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Remote sensing and AIS integration for strategic maritime surveillance: A geoint-based approach to securing Indonesia's Archipelagic Sea Lanes

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ABSTRACT

Background: Indonesia's strategic position within the Indo-Pacific maritime domain underscores its critical role in global trade and regional security. The Indonesian Archipelagic Sea Lanes (*ALKI*), although regulated under UNCLOS, remain vulnerable to transnational threats such as illegal fishing, smuggling, and terrorism. Infrastructure limitations and fragmented inter-agency coordination weaken surveillance capacity, thereby necessitating a geospatial intelligence-based framework that integrates advanced technologies to strengthen Maritime Domain Awareness (MDA). **Methods**: This study employs a descriptive qualitative approach supported by systematic literature review. Academic sources include Scopus-indexed journals (Q1–Q2), national policy documents, and international reports focusing on GEOINT, remote sensing, and maritime threat detection. The analysis is grounded in GEOINT and MDA theories, synthesizing AIS data, satellite imagery (SAR/optical), and naval response capabilities into a conceptual surveillance model for *ALKI* zones. **Findings:** Integrating AIS, satellite remote sensing, and rapid naval response significantly enhances detection of dark vessels, spoofing tactics, and unauthorized maritime activities. The effectiveness of the system depends on cross-agency data interoperability, robust satellite infrastructure, and spatially-adaptive response strategies. This framework contributes to predictive operational readiness and informs policy reforms for Indonesia's maritime security architecture. **Conclusion**: This study emphasizing developing a high-tech *ALKI* surveillance system grounded in integrated data and rapid response represents far more than a sectoral policy not only for mitigating current threats but also for preparing the nation to confront the more complex, multi-dimensional maritime challenges of the future. **Novelty/Originality of this article:** Integrating the Automatic Identification System (AIS), remote sensing technologies, and naval rapid response mechanisms to enhance surveillance across Indonesia's Archipelagic Sea Lanes (*ALKI*). This study highlights the strategic use of geospatial technologies in addressing surveillance blind spots and mitigating potential sovereignty violations along the nation's critical maritime corridors.

KEYWORDS: Archipelagic Sea Lanes (*ALKI*); geospatial-driven; global maritime fulcrum; maritime border security.

1. Introduction

Indonesia holds a strategically vital position in global maritime trade and transportation. Geographically situated at the crossroads of the Pacific and Indian Oceans, the nation possesses vast maritime resources. This establishes Indonesia as a global

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maritime axis while simultaneously presenting increasingly complex challenges in its maritime domain (Puspitawati, 2018). As the world's largest archipelagic state with more than 17,000 islands, Indonesia possesses three international trade routes known as the Indonesian Archipelagic Sea Lanes/*Alur Laut Kepulauan Indonesia* (*ALKI*). However, Indonesia's dispersed geography, limited surveillance infrastructure, and the vast coverage area render the monitoring of *ALKI* highly challenging (Octavian & Jatmiko, 2020).

Data from the Marine Security Agency and Indonesian Navy (*TNI AL*) indicate that territorial violations by foreign vessels including those deactivating AIS (Automatic Identification System) upon entering Indonesian waters remain frequent, particularly in strategic zones like the Makassar Strait and Natuna Sea (Arifin et al., 2024). These incidents are exacerbated by limited conventional radar coverage and insufficient integration between patrol systems and command centers. Consequently, traditional *ALKI* surveillance relying on conventional patrols is no longer adequate for securing maritime territories. Recent technological advancements such as : AIS, remote sensing, and Artificial Intelligence (AI) offer significant opportunities to develop adaptive, real-time maritime monitoring systems. Nations like India, South Korea, and the U.S. have integrated these technologies into their naval defense systems to substantially enhance Maritime Domain Awareness (MDA) (Kim, 2024). Geospatial technology plays a central role in improving maritime surveillance efficacy. Remote sensing data from satellite imagery to airborne radar can address blind spots in maritime radar coverage. Research by Avtar et al. (2021) demonstrates that combining AIS with multispectral satellite imagery can detect illegal activities in Exclusive Economic Zones (EEZs), even when vessels disable AIS transponders. Real-time AIS integration enables vessel tracking by identity, direction, and speed. However, AIS limitations exist, as ships may intentionally deactivate systems. Here, remote sensing becomes vital: high-resolution satellites (e.g., Sentinel-1, PlanetScope) and High-Altitude Pseudo-Satellites (HAPS) can visually and thermally track "unidentified" vessels (Yusdian et al., 2023). Additionally, Vessel Traffic Services (VTS) and big data analytics can unify marine sensors, coastal radar, AIS, and satellite data into an integrated platform, enabling decision support systems for maritime patrols (Li et al., 2023).

Current *ALKI* surveillance involves multiple entities including *TNI AL, Bakamla* (Maritime Security Agency), MMAF (Ministry of Marine Affairs and Fisheries), and sea police often lacking unified communication systems, leading to interagency coordination deficits (Saadia et al., 2022). Rudolph et al. (2023) note that while AIS and satellite data effectively record maritime violations, without rapid response systems, such data become meaningless archives rather than law enforcement solutions. Establishing a maritime surveillance roadmap is thus critical for achieving security and sovereignty objectives. This roadmap comprises three phases: (1) Phase 1: Identifying vulnerable "blind spot" areas in Indonesian waters, (2) Phase 2: Developing cross-sectoral command and coordination centers, (3) Phase 3: Integrating weather data and fostering global maritime cooperation. These phases collectively enable information integration, rapid decision-making, and tactical responses to national threats.

Phase 1 focuses on analyzing vulnerable blind spots, exemplified by the Sunda Strait one of Indonesia's busiest international shipping lanes. As part of *ALKI*-1 (Malacca-Sunda route), this strait experiences frequent maritime violations, including theft, smuggling, and unidentified foreign vessels. Notable incidents include the 2016 smuggling of 54 kg of methamphetamine and 40,000 ecstasy pills, and the 2017 seizure of 1 ton of methamphetamine in Tanjung Berakit, Riau Islands (Rachmad et al., 2021). Historically, British warships (HMS Victorious and two destroyers) traversed the Sunda Strait without authorization in a 1964 "Show of Force." Illegal fishing activities further threaten national interests (Rachmad et al., 2021). Pervasive violations in the Sunda Strait reflect weaknesses in Indonesia's early detection and law enforcement systems. Purnama et al. (2024) identify key challenges: lax enforcement causing noncompliance with VTS directives; inadequate sailor education on Traffic Separation Schemes (TSS) leading to navigation errors; limited VHF radio range and volatile weather hindering communication/safety; and low vessel compliance with VTS instructions.

