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# Enhancing Vessel Operational Safety and Security through Cross-Layer Data Fusion: A Reliability-Oriented Maritime Surveillance Framework

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## Abstract

Ensuring the operational safety of vessels and offshore infrastructure has become increasingly complex due to hybrid maritime threats, fragmented sensing coverage, and vulnerabilities in vessel identification mechanisms. Conventional single-layer monitoring approaches are insufficient to provide reliable and timely situational awareness for safety-critical maritime operations under dynamic and uncertain conditions.

To address these challenges, this study develops a heterogeneous multi-layer (HML) maritime surveillance architecture that integrates satellite-based SAR and optical sensing for wide-area monitoring, UAV and aerostat platforms for rapid tactical verification, and surface-layer systems including AIS, VHF, and LoRa-enabled maritime IoT sensors for continuous vessel-state observation. A cross-layer data fusion framework is introduced to enhance temporal consistency, spatial alignment, and information credibility across heterogeneous sensing sources. In addition, analytical models are formulated to evaluate system-level responsiveness and to quantify AIS identity integrity using a probabilistic consistency-based assessment scheme. The proposed framework is examined through four representative safety-critical maritime scenarios, including illegal oil discharge monitoring, vessel identity inconsistency detection, night-time illicit activity verification, and grounding risk assessment. The results indicate that the integrated architecture effectively mitigates the limitations of individual sensing layers, reduces uncertainty through cross-layer validation, and enables earlier and more reliable operational responses in complex maritime environments.

This work emphasizes system-level reliability and operational decision support rather than detection accuracy, demonstrating that cross-layer consistency plays a critical role in enhancing maritime safety. The proposed framework provides a scalable and engineering-oriented foundation for next-generation maritime surveillance systems and digitalized safety management in ship and offshore operations.

**Keywords:** *Maritime Operational Safety; Cross-Layer System Reliability; Maritime Surveillance Architecture; AIS Integrity Assessment; Safety-Critical Decision Support; Offshore Risk Monitoring.*

## I. INTRODUCTION

Maritime safety operations are increasingly driven by the need to make timely and reliable decisions under uncertain and dynamically evolving conditions. In modern maritime environments, safety-critical actions—such as collision avoidance, grounding prevention, and environmental hazard response—must be executed within constrained time windows while relying on heterogeneous and potentially inconsistent data sources. This evolution has shifted the role of Maritime Domain Awareness (MDA) from traditional data collection toward system-level reliability and decision-oriented situational awareness (Lee & Lam, 2020; Harish & Tam, 2024).

With the continued growth of global maritime traffic and the emergence of complex grey-zone activities, conventional surveillance approaches are no longer sufficient to support timely safety interventions in congested or environmentally sensitive waters (Karahalios, 2018; Özkan & Sevgili, 2025). In such contexts, operational effectiveness depends not only on data availability but also on the integrity and cross-

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consistency of multi-source observations (Zhang et al., 2019).

This challenge becomes particularly evident in high-risk maritime regions surrounding Taiwan—including the Taiwan Strait, Penghu Channel, and Bashi Channel—where dense vessel traffic, constrained navigation routes, and highly variable sea conditions significantly increase operational complexity (Yurt & Şakar, 2025). Under these conditions, the identification and verification of abnormal vessel behavior—such as unauthorized discharges, identity inconsistencies, and unsafe navigation patterns—become more difficult and prone to uncertainty (Louart et al., 2024; Duzenli et al., 2025). Although existing monitoring technologies provide complementary sensing capabilities, their fragmented deployment and inherent limitations reduce their effectiveness in supporting reliable risk assessment and operational safety (International Telecommunication Union, 2014).

From a sensing perspective, satellite-based systems provide extensive spatial coverage and persistent observation capabilities, making them indispensable for large-scale maritime monitoring. However, their effectiveness is constrained by revisit intervals and environmental conditions, limiting their ability to capture transient or rapidly evolving events (Bradbury et al., 2019). Aerial platforms, including Unmanned Aerial Vehicles (UAVs) and aerostats, offer high-resolution and near-real-time observation, yet their endurance and coverage remain limited (Han et al., 2025; Yu et al., 2022). At the surface level, the Automatic Identification System (AIS) remains the primary source for vessel tracking and traffic management; however, its lack of authentication and encryption mechanisms exposes it to spoofing, replay, and identity manipulation, thereby undermining the reliability of safety-critical decision-making (Louart et al., 2024; Duzenli et al., 2025; Lv et al., 2023; Xu et al., 2025).

Recent developments in maritime communication technologies, including the VHF Data Exchange System (VDES) and hybrid satellite–terrestrial networks, have improved connectivity and enabled advanced applications such as cooperative navigation and autonomous vessel operations (International Telecommunication Union, 2022; Alqurashi et al., 2022). However, these advancements primarily address communication efficiency and do not fundamentally resolve the challenge of ensuring consistent and reliable information across heterogeneous sensing layers. In practice, discrepancies caused by multipath propagation, sea-surface curvature, and environmental interference can significantly degrade data reliability, leading to delayed or inaccurate operational decisions (Du et al., 2021; Chen et al., 2021; Pogány et al., 2018).

