSS) significantly strengthens field operational decision-making by transforming complex data into actionable intelligence.

The implementation of this maritime surveillance system has far-reaching impacts, extending beyond national defense and security aspects to establish a foundation for- data-driven maritime policy formulation. Beyonf strengthening Indonesia's strategic position in ASEAN regional maritime security cooperation, the system is also compatible for development within multilateral frameworks such as Singapore's Information Fusion Centre (IFC), ReCAAP, and IORA. This presents significant opportunities for cross-border data integration tobuild collective situational awareness and accelerate responses to transnational maritime threats. However, the system's success depends on the availability of competent human resources. Technical training and capacity building for key institutions including the Indonesian Navy, the Indonesian Sea and Coast Guard (Bakamla), and the Geospatial Information Agency (BIG) have become urgent priorities, given the system's operational complexity involving data fusion, spatial interpretation, and data-driven decision-making processes.

Furthermore, ethical considerations and privacy protection must be given serious attention, particularly regarding the collection and utilizationa of AIS and remote sensing data, which could potentially be missued without stringent oversight. In the long erm, this geospatial-based maritime surveillance system will serve as a key catalyst for inclusive and sustainable blue economy development. By enhancing maritime stability and legal certainty, the system safeguards coastal communities' economic activities from disruptions while fostering a more conducive investment climate in the marine sector. This system not only functions as a national defense shield buat also establihses a robust foundation for creating a secure, intelligent, responsive, and globally competitive Indonesian maritime domain.

Acknowlegdment

The author would like to express their gratitude to the honorable Marsda TNI (Purn.) Prof. Dr. Ir. A. Adang Supriyadi, S.T., M.M., IPU., ASEAN Eng. for their support and guidance.

Author Contribution

The author contributed fully to the research.

Funding

This research did not receive funding from anywhere.

Ethical Review Board Statement
Not available.

Informed Consent Statement
Not available.

Data Availability Statement
The data supporting the findings of this study are available in the bibliography with links provided.

Conflicts of Interest
The author declare no conflict of interest.

Open Access

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