Phase 2 entails establishing a national maritime command center incorporating all *ALKI*-related agencies: *TNI AL, Bakamla*, Water Police (*Ditpolair*), Merak VTS Station, and relevant security entities. This center aims to enhance integrated communication and operational synchronization, streamlining coordination and synergizing existing maritime resources (Rachmad et al., 2021). Indonesia's *ALKI*-II command integration already incorporates risk management and resource optimization, involving military, naval police, and port authorities (Hidayat et al., 2024). This structure addresses evolving national dynamics notably the capital's relocation to East Kalimantan requiring robust command frameworks and clear maritime doctrine for rapid incident response. Success hinges on multi-agency collaboration spanning physical, technical, and dynamic dimensions.

Phase 3 leverages technology and policy for early detection of maritime weather conditions critical given weather's impact on shipping routes. Maritime weather data (e.g., sea winds, humidity, monsoon patterns) influence coastal pollution dispersion, affecting international shipping. AIS data can assess air quality impacts on coastal communities (Ma et al., 2024). Globally, shared weather data monitors transboundary pollution from international shipping, mitigating vessel emissions' environmental impact. Such cooperation can be facilitated through the International Maritime Organization (IMO). Quantifying weather exposure is essential for maritime mitigation policies (Ma et al., 2020), utilizing approaches like remote sensing inversion interpolation and Land Use Regression (LUR) modeling (Li et al., 2023). Integrated big data analytics can strengthen *ALKI* command centers through real-time multisensor data processing (Li et al., 2023). Within Southeast Asia's geopolitical and maritime security dynamics, Indonesia faces significant challenges in managing its vast, strategic waters particularly along the *ALKI* corridors. As the world's largest archipelagic state and a global trade nexus, Indonesia must ensure navigational safety and enforce territorial sovereignty. Its complex geography thousands of islands and narrow straits renders conventional surveillance inadequate against modern threats like smuggling, illegal fishing, and territorial breaches by foreign vessels. Limitations in traditional monitoring systems necessitate technology-driven transformation and interagency coordination.

Geopolitical rivalry in the Indo-Pacific region has become increasingly dynamic, characterized by competing state strategies aimed at counterbalancing one another. Several key actors are directly involved in this competition. China, through its Belt and Road Initiative (BRI), advances both the overland Silk Road Economic Belt—connecting China with Central Asia, Russia, the Middle East, and Europe—and the maritime 21st Century Maritime Silk Road, which links Chinese ports with Southeast Asia, South Asia, the Middle East, and Europe (Blanchard, 2018; Flint & Zhu, 2019). This infrastructure development is designed to strengthen regional and global trade relations while simultaneously enhancing China's influence in East and Southeast Asia, thereby intensifying its geopolitical rivalry with the United States (Yu, 2020).

In contrast, the United States has pursued the Free and Open Indo-Pacific (FOIP) strategy in collaboration with Japan, Australia, and India—an initiative frequently associated with the Quadrilateral Security Dialogue (QUAD). QUAD was initially launched in 2007 by Japanese Prime Minister Shinzo Abe but was suspended after Australia's withdrawal under Prime Minister Kevin Rudd. It was later revived at the ASEAN Summit in Manila in November 2017, largely in response to China's growing influence in the Indo-Pacific (White House, 2017). Beyond maintaining regional stability, the initiative seeks to safeguard freedom of navigation and overflight in international waters, promote free and fair trade, and reinforce international law, particularly the United Nations Convention on the Law of the Sea (UNCLOS) 1982 (Roy et al., 2018). In September 2021, Australia announced a new trilateral security pact with the United Kingdom and the United States, known as AUKUS (Prime Minister of Australia, 2021). This agreement, however, was met with strong opposition from several states, most notably China, which condemned AUKUS as an irresponsible arrangement involving nuclear elements that threatens regional peace and stability (CNN Indonesia, 2021). While China views AUKUS as destabilizing, many Indo-Pacific states have also expressed concern over China's increasingly assertive behavior in the South China Sea (SCS). Such actions include direct confrontations with other claimant states such as the Philippines, violations of Indonesia's maritime boundaries through the so-called "nine-dash line" claims, and the strategic placement of Chinese and U.S. military bases across the region, as shown in Figure 1 .

Fig. 1. Locations and network of Chinese and U.S. military bases in the Indo-Pacific Region (Goodman, 2017; Delanova, 2021).

This study thus highlights the urgency of integrating modern technologies to establish a responsive, adaptive, and comprehensive *ALKI* surveillance model. The framework synergizes three core components: (1) AIS: Critical for real-time vessel detection and tracking (identity/position/speed/direction), though limited by intentional transponder deactivation, (2) Remote sensing: Optical/radar-based systems (e.g., SAR satellites) identify maritime objects despite weather/night conditions, covering AIS blind spots, (3) Rapid naval response: *TNI AL* and *Bakamla* patrol units. AI-driven spatial analysis of integrated AIS/remote sensing data enables proactive anomaly detection and movement pattern prediction, guiding targeted patrol deployment for routine surveillance or strategic intervention. This tripartite approach significantly enhances *ALKI* surveillance efficacy while preventing maritime violations, safeguarding national sovereignty, and advancing Indonesia's vision as a Global Maritime Fulcrum. This integrated model reflects Indonesia's paradigm shift toward data-driven, technology-based, and cross-sectoral maritime governance.