These limitations reveal a critical gap in current maritime monitoring systems: the absence of an integrated, operation-oriented framework that explicitly considers cross-layer consistency, system reliability, and response timeliness in safety-critical scenarios. Existing approaches often emphasize individual sensing technologies or algorithmic performance, without adequately addressing how system-level integration influences decision reliability under real-world constraints.

To address this gap, this study proposes a reliability-oriented cross-layer maritime surveillance framework that integrates satellite, aerial, and surface-based sensing into a unified operational architecture. Through structured data fusion and consistency-based verification, the proposed framework enhances temporal alignment, spatial coherence, and information credibility across heterogeneous data sources. Unlike conventional approaches that emphasize detection accuracy or communication performance, this work focuses on system-level reliability and operational responsiveness as key determinants of maritime safety.

The proposed framework is designed to support timely and reliable decision-making in complex maritime environments, thereby strengthening vessel operational safety and enabling more effective risk-informed maritime management (Sun et al., 2025; Zhang et al., 2024).

## II. RELIABILITY CHALLENGES IN MARITIME SURVEILLANCE SYSTEMS

This section re-examines existing maritime monitoring approaches from a reliability-oriented perspective, emphasizing how sensing limitations, communication constraints, and cross-source inconsistencies influence safety-critical decision-making in complex maritime environments. Rather than evaluating individual technologies in isolation, the discussion focuses on system-level factors that affect operational reliability and response effectiveness (Lee & Lam, 2020; Harish & Tam, 2024).

### ➢ *Reliability Requirements in Safety-Critical Maritime Operations*

Maritime safety operations require timely, consistent, and trustworthy information to support critical decisions such as collision avoidance, grounding prevention, and emergency response (Karahalios, 2018; Özkan & Sevgili, 2025). Unlike conventional monitoring tasks, these operations are constrained by strict response windows and high uncertainty, making system reliability a fundamental requirement rather than a secondary performance metric.

In practical settings, decision effectiveness depends not only on data availability but also on the integrity and cross-consistency of heterogeneous observations collected from multiple sensing platforms (Zhang et al., 2019).

### ➢ *Cross-Source Inconsistency in Maritime Observations*

A major challenge in modern maritime surveillance lies in the inconsistency among heterogeneous sensing sources. Satellite observations, aerial imaging, and AIS-based reporting often exhibit spatial, temporal, and behavioral discrepancies, which can degrade situational awareness and delay operational responses (Chen et al., 2021).

Such inconsistencies may arise from environmental factors—including sea clutter, atmospheric interference, and sensing limitations—as well as communication-related uncertainties (Alqurashi et al., 2022). In addition, differences in spatial resolution and observation frequency may result in fragmented or incomplete representations of vessel behavior (Lv et al., 2023).

These limitations become particularly critical when monitoring non-cooperative or “dark” vessels and detecting short-duration activities, where inconsistent observations can significantly reduce decision reliability (Louart et al., 2024).

- *Communication-Constrained Verification Processes*

In safety-critical maritime scenarios, the effectiveness of anomaly verification depends not only on sensing accuracy but also on communication performance. Delays introduced by satellite propagation, UAV relaying, and channel congestion can significantly affect the timeliness of information delivery and response execution (Du et al., 2021).

For instance, satellite-based systems provide wide-area coverage but are constrained by revisit intervals and transmission latency, limiting their ability to support rapid operational intervention (Bradbury et al., 2019; Ivanov & Kucheiko, 2014). Similarly, aerial platforms such as UAVs and aerostats offer high-resolution observation but are limited by endurance and coverage constraints (Han et al., 2025; Yu et al., 2022).

As a result, the verification process becomes inherently constrained by system-level latency, requiring coordinated integration of sensing and communication layers to ensure timely and reliable response.

- *Vessel Identity Credibility and Operational Uncertainty*

AIS-based vessel identification plays a central role in maritime traffic management and navigational safety (Karahalios, 2018; Wei, 2017). However, the absence of authentication and encryption mechanisms exposes AIS transmissions to spoofing, replay attacks, and positional manipulation (Louart et al., 2024; Duzenli et al., 2025).

These vulnerabilities introduce significant uncertainty into vessel-state estimation, potentially leading to incorrect trajectory prediction and delayed hazard detection (Lv et al., 2023; Xu et al., 2025). Although emerging communication systems such as the VHF Data Exchange System (VDES) improve data throughput and support advanced applications, they do not inherently resolve the issue of data credibility without independent cross-layer verification (Bradbury et al., 2019; ITU, 2014; ITU, 2022).