2. Methods

This study employs a descriptive qualitative approach through literature review and document analysis to develop a conceptual framework for maritime security in the Indo-Pacific region. The literature search used keyword such as "geospatial maritim"; "Indonesian Archipelagic Sea Lanes (*ALKI*)", "remote sensing"; "Automatic Identification

System (AIS)", "maritim security", "maritim policy", IPMDA (Indo-Pacific Partnership for Maritime Domain Awareness), and artificial intelligence (AI) based maritime security system. The primary literature sources in this study Scopus-indexed international journals ranked Q1 and Q2 and addition 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 (KKP), Coordinating Ministry for Maritime Affairs and Investement (Kemenko Marves), and Indonesian Sea and Coast Guard (*Bakamla*). To strengthen the validity of the conceptual framework, this study integrates secondary data and case examples of transnational maritime incidents in the Indonesian Archipelagic Sea Lanes (*ALKI*), including illegal fishing, smuggling, and maritime terrorism during the period 2015–2024. The analysis focuses on identifying patterns, trends, and their implications for Indo-Pacific geopolitical dynamics. The aim is to understand and explore the conceptual integration of geospatial technologies in developing a resilient maritime security system. Accordingly, this study employs a strategic framework designed to enhance sovereignty protection across Indonesia's critical maritime corridors.

3. Results and Discussion

3.1 Indonesia as the global maritime fulcrum

Indonesia's identity as a maritime nation has been recognized since the eras of the Srivijaya and Majapahit kingdoms. However, during the New Order period, the government's focus shifted somewhat towards terrestrial development. Subsequently, in 2014, President Joko Widodo declared the vision of Indonesia as the Global Maritime Fulcrum (Ramadhani et al., 2025). This vision represents a national strategic policy aimed at restoring the archipelago's maritime glory as a global sea-lane hub and a regional maritime power. According to Effendi (2025), this vision constitutes a revitalization of Indonesia's long-marginalized maritime identity, resulting from a land-based development paradigm persisting from the colonial era through the New Order period. President Joko Widodo initiated this concept in 2014 through five key pillars: (1) revitalization of maritime culture, (2) sustainable marine resource management, (3) development of connectivity infrastructure, (4) maritime diplomacy, and (5) enhancement of maritime defense. This vision aligns with Alfred Thayer Mahan's sea power theory, which asserts that command of the sea determines national prosperity. Indonesia fulfills five of Mahan's six prerequisites: geographical position, coastal configuration, territorial extent, population size, and national character with the exception of consistent government policy (Padillah et al., 2024).

The first pillar, revitalization of maritime culture, involves maritime heritage education, traditional festivals, and preservation of the UNESCO recognized Pinisi ships. Mandar's study (2025) found that this strategy includes public education through *sandeq* boat-making, festivals, and underwater heritage conservation. Its objectives extend beyond enhancing cultural awareness to strengthening community-based maritime defense. The second pillar, sustainable marine resource management, aims to demonstrate the synergy between policy, infrastructure, and defense in advancing the sustainable maritime sector and promoting responsible ocean governance (Pandjaitan et al., 2025). The third pillar, development of connectivity infrastructure, has been realized through the concrete policy of the Sea Toll program. This initiative establishes a regular inter-island shipping network to reduce price disparities, improve logistics, and enhance connectivity to remote regions. Research by Hatta et al. (2020) indicates that Sea Toll development in the Makassar Strait can increase efficiency in sustainable fisheries resource management. This maritime development program has the potential to raise district revenues by approximately Rp 5 to 28 billion per month over 120 months across 11 regencies/cities along the Makassar Strait coast. Although facing challenges such as backhaul underutilization – with Route T-4 studies recommending targeted subsidies, port facility improvements, and partnerships with pioneer shipping lines – the project can still be considered successful in its societal implementation.

The fourth pillar, maritime diplomacy, serves as a cornerstone for Indonesia's active participation in international forums such as IORA, ASEAN, UNCLOS, and G20 cooperation. This diplomatic policy is credited with advancing maritime security, connectivity, resource management, and culture; facilitating trilateral patrols (Indomalphi); and promoting the South China Sea Code of Conduct for peaceful Exclusive Economic Zone (EEZ) boundary resolution (Pandjaitan et al., 2025). The fifth pillar, maritime security enhancement, is prioritized through *BAKAMLA* (Indonesian Coast Guard)-USCG cooperation, joint patrols, trilateral patrols, and empowering maritime communities for surveillance roles. Strengthening traditional maritime culture has reduced maritime violations by 55% and increased community participation by 65% (Aurelia, 2025). Achieving Indonesia's vision as a Global Maritime Fulcrum necessitates improved inter-agency coordination, as significant challenges remain in areas including maritime human resource development and regulatory frameworks that promote cross-sectoral maritime policy integration. Initiated in 2014, the Global Maritime Fulcrum vision represents a transformational policy rooted in history and Mahan's sea-power theory. Its five strategic pillars (culture, resources, connectivity, diplomacy, defense) must be mutually reinforcing and synergistic. Implementation has demonstrably yielded concrete positive effects, such as reduced staple goods prices and increased coastal regional revenues. Nevertheless, realizing this vision continues to face challenges related to institutional coordination, human resources, technology, regulation, and maritime security.

3.2 Indonesia’s Archipelagic Sea Lanes (ALKI)

Indonesia’s Archipelagic Sea Lanes (*ALKI*) constitute the designated passage routes that international vessels must follow when traversing Indonesian waters without infringing upon state sovereignty. The right to designate ALKI is enshrined in the United Nations Convention on the Law of the Sea (UNCLOS 1982). In Figure 2. showed the three primary *ALKI* routes are: (1) A*LKI* I: South China Sea – Karimata Strait – Java Sea – Sunda Strait, (2) *ALKI* II: Sulawesi Sea – Makassar Strait – Flores Sea – Lombok Strait, (3) *ALKI* III: Pacific Ocean – Maluku Sea – Seram Sea – Banda Sea – Sawu Sea

ALKI I serves as the principal shipping corridor connecting the South China Sea via the Natuna Sea, Karimata Strait, Java Sea, and Sunda Strait, terminating in the Indian Ocean. This route holds significant strategic importance, as the South China Sea periphery is an exceptionally busy global corridor. International Maritime Organization (IMO) data indicates that approximately 31% of global trade volume transits this route. The Karimata Strait functions as a vital transit point between Indonesia's western and eastern coasts, with an estimated 60% of transiting vessels being foreign-flagged and generating around 70% extra-regional economic interaction. The foremost challenges confronting *ALKI* I are strong currents and volcanic hazards posed by the Anak Krakatau eruption potential in the Sunda Strait (Monika et al., 2020).

ALKI II links the Sulawesi Sea through the Makassar Strait, Flores Sea, and Lombok Strait to the Indian Ocean. It provides an alternative logistical and economic corridor from Sulawesi and Eastern Indonesia to Southeast Asian, African, and Australian markets. While the Sulawesi region possesses strong potential as a logistics hub, current infrastructure remains inadequate, characterized by limited port access and minimal cold storage facilities. The Makassar Strait (within *ALKI* II) is notably identified as a strategic choke point connecting South China Sea routes with Australia and the Indian Ocean (Muhdar et al., 2022). This renders the *ALKI* II zone highly strategic yet vulnerable to geopolitical tensions. Despite its open-access status, *ALKI* II faces numerous security threats, necessitating the application of remote sensing and artificial intelligence (specifically YOLO-SAR) to detect vessels operating illicitly without activating their Automatic Identification System (AIS) a tactic commonly employed by illegal fishing vessels or infiltrating foreign military ships (Hayati et al., 2025).

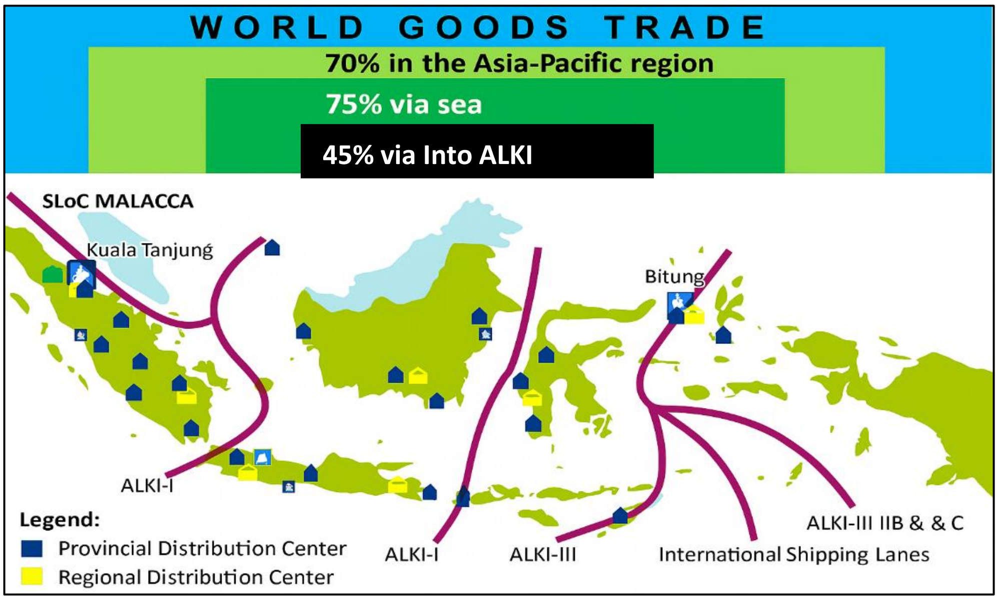

Fig. 2. Three point primary ALKI
(Indonesia Global Maritime Forum (n.d.))

A key geopolitical challenge stems from the unresolved maritime boundary disputes with Malaysia concerning Ambalat, Sipadan, and Ligitan. Consequently, an integrated approach involving relevant agencies (Indonesian Navy [TNI AL], National Police [Polri], Coast Guard [*BAKAMLA*], Ministry of Maritime Affairs and Fisheries [KKP]) through national maritime security forums and international cooperation (e.g., with Australia and the Philippines) is proposed as a multidimensional solution to address criminal threats and maritime security disparities (Hidayat, 2019). *ALKI* III comprises three main sub-routes: (a) *ALKI* III-A: Pacific Ocean via Maluku Sea – Seram Sea – Banda Sea – Ombai Strait – Sawu Sea, (b) *ALKI* III-B: Similar to III-A but diverges through the Leti Strait towards the Timor Sea, (c) *ALKI* III-C: Pacific Ocean via Maluku Sea – Seram Sea – Banda Sea – Arafura Sea, connecting the Indian and Pacific Ocean basins.

These routes serve as corridors between Asia-Pacific (including Japan, the Philippines, Australia) and Australia/the Pacific. Wave conditions in this zone are relatively moderate compared to open ocean conditions (with less than 5% probability of high waves during monsoon transitions), although the Banda Sea exhibits wave height potential reaching 70% during certain seasons. *ALKI* III is regarded as an area requiring special attention. Maximizing its potential necessitates coordinated development of hub ports (e.g., Ambon, Ternate, Sorong) and standardization of maritime navigation and communication systems supported by modern technology for enhanced security and surveillance. Proposals for pioneer routes like the Sulawesi Canal remain under discussion but are not yet prioritized due to tremendous geographical complexity and low international transit volumes. The designation of the *ALKI* system represents a strategic measure to protect international shipping and aviation activities, ensuring their continuity, speed, and efficiency (Nainggolan, 2015).

Collectively, the *ALKI* routes function as international transit corridors while simultaneously serving as crucial points for national defense (Supriyanto, 2018). This dual role positions *ALKI* as a vital instrument within Indonesia's maritime diplomacy. Through international forums such as IORA, IMO, and ADMM-Plus, Indonesia promotes the *ALKI* as zones of peace, nuclear-free status, and non-use for military maneuvers, aiming to counterbalance the hegemony of major powers like the US and China in the Indo-Pacific region (Dorigné-Thomson, 2023). *ALKI* constitutes a vital passage for 40–50% of global seaborne trade transiting Indonesian waters annually (Dorigné-Thomson, 2023). While many vessels transit without calling at Indonesian ports, Indonesia retains the obligation to safeguard maritime security and protect its waters from risks such as oil spills, pollution, or latent military conflicts. The respective roles of *ALKI* I, II, and III demonstrate that these routes transcend mere lines on a map; they hold strategic significance as determinants of national security, connectivity, and sovereignty. The exercise of the right of innocent passage must be carefully balanced with robust national maritime management policies. Maritime security strategies require adaptive, evidence-based approaches incorporating cutting-edge technology. Despite this, the challenges spanning technical and institutional dimensions remain complex. Numerous monitoring systems lack integration, and inter-agency coordination (involving *BAKAMLA, TNI AL, KKP*, and port authorities) remains suboptimal. A holistic and measurable approach is imperative to establish an *ALKI* Command Center. This center would enable real-time coordination of navigation, security, and maritime logistics, thereby enhancing coordination and establishing a rapid response system.