- *Limitations of Current Integration Approaches*

To overcome the limitations of single-source monitoring, recent studies have explored multi-source data fusion and intelligent analytics for Maritime Domain Awareness (MDA) (Zhang et al., 2019; Sun et al., 2025). These approaches support applications such as collision risk prediction, anomaly identification, and digital twin-based monitoring of ships and offshore structures (Mikami & Murayama, 2025; Samaei & Riffat, 2025).

However, many existing approaches focus primarily on improving algorithmic performance, without explicitly addressing system-level reliability in operational environments. In particular, the combined effects of communication degradation, environmental uncertainty, and cross-layer inconsistency on real-time decision-making remain insufficiently explored (Harish & Tam, 2024; Azdem et al., 2025).

Consequently, the practical applicability of these methods in safety-critical maritime operations remains limited, especially under conditions where data quality and availability cannot be guaranteed.

- *Research Gap and Motivation*

The above observations reveal several critical limitations in current maritime surveillance systems from an engineering perspective. First, sensing and communication components are often treated as independent subsystems, lacking an integrated architecture that supports operational safety (Lee & Lam, 2020; Chen et al., 2021). Second, the impact of latency, data availability, and integrity across heterogeneous layers on real-time decision-making is not fully understood (Alqurashi et al., 2022; Du et al., 2021). Third, AIS credibility assessment is rarely combined with physical-layer verification, resulting in incomplete risk evaluation frameworks (Louart et al., 2024; Duzenli et al., 2025). Finally, system performance under degraded communication and harsh environmental conditions remains insufficiently investigated (Karahalios, 2018; Harish & Tam, 2024).

These limitations highlight the need for a unified, reliability-oriented framework that explicitly integrates heterogeneous sensing, cross-layer data fusion, and operational decision support. In response, this study proposes a cross-layer maritime surveillance architecture that prioritizes consistency verification, response timeliness, and system-level reliability for safety-critical maritime operations.

## III. RELIABILITY-ORIENTED MULTI-LAYER MARITIME SURVEILLANCE ARCHITECTURE

- *Strategic Observation Layer (Space-Based Monitoring)*

The strategic observation layer provides wide-area situational awareness using satellite-based sensing systems. This layer is responsible for large-scale monitoring and early identification of potential maritime risks across offshore and open-sea environments.

By integrating SAR and optical sensing, this layer enables robust observation under diverse environmental conditions while supporting large-area screening. The overall interaction between system components is illustrated in Figure 1.