Study by Mantoro (2025) highlights several factors influencing shipping safety in the Indonesian Archipelagic Sea Lanes (*ALKI*), including hydro-oceanographic conditions, vessel traffic density, the availability of navigational aids, regulatory compliance, as well as the competence and readiness of ship crews. Hidayat et al. (2024) emphasize that shipping safety in *ALKI* must be aligned with its security level, noting that factors such as tactics and operational procedures, weapons and sensor capabilities, command-and-control effectiveness, training, and overall operational efficiency have a direct impact on the success of maritime security strategies in *ALKI* II. The deployment of patrol vessels to safeguard *ALKI* is therefore essential; however, the availability of Indonesian Navy (KRI – Republic of Indonesia Ships) assets and the readiness of supporting technologies, particularly communication systems, remain limited. Consequently, increased budget allocations are required for the procurement of defense equipment, the development of communication systems, and the strengthening of inter-agency cooperation (Wahyudi, 2024).

Opportunities for cooperation with countries in the Indo-Pacific region can be considered to enhance the safety of navigation and the security of the Indonesian Archipelagic Sea Lanes (*ALKI*). One potential partner is China, despite existing military tensions between China and Indonesia in the Natuna area. Nevertheless, both countries have agreed to jointly advance national development by continuing major projects in Indonesia, with the objective of expanding their economic interests in the Natuna Sea. Indonesia–China cooperation can also be seen as politically important to maintain the government's popularity while simultaneously leveraging natural resources desired by China.

In addition, cooperation with ASEAN and Russia is necessary to counterbalance China's military dominance, thereby reducing the risk of conflict in the maritime domain (Zou, 2023). Collaboration between Indonesia and India is also worth considering, as India is a member of the QUAD but pursues a somewhat different mission compared to its partners. India emphasizes building an international order based on pluralism and diversity among states (Sullivan de Estrada, 2023). This stance aligns closely with Indonesia's "free and active" foreign policy principle, which also rejects domination by any single power and positions both states as potential balancers in the regional order. If Indonesia–India cooperation can be further strengthened, the Indo-Pacific may be better safeguarded against open conflict and instead focus on advancing maritime domain awareness (MDA), search and rescue (SAR), anti-piracy efforts, and the protection of strategic sea lines of communication such as the Malacca Strait, the Natuna Sea, and the Indian Ocean.

3.3 Automatic Identification System (AIS)

The Automatic Identification System (AIS) is a radio frequency-based communication system designed to enhance maritime navigational safety by automatically providing vessel position, course, speed, and identity data. Introduced in the early 2000s and mandated by the International Maritime Organization (IMO) for vessels of certain sizes, AIS has become an essential component of Maritime Domain Awareness (MDA) systems and maritime surveillance. According to Harati-Mokhtari et al. (2007), AIS is a transponder system installed aboard vessels to automatically enhance navigational safety. Li et al. (2023) state that AIS serves as a tool for predicting vessel trajectories based on data used to identify abnormal ship behaviour, thereby mitigating maritime risks such as collisions, groundings, and loss of contact. Accurate vessel trajectory prediction can significantly improve maritime safety. AIS has evolved into a primary data source not only for navigation but also for maritime security, vessel traffic analysis, monitoring of maritime law violations, and research on global shipping pattern changes (Yang et al., 2024). AIS operates using Very High Frequency (VHF) bands, transmitting data in real-time between vessels and to shore stations. The two main types are Class A (used by large commercial vessels) and Class B (for smaller craft). Additionally, Satellite-AIS (S-AIS) enables vessel tracking in open waters beyond the coverage of radar or coastal stations (Zheng et al., 2023). The AIS broadcast system includes dynamic, static, and voyage-related information, which is critical for real-time situational awareness in congested sea lanes (Mao et al., 2018).

AIS has significantly enhanced vessels' ability to avoid collisions at sea, particularly in high-density areas like the Strait of Malacca. Gao et al. (2018) demonstrate that the AIS system reduced collision incidents by 40% following its implementation by providing vital information to Vessel Traffic Services (VTS). Zhang and Bateman (2017), in their research, applied machine learning to AIS data to identify vessels intentionally disabling their transponders ("dark ships"), a tactic commonly employed by maritime law violators. Tu et al. (2018) state that Satellite-AIS integration improves vessel detection capabilities to 97% in remote Exclusive Economic Zones (EEZs). Beseng and Malcolm (2021) utilized a combined approach of AIS and satellite imagery (SAR and optical imaging) in the Mediterranean Sea, successfully identifying 134 "dark" vessels within 10 days. The integration of Automatic Identification System (AIS) data and Synthetic Aperture Radar (SAR) imagery significantly enhances efforts to monitor maritime activities (Graziano & Moccia, 2019). Future applications of AIS will form part of the Maritime Internet of Things (MIoT) ecosystem. Within this framework, vessels will be equipped with smart sensors transmitting not only position data but also real-time information on weather, water temperature, engine conditions, and cargo load (Chen & Zheng, 2023).

3.4 Remote sensing

Remote Sensing (RS) is a method of gathering information about objects or areas on the Earth's surface without direct contact, typically employing satellites or airborne sensors. This technology has revolutionized Earth observation across environmental science, agriculture, oceanography, disaster mitigation, and urban planning (Zhu et al., 2022). Remote sensing relies on detecting reflected or emitted electromagnetic radiation from observed targets. Remote sensing systems are categorized as: (a) Passive: Relying on solar illumination (e.g., Landsat, Sentinel-2), (b) Active: Utilizing sensors that emit their own energy (e.g., RADAR, LiDAR, Synthetic Aperture Radar - SAR), (c) Remote Sensing has become a pivotal technology supporting Marine Spatial Planning (MSP) and Integrated Coastal Area Management (ICAM), particularly in archipelagic nations like Indonesia.