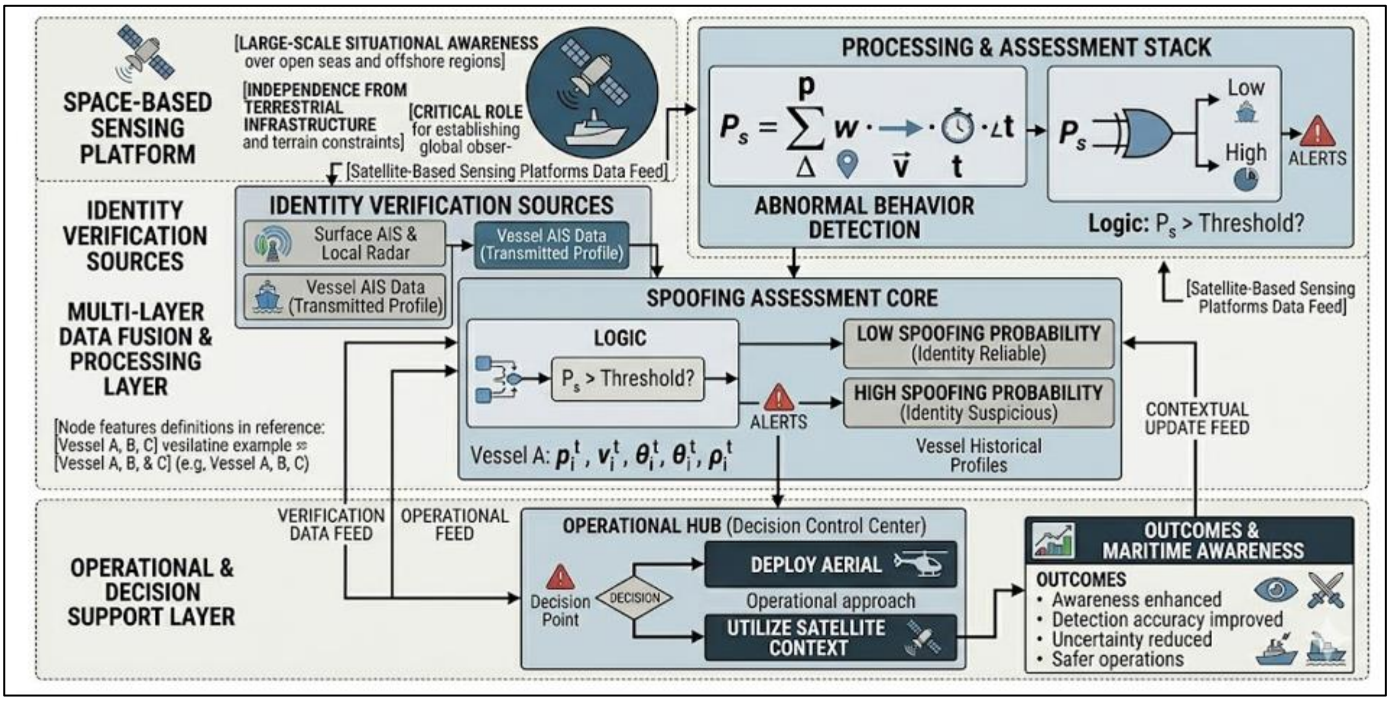

Fig 1 Reliability-Oriented Multi-Layer Maritime Surveillance Architecture

This layer combines Synthetic Aperture Radar (SAR) and high-resolution optical imaging to exploit complementary sensing characteristics. SAR enables continuous, all-weather observation, while optical sensors provide detailed visual information for vessel classification and environmental assessment under favorable conditions. The integration of these modalities improves observational robustness and reduces uncertainty in wide-area monitoring.

To evaluate the consistency between physical observations and reported vessel information, a position consistency metric is introduced:

$$\delta_p = \| \mathbf{x}_{obs} - \mathbf{x}_{ais} \|$$

Where

$\mathbf{x}_{obs}$denotes the vessel position inferred from satellite sensing, and
$\mathbf{x}_{ais}$represents the corresponding AIS-reported position.

Instead of treating discrepancies as binary anomalies, this formulation interprets $\delta_p$as a continuous reliability indicator. When AIS data are unavailable, the vessel is categorized as non-cooperative; when $\delta_p$exceeds a predefined operational threshold, the vessel is assigned an elevated risk level requiring further verification. This formulation provides a structured basis for prioritizing safety-critical interventions.

➢ *Adaptive Verification Layer (Aerial Platforms)*

The adaptive verification layer focuses on resolving uncertainty identified in the strategic layer. It provides targeted, high-resolution inspection through UAVs and aerostat platforms, enabling rapid validation of vessel identity, onboard activities, and environmental conditions.

This layer operates dynamically, allocating sensing resources based on system-level uncertainty and operational priority.

Unmanned Aerial Vehicles (UAVs) are deployed to capture high-resolution electro-optical and infrared imagery, enabling detailed inspection of vessel identity, onboard activities, and possible environmental violations. Aerostats complement UAV operations by offering extended observation duration and communication relay capabilities, particularly in offshore regions where terrestrial infrastructure is limited.

Rather than maximizing communication throughput, this layer is designed to satisfy operational verification constraints, where transmission capacity is dimensioned to ensure timely delivery of critical evidence (e.g., real-time imagery). The focus is on minimizing decision latency and enabling rapid escalation from detection to verification within safety-critical time windows.

➢ *Continuous State-Awareness Layer (Surface Systems)*

The continuous state-awareness layer provides real-time vessel-state information through AIS, VHF, and maritime IoT systems. It supports continuous tracking and fine-grained monitoring of vessel behavior.

However, this layer is subject to communication congestion and data integrity challenges, necessitating cross-layer validation.

Although this layer offers low-latency updates and continuous tracking capability, it is inherently vulnerable to communication congestion, spoofing attacks, and line-of-sight limitations. These factors introduce uncertainty in vessel-state estimation and may degrade the reliability of collision avoidance and grounding prevention systems.

To characterize communication delay at this layer, a layer-specific latency model can be expressed as:

$$D_\ell = D_{prop} + D_{access}$$

Where

$D_\ell$denotes the total communication delay at layer $\ell$,
$D_{prop}$represents propagation delay, and
$D_{access}$accounts for access delay due to channel contention (e.g., SOTDMA congestion).

The communication characteristics and latency constraints of each layer are summarized in Table 1a, while the sensing capabilities and operational roles are summarized in Table 1b. These tables provide a structured comparison of how each layer contributes to system-level safety performance.

Table 1 Operational Communication Requirements and Link Performance of HML Architecture

| **Layer** | **Platform Types** | **Link Type** | **Latency $D_{\text{layer}}$** | **Bandwidth** | **Capacity Requirement $C$** |
|---|---|---|---|---|---|
| High | LEO / GEO Satellites | X-/Ka-band; SATCOM | Hundreds of ms to seconds | Medium | Power-constrained |
| Mid | UAVs, Aerostats | 5G/LTE; Microwave | Tens to hundreds of ms | High | $C \geq 10$Mbps |
| Low | AIS, VHF, LoRa | VHF; LoRaWAN | Milliseconds to tens of ms | Low–Medium | SOTDMA-constrained |

The functional strengths and operational limitations of each sensing layer are summarized in Table 1b.