The quality of the imagery depends critically on spatial, spectral, radiometric, and temporal resolution (Ustin & Gamon, 2020). RS is widely employed in environmental monitoring; for instance, MODIS imagery is used to map land cover degradation in the Amazon resulting from agricultural expansion (Tang et al., 2020). In natural disaster monitoring, especially for early detection and mitigation, radar sensors (SAR) can detect ground displacement for earthquake monitoring, Sentinel-1 is utilized to identify flood inundation areas in near real-time, and thermal sensors from MODIS or VIIRS are deployed for fire hotspot and smoke emission detection to monitor wildfire events (Wang et al., 2022). Within the marine domain, ocean remote sensing is used to monitor Sea Surface Temperature (SST), identify phytoplankton blooms (chlorophyll-a concentration), and track coral reef health and oil spills. SAR sensors like Sentinel-1 enable vessel detection regardless of adverse weather conditions or nighttime. Zhu et al. (2022) successfully identified Illegal, Unreported, and Unregulated (IUU) fishing activities using machine learning algorithms applied to SAR and AIS data. Sentinel-3 data over the Pacific Ocean facilitates tracking of ocean currents and sediment distribution (Novelli, 2020). The integration of satellite imagery with AIS and AI models is increasingly being applied in maritime security systems and dynamic voyage planning.

Agarwal et al. (2025), in their research, demonstrated the use of remote sensing and AI/ML to support the blue economy in India, utilizing satellites such as Oceansat-3 and SWOT for identifying sustainable fishing zones, detecting oil spills and marine debris, and providing early warnings for hazardous ocean currents. Ouellette and Getinet (2016) state that remote sensing supports Integrated Coastal Area Management (ICAM) and Marine Spatial Planning (MSP) in European regions. In this context, the technology plays a critical role in monitoring coastal ecosystem health, Managing conflicts in marine spatial use, providing data for transboundary policy development in the Baltic and Mediterranean Seas

According to Ouellette and Getinet (2016), remote sensing provides a conceptual framework within Marine Spatial Planning (MSP) and Integrated Coastal Area Management (ICAM), comprising five main components emphasizing multidisciplinary and ecosystem-based approaches: (1) Ecosystem Health and Pollution: Aims for early detection of chlorophyll levels and oil spills using sensors like MODIS and Sentinel-3, (2) Coastal Hazards: Focuses on analyzing shoreline changes caused by natural processes (coastal erosion) or human activities (reclamation) utilizing Landsat-8 and Sentinel-2 sensors, (3) Marine Spatial Use Patterns: Tracks foreign or illegal vessel incursions into national waters by mapping vessel traffic routes through the integration of SAR sensors and AIS data, (4) Coastal Land Cover: Supports coastal land-use zoning and planning. Its primary objective is to establish sustainable, equitable, and evidence-based coastal governance, preventing sectoral overlap—particularly concerning fisheries, marine tourism, conservation, shipping, and other coastal/marine activities. Monitoring technologies include Sentinel-2 imagery and UAV (Unmanned Aerial Vehicle) imagery, (5) Population Dynamics: Refers to changes in the number, distribution, and characteristics of coastal populations over time. This concept is vital for marine spatial planning and coastal management due to its direct link to pressures on natural resources, land-use changes, and vulnerability to disasters.

Each component is linked to specific data acquisition objectives for monitoring, risk assessment and mitigation, and utilizes appropriate RS sensor types (optical, radar, hyperspectral). Despite the sophistication of remote sensing technology, significant challenges persist, including potential data overload and large storage requirements, temporal resolution limitations of passive satellites, and ethical concerns surrounding individual privacy, military applications, and the use of data for commercial purposes and surveillance. Consequently, there is a pressing need to evaluate and establish adaptive, suitable regulatory frameworks to safeguard the security interests of Indonesia's maritime domain.

3.4 Indonesian maritime security agency (bakamla)

The Indonesian Maritime Security Agency (*Badan Keamanan Laut Republik Indonesia - Bakamla*) was established under Law Number 32 of 2014 on Maritime Affairs to safeguard maritime sovereignty and security. *Bakamla* plays a crucial role in ensuring security, safety, and law enforcement within Indonesian jurisdictional waters. Its primary objectives are combating maritime violations such as illegal fishing, smuggling, human trafficking, and unauthorized incursions by foreign vessels. *Bakamla*'s formation represents a reform initiative addressing increasingly complex maritime security challenges in the era of globalization and digitalization. The agency reports directly to the President and is mandated to: (a) Conduct security and safety patrols within Indonesian waters and jurisdictions, (b) Formulate national maritime security policies, (c) Coordinate with other agencies, including the Indonesian Navy (*TNI AL*), Marine Police (Polair), Ministry of Maritime Affairs and Fisheries (*KKP*), Customs, and Immigration.

However, Dirhamsyah et al. (2022) note that jurisdictional overlaps between ministries/institutions persist, hindering operational effectiveness. A significant threat to

Indonesian sovereignty is Illegal, Unreported, and Unregulated (IUU) Fishing, which has triggered territorial conflicts, notably in the North Natuna Sea. These incidents serve as practical tests of *Bakamla*'s capacity to counter intrusions by foreign fishing and coast guard vessels, particularly from China and Vietnam (Putra, 2023; Kim, 2024). *Bakamla* also functions as an instrument of Indonesian maritime diplomacy. Cooperation with nations such as the United States, Japan, and Malaysia, particularly in Maritime Domain Awareness (MDA) and joint patrols, constitutes a vital element of its soft power approach (Kim, 2024; Lau, 2024).

Embracing digitalization, *Bakamla* has developed information systems like the Indonesia Maritime Information Center (IMIC), enabling real-time data and intelligence sharing. Komala and Purmanasari (2021) highlight this innovation, noting enhanced efficiency in maritime incident response. In recent years, *Bakamla* has been directly involved in apprehending foreign vessels in the North Natuna Sea. These incidents serve as benchmarks for Indonesia's tactical capacity and maritime diplomacy. Magunna (2024) observes that such operations signify *Bakamla*'s growing engagement at the regional geopolitical level. Future strengthening of *Bakamla* necessitates to fleet and surveillance technology modernization, enhanced harmonization with TNI AL and Polair, legal framework reinforcement to grant *Bakamla* full authority comparable to developed nations' coast guards, and human resource development and maritime diplomacy strategies grounded in peace principles and national sovereignty, to achieve resilient, sovereign, and sustainable maritime security (Arif, 2019; Bergin, 2021).