Table 2 Multi-Source Sensing Capabilities and Maritime Safety Application Scenarios

| **Layer** | **Sensing Modalities** | **Key Strengths** | **Safety Application Scenarios** | **Operational Limitations** |
|---|---|---|---|---|
| High | SAR, Optical imagery | All-weather wide-area reconnaissance | Oil spill pre-screening; Dark-vessel detection | Cloud impact; Low revisit rate |
| Mid | EO/IR; Thermal imaging | Near-real-time tactical verification | AIS spoofing validation; Night-time STS activity | Weather sensitivity; Endurance limits |
| Low | AIS; Radar; IoT sensors | Granular vessel-state tracking | Grounding risk; Route deviation monitoring | AIS spoofing; SOTDMA congestion |

- *Cross-Layer Fusion and Decision Workflow*

The architecture integrates heterogeneous sensing outputs into a unified decision-support system, where information consistency, latency, and reliability are jointly evaluated.

Through coordinated interaction between layers, the system enables progressive uncertainty reduction and supports timely safety-critical decision-making.Instead of treating sensor outputs as independent data streams, the system integrates multi-layer information to form a unified representation of the maritime environment.

Let the aggregated system state be represented as:

$$\mathbf{s}(t) = \Phi\left(\mathbf{s}_{space}, \mathbf{s}_{air}, \mathbf{s}_{surface}\right)$$

Where

$\mathbf{s}_{space}$, $\mathbf{s}_{air}$, and $\mathbf{s}_{surface}$denote observations from the satellite, aerial, and surface layers, respectively, and
$\Phi(\cdot)$represents a fusion function that combines heterogeneous data while preserving temporal and spatial consistency.

A cross-layer consistency condition is defined as:

$$\Gamma = \| \mathbf{s}_{obs} - \mathbf{s}_{reported} \|$$

Where $\Gamma$quantifies the discrepancy between observed physical states and reported vessel information. When $\Gamma$exceeds an operational threshold, the system triggers an escalation mechanism, such as UAV deployment, to reduce uncertainty and improve decision confidence.

Tables 1a and 1b illustrate how communication constraints and sensing capabilities across layers jointly influence system performance. The complementary nature of the three layers enables the architecture to compensate for individual limitations; for instance, inconsistencies detected at the surface layer can be resolved through aerial verification, while satellite observations provide contextual support for large-scale anomaly screening.

Figure 2 presents the overall cross-layer data fusion and operational workflow, highlighting the progression from wide-area observation to localized verification and final safety assessment. Through coordinated multi-layer interaction, the proposed architecture enhances situational awareness, reduces uncertainty, and supports timely, reliability-oriented decision-making in maritime safety operations.

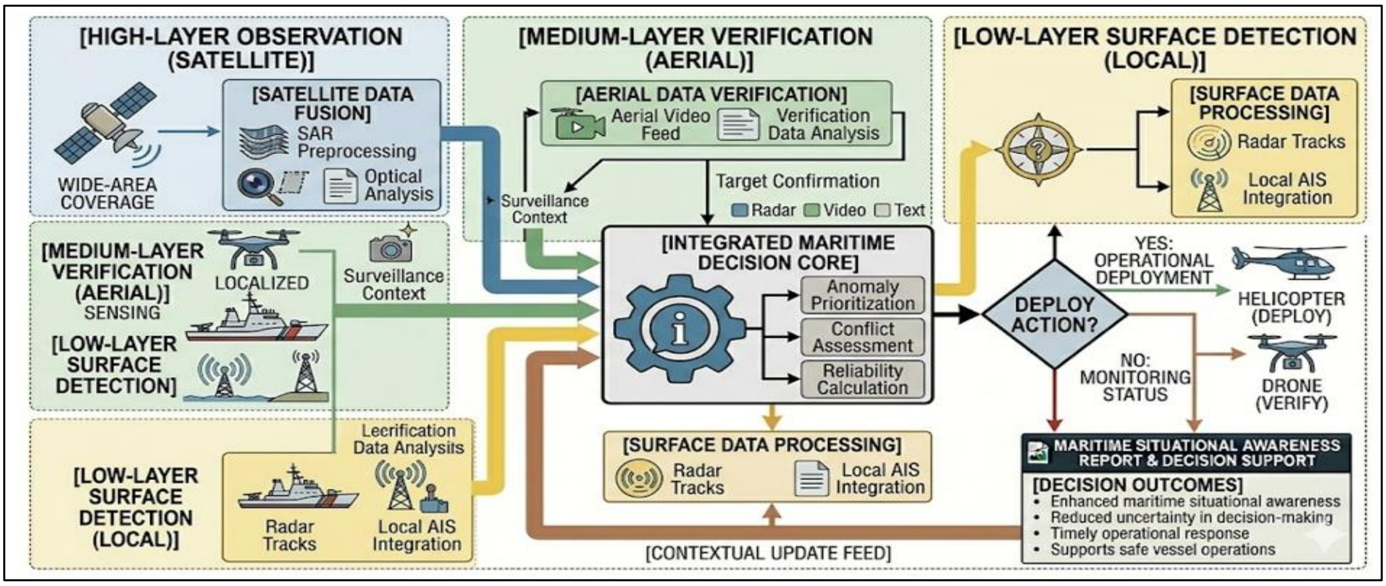

Fig 2 Cross-Layer Data Fusion and Processing Workflow

## IV. RELIABILITY-CENTRIC MODELING FOR SAFETY-CRITICAL MARITIME OPERATIONS

From an engineering perspective, the effectiveness of maritime safety operations is fundamentally governed by the timeliness, consistency, and credibility of heterogeneous observational data. Rather than evaluating communication performance in isolation, this section develops a set of analytical formulations to assess whether the proposed Heterogeneous Multi-Layer (HML) architecture satisfies the operational requirements of safety-critical maritime tasks, including collision avoidance, grounding prevention, and risk-informed verification.

The modeling framework captures six interdependent components:

- System-level response latency,
- Space-layer propagation characteristics,
- Aerial relay delay,
- Surface-layer communication constraints,
- Operational data availability, and
- Vessel identity integrity.

Together, these components establish a quantitative basis for evaluating system responsiveness and reliability under real-world maritime conditions.

➢ *Notation and Parameter Definition*

The primary variables used in the proposed models are summarized in Table 2. Delay-related parameters represent temporal constraints that directly influence operational response capability, while consistency-related variables quantify the credibility of vessel-state information across sensing layers.

Table 2 Definition of Key Variables and Parameters in Reliability Modeling

| Symbol | Term | Definition | Unit |
|---|---|---|---|
| $T_{sys}$ | System response time | Total end-to-end delay across all layers | s |
| $T_{space}$ | Space-layer delay | Delay from satellite sensing and transmission | s |
| $T_{air}$ | Aerial-layer delay | Delay from UAV/aerostat relay and verification | s |
| $T_{surface}$ | Surface-layer delay | Communication delay in AIS/VHF/IoT layer | s |
| $T_{proc}$ | Processing delay | Data processing and fusion latency | s |
| $C_{eff}$ | Effective capacity | Achievable communication throughput | bps |
| $B$ | Bandwidth | Channel bandwidth | Hz |
| $\gamma$ | SNR | Signal-to-noise ratio | – |
| $\delta_p$ | Position inconsistency | Difference between observed and reported positions | m |
| $\delta_v$ | Velocity inconsistency | Deviation in vessel speed/behavior | m/s |
| $\delta_t$ | Temporal inconsistency | Timestamp deviation | s |
| $R_{id}$ | Identity risk index | Probability of vessel identity inconsistency | – |
| $\alpha, \beta, \gamma$ | Weight coefficients | Relative importance of inconsistency factors | – |
| $\Gamma$ | Consistency threshold | Threshold for triggering verification | – |
| $\mathbf{z}_{space}$ | Space-layer state | Satellite-derived observation vector | – |
| $\mathbf{z}_{air}$ | Air-layer state | UAV/aerostat observation vector | – |
| $\mathbf{z}_{surface}$ | Surface-layer state | AIS/IoT observation vector | – |
| $\mathcal{F}(\cdot)$ | Fusion function | Cross-layer data integration operator | – |
| $\Delta T_{alert}$ | Early warning time | Time advantage over conventional systems | min |

- *System-Level Response Time Constraint*

For safety-critical maritime operations, the total response time determines whether intervention can be performed within an effective decision window. The overall system latency is defined as:

$$T_{sys} = T_{space} + T_{air} + T_{surface} + T_{proc} \tag{1}$$

Where

$T_{sys}$ denotes the total system response time,
$T_{space}$, $T_{air}$, and $T_{surface}$ represent delays associated with satellite, aerial, and surface layers, respectively, and
$T_{proc}$ corresponds to processing and fusion latency.

This formulation reflects operational responsiveness, rather than purely communication delay, and directly links system performance to maritime safety requirements.

- *Space-Layer Propagation Model*

In wide-area maritime monitoring, the delay associated with satellite communication forms a dominant component of system latency. The propagation delay can be approximated as:

$$T_{space} \approx \frac{H}{c \cdot \sin(\theta)} + T_{link} \tag{2}$$

Where

$H$ denotes satellite altitude,
$c$ is the speed of light,
$\theta$ is the elevation angle, and
$T_{link}$ represents additional transmission overhead.

This formulation highlights that orbital geometry and link conditions jointly influence response timeliness, particularly in large-scale offshore monitoring scenarios.

- *Aerial Relay Delay Model*

The aerial layer introduces additional delay components associated with data acquisition, processing, and transmission. The effective delay can be expressed as:

$$T_{air} = \frac{d_{air}}{c} + T_{access} + T_{encode} + T_{stream} \tag{3}$$

Where

$d_{air}$ denotes communication distance,
$T_{access}$ represents medium access delay,
$T_{encode}$ corresponds to encoding latency, and
$T_{stream}$ captures real-time data streaming overhead.

In practical applications, $T_{stream}$ becomes the dominant factor for EO/IR video transmission, directly affecting verification timeliness in safety enforcement tasks.