3.6 Geospatial integration for maritime border security

Maritime border security is a strategic element for maintaining state sovereignty, safeguarding maritime economic interests, and combating cross-border threats such as smuggling, IUU Fishing, and maritime law violations. Amidst these challenges, geospatial data integration emerges as a vital instrument for building intelligent, adaptive, and evidence-based maritime surveillance and response systems. Scholten et al. (2020) posit that geospatial technology lies at the core of transforming maritime security policy, primarily through satellite data, AIS, radar, and Geographic Information Systems (GIS). This integration strengthens detection systems, vessel track mapping, and verification of maritime law violations in border areas.

Geospatial data encompasses the position, time, and form of objects on the Earth's surface, including oceans. In the maritime context, sources include: satellite imagery (optical and radar), Automatic Identification System (AIS), marine LiDAR and underwater sonar, Drones and underwater vehicles (AUV/ROV), weather and oceanographic sensors. Geospatial integration significantly aids maritime security by enabling: maritime boundary delineation (baselines and EEZs), monitoring of international and national shipping lanes (*ALKI*), identification of vessel traffic patterns, prediction of potential violations or maritime incidents. Consequently, fused geospatial data generates actionable intelligence for maritime border security (Kim et al., 2021). Geospatial integration for maritime borders represents a revolutionary shift from conventional to digital surveillance, forming an integrated Maritime Domain Awareness (MDA) system capable of high-accuracy, real-time border monitoring. This integrated model creates a closed-loop system spanning detection to response (Figure 3).

Implementing such systems requires a solid policy foundation: (1) United Nations Convention on the Law of the Sea (UNCLOS): As the "constitution for the oceans," UNCLOS provides the legal framework for establishing maritime boundaries and state obligations in jurisdictional surveillance. Article 76 specifically governs continental shelf delimitation, requiring accurate geospatial data support. (2) International Hydrographic Organization (IHO) Standards: The IHO S-100 standard provides an interoperability framework for hydrographic and navigational data, enabling integration of diverse national geospatial systems. (3) Controlled Open Data Policy: Sharing sensitive maritime data necessitates policies balancing transparency and national security. Models like the EU's INSPIRE

Directive offer practical guidance for spatial data sharing with layered access control. (4) Cybersecurity Framework for Geospatial Infrastructure: Rising cyber threats demand specialized security standards (e.g., adaptation of ISO/IEC 27001) for protecting critical maritime Spatial Data Infrastructure (SDI) (Isbaek et al., 2025).

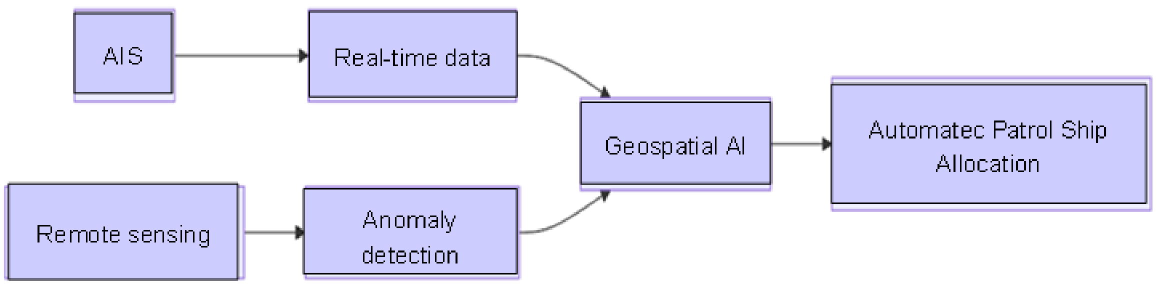

Fig. 3. Closed-loop model geospatial integration

As a vast archipelagic state, Indonesia faces multifaceted challenges: (1) Technological Infrastructure Limitations: Insufficient Geospatial Information System (GIS) infrastructure, including hardware for big data processing, cloud storage, and real-time network connectivity. Many institutions rely on conventional desktop GIS, incapable of handling high-resolution satellite data or multi-source processing (Kim et al., 2021). (2) Dependence on External Data Sources: Indonesia, the Philippines, and Pacific nations often depend on foreign satellites (e.g., Sentinel, Landsat, WorldView), restricting monitoring frequency and resolution, hindering rapid detection of dynamic illegal activities or intruding vessels (Weiß et al., 2025). The lack of a sovereign satellite constellation is a significant impediment. (3) Inter-Agency Fragmentation: A major challenge in developing nations is institutional silos. Marine geospatial data is often dispersed across *TNI AL*, the Ministry of Marine Affairs, *Bakamla*, and BPPT. Lack of system integration and communication causes redundancy, analytical delays, and inter-agency conflicts (Kim et al., 2021). (4) Human Resource and Analytical Expertise Shortages: Processing geospatial data requires expertise in: Marine GIS, remote sensing, Artificial Intelligence (AI) for anomaly detection. Developing nations frequently lack professionals effectively integrating these domains. Training often focuses on basic software use without integration into defense systems or AI (Marinaro et al., 2022). (5) Legal and Ethical Barriers: In some countries, like India, satellite or drone-based monitoring faces regulatory hurdles concerning airspace sovereignty, data protection, and traditional fishermen's privacy rights, hindering full adoption despite technical availability (Vo et al., 2023).

Maritime border security is crucial for safeguarding state sovereignty, protecting maritime economic interests, and combating cross-border threats. Conventional approaches are insufficient in an era of complex, dynamic threats. Geospatial data integration thus emerges as a strategic solution enabling intelligent, responsive, and data-driven maritime surveillance and response systems, positioning geospatial technology as the transformative core of a new global maritime security paradigm. Integrating satellite technology, AIS, radar, and GIS empowers maritime authorities with early detection, vessel track monitoring, and mapping of high-risk violation zones. Scholten et al. (2020) assert this integration transforms surveillance from reactive approaches to an integrated Maritime Domain Awareness (MDA) system. Maritime geospatial data includes spatial and temporal information from diverse sources. Combining these enables precise modeling of maritime zones, monitoring of shipping lanes, vessel traffic analysis, and threat prediction. This capability facilitates closed-loop surveillance systems from detection and verification to rapid incident response significantly enhancing border security effectiveness, especially for archipelagic states like Indonesia with vast coastlines and numerous vulnerabilities.