- *Surface-Layer Communication Constraints*

Surface-layer communication, particularly AIS-based transmission, is subject to channel contention and access delays. The effective delay is modeled as:

$$T_{surface} = T_{queue} + T_{vhf} \tag{4}$$

Where

$T_{queue}$ represents waiting time due to SOTDMA slot contention, and
$T_{vhf}$ denotes propagation delay over VHF communication.

Under high traffic density, $T_{queue}$ increases significantly, reducing the reliability of collision warning systems and degrading situational awareness.

- *Data Availability and Transmission Capability*

For safety-critical verification, the system must ensure that sufficient data can be transmitted within the operational response window. The communication capacity is evaluated using:

$$C_{eff} = B \cdot \log_2(1 + \gamma) \tag{5}$$

Where

$C_{eff}$ denotes effective link capacity,
$B$ is channel bandwidth, and
$\gamma$ represents the signal-to-noise ratio (SNR).

Rather than maximizing throughput, this formulation evaluates whether the communication system can sustain timely delivery of safety-relevant information, such as real-time imagery for anomaly verification.

- *Vessel Identity Integrity Modeling*

To quantify the reliability of AIS-reported vessel information, a consistency-based integrity model is introduced. The spoofing likelihood is defined as:

$$P_{risk} = \sigma\left(\alpha \cdot \delta_p + \beta \cdot \delta_v + \gamma \cdot \delta_t\right) \tag{6}$$

Where

$\delta_p$, $\delta_v$, and $\delta_t$ denote position, velocity, and temporal inconsistencies, respectively,
$\alpha, \beta, \gamma$ are weighting coefficients, and
$\sigma(\cdot)$ is a sigmoid normalization function.

This formulation transforms heterogeneous inconsistencies into a continuous risk indicator, enabling adaptive decision-making rather than binary anomaly classification.

The conceptual structure of this model is illustrated in Figure 3.

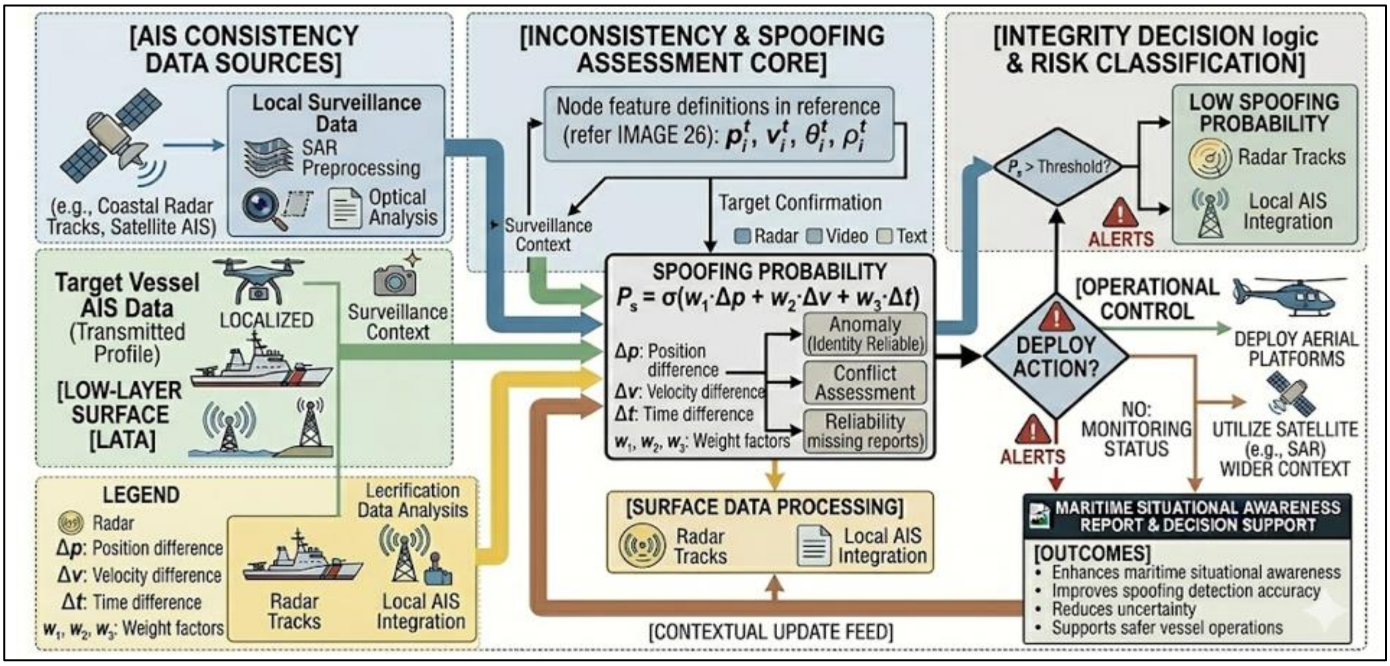

Fig 3 Reliability-Oriented Vessel Integrity Assessment Model (Conceptual Structure)

➢ *Cross-Layer Consistency and Fusion Mechanism*

To integrate heterogeneous observations, a unified state representation is defined as:

$$\mathbf{z}(t) = \mathcal{F}\left(\mathbf{z}_{space}{}^{\prime}\, \mathbf{z}_{air}{}^{\prime}\, \mathbf{z}_{surface}\right) \tag{7}$$

Where

$\mathbf{z}_{space}$, $\mathbf{z}_{air}$, and $\mathbf{z}_{surface}$denote state vectors from each layer, and
$\mathcal{F}(\cdot)$represents a cross-layer fusion operator.

A consistency condition is then evaluated as:

$$\parallel \mathbf{z}_{obs} - \mathbf{z}_{rep} \parallel > \Gamma \tag{8}$$

Where $\Gamma$is a predefined operational threshold.

When this condition is satisfied, the system triggers a verification escalation process (e.g., UAV deployment), enabling rapid transition from large-scale monitoring to localized inspection. This mechanism reduces uncertainty and enhances decision reliability in safety-critical scenarios.

➢ *Data Description and Evaluation Scope*

This study employs a hybrid data strategy combining literature-derived parameters and synthetic scenario-based datasets to evaluate system performance. The modeling parameters—including satellite delay, aerial relay latency, AIS transmission characteristics, and communication constraints—are selected based on established values reported in maritime communication and offshore engineering studies.

The evaluation scenarios are designed to reflect realistic maritime operations, including illegal discharge events, identity inconsistencies, night-time vessel interactions, and grounding risks. Vessel kinematics and anomaly indicators $(\delta_p, \delta_v, \delta_t)$ are generated within physically plausible ranges consistent with maritime operational behavior.

It should be noted that the synthetic datasets are intended to demonstrate system behavior and reliability characteristics rather than replicate exhaustive real-world observations. This approach enables systematic evaluation of cross-layer consistency and response performance without reliance on sensitive operational data.

The data set used in this study is publicly available in the Zenodo repository, as described in the Data Availability Statement.

## V. OPERATIONAL EVALUATION FRAMEWORK (REWRITTEN)

This section evaluates the proposed system from an operational reliability perspective, focusing on how cross-layer coordination improves decision timeliness and reduces uncertainty in safety-critical maritime scenarios.

Rather than treating case studies as isolated detection tasks, the analysis interprets each scenario as a decision-making process under time constraints, where the effectiveness of the system is determined by its ability to provide consistent, timely, and actionable information.

Each scenario is therefore assessed based on three criteria:

- Response latency $(T_{sys})$
- Information consistency $(\Gamma)$
- Decision confidence $(R_{id})$

This formulation allows the evaluation to move beyond detection performance and instead quantify how system design influences real-world maritime safety outcomes.

➢ *Case Study 1: Time-Critical Oil Spill Response*

Illegal oil discharge events represent a time-sensitive environmental hazard, where observable evidence may degrade rapidly within a limited time window (typically 1–2 hours). Effective response therefore depends on both early detection and rapid verification.

- *Operational Process*

At the space layer, LEO-based SAR performs wide-area observation to identify surface anomalies indicative of oil slicks. Once a candidate region is detected, the system evaluates the cross-layer consistency condition defined in Eq. (8). When uncertainty exceeds the predefined threshold, an aerial verification task is triggered.

- *Response Time Analysis*

The verification latency is dominated by aerial relay delay:

$$T_{verify} \approx T_{air} \in [0.08, 0.2] \text{ s} \tag{9}$$

This low-latency response enables near-real-time confirmation through EO/IR imaging.

- *Operational Reliability Impact*

Given the communication capacity constraint:

$$C_{air} \geq C_{min} \approx 10 \text{ Mbps} \tag{10}$$

The system can sustain continuous high-resolution video transmission, ensuring traceable and verifiable evidence prior to environmental dispersion.

This capability significantly enhances enforcement reliability and supports regulatory compliance by preserving the evidentiary chain in time-critical scenarios.

➢ *Case Study 2: Vessel Identity Consistency Assessment*

Vessel identity inconsistency, including MMSI duplication and falsified positional data, introduces substantial risks to maritime situational awareness and automated navigation systems.

- *Risk Modeling*

The vessel identity reliability is quantified using the consistency-based risk function defined in Eq. (6), rewritten here as:

$$R_{id} = \sigma(\alpha\delta_p + \beta\delta_v + \gamma\delta_t) \tag{11}$$

Where $R_{id}$ represents identity inconsistency risk.

- *Cross-Layer Verification Mechanism*

When satellite observations detect a physical target without corresponding AIS data, the vessel is classified as non-cooperative. Additionally, when the spatial inconsistency satisfies:

$$\delta_p > \delta_{crit} \approx 500 \text{ m} \tag{12}$$

The system assigns a high-risk state ($R_{id} > 0.9$) and triggers verification.

- *