However, implementation requires robust policy underpinnings, including UNCLOS, IHO interoperability standards (e.g., S-100), balanced open data policies like the INSPIRE Directive, and cybersecurity frameworks (e.g., ISO/IEC 27001) for critical geospatial infrastructure (Vo et al., 2023). Despite its immense potential, developing nations like Indonesia face structural challenges: technological infrastructure deficits, reliance on foreign satellites, inter-agency fragmentation, shortages of specialized human resources, and legal-ethical barriers. Overall, geospatial integration is fundamental to strengthening maritime border security. Its effectiveness, however, hinges on infrastructure readiness, human resource capability, and political commitment to building inclusive, evidence-based, and adaptive cross-sectoral surveillance systems. Indonesia thus requires a strategic roadmap towards integrated and sustainable digital maritime sovereignty.

4. Conclusions

As an archipelagic nation encompassing over 17,000 islands, Indonesia occupies a highly strategic position within global shipping networks. The Indonesia Archipelagic Sea Lanes (*ALKI*) I, II, and III serve not only as critical conduits for global logistics and trade but also as zones acutely sensitive to issues of sovereignty, maritime security, and natural resource governance. Consequently, surveillance of the *ALKI* transcends mere administrative duty; it constitutes an integral component of Indonesia's national strategy to safeguard territorial integrity and sustain its marine economy. The foremost challenge confronting Indonesia in *ALKI* management is the persistence of "surveillance blind spots" – maritime zones lacking optimal coverage by the national monitoring system. These vulnerable areas frequently witness legal violations, ranging from Illegal, Unreported, and Unregulated (IUU) fishing by foreign vessels to intelligence-gathering activities by advanced research ships. Such threats inflict direct losses upon the state, both economically and in terms of sovereign rights. Research indicates that annual losses attributable to IUU fishing practices reach trillions of rupiah, excluding the severe ecological impacts on fish stocks and marine ecosystem sustainability.

The Indonesian government, through agencies including the Maritime Security Agency (*Bakamla*), the Indonesian Navy (*TNI AL*), the Ministry of Maritime Affairs and Fisheries (*KKP*), and the Marine Police, has implemented multifaceted countermeasures. These encompass regular maritime patrols, strategic fleet base development, and joint law enforcement operations. A particularly significant initiative is the Indonesia Maritime Information Center (IMIC), launched in 2020. IMIC functions as a central hub integrating maritime data from diverse agencies, leveraging Automatic Identification System (AIS) technology, satellite imagery, and cross-institutional intelligence. This integrated approach has demonstrably enhanced the efficiency of maritime violation detection and response.
Nevertheless, the effectiveness of Indonesia's maritime surveillance system faces persistent structural constraints. A primary limitation is fragmented information integration across agencies. Coordination processes still heavily reliant on manual communication methods (e.g., telephone, email) impede real-time information sharing. Furthermore, the presence of sophisticated foreign surveillance vessels evading automated monitoring systems underscores persistent gaps in the national maritime defense architecture.

Addressing these challenges necessitates the adoption of a closed-loop surveillance system. This approach emphasizes a continuous, technology-driven cycle encompassing data collection, analysis, detection, response, and evaluation. Implementing such a system enables proactive and adaptive surveillance, capable of countering increasingly complex maritime threats. Building a robust and integrated maritime surveillance framework rests upon five foundational pillars: (a) Unified Cross-Agency Data System: Eliminating information fragmentation to facilitate decisive action. (b) Enhanced Real-Time Monitoring: Scaling up AIS and satellite-based surveillance for automated vessel detection, including nighttime operations. (c) Rapid Response Capability: Prioritizing patrols and sensor activation in critical chokepoints like *ALKI* II to interdict violations swiftly. (d) Integrated Law Enforcement: Ensuring stringent prosecution through inter-agency synergy, including Task Force 115 (Satgas 115). (e) Long-Term Sustainability: Embedding ecological preservation and intergenerational equity in maritime resource governance as the system's core objective.

Transforming the *ALKI* from mere shipping routes into a robust digital maritime bulwark demands not only technological advancement but also political will and institutional capacity. Within an increasingly competitive geopolitical landscape marked by complex maritime threats, Indonesia must position the *ALKI* as an active defense instrument supporting national interests in security, economy, and maritime diplomacy. This integrated approach can significantly bolster Indonesia's standing in regional maritime affairs, particularly across Southeast Asia and the Indian Ocean. By demonstrating modern and responsive maritime surveillance capabilities, Indonesia not only protects its own sovereignty but also contributes substantively to global maritime stability and security. Therefore, developing a high-tech *ALKI* surveillance system grounded in integrated data and rapid response represents far more than a sectoral policy. It constitutes an essential element of the grand vision for Indonesia's digital maritime sovereignty. This study underscores the importance of multi-stakeholder integration and the utilization of maritime-based Internet of Things (IoT) technologies to strengthen surveillance, accelerate response, and ensure safety at sea. Accordingly, the following strategic measures are recommended to optimize the surveillance system amidst the evolving geopolitical dynamics of the Indo-Pacific, such as: 1) The government is advised to strengthen an integrated cross-agency data system with standardized real-time communication protocols to overcome information fragmentation among institutions such as *Bakamla*, the Indonesian Navy (*TNI AL*), the Ministry of Maritime Affairs and Fisheries (*KKP*), and the Marine Police; 2) Increasing investment in modern technologies, including the expansion of AIS coverage, the use of high-resolution satellite systems, maritime drones, and underwater sensors, in order to minimize blind spots along critical *ALKI* corridors; 3) Allocating sufficient budgetary resources to support infrastructure development and optimize human and technical capacities for early detection of potential maritime violations; and 4) Enhancing regional cooperation within ASEAN and the broader Indo-Pacific through maritime diplomacy to strengthen international legitimacy over Indonesia's maritime sovereignty."

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During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication

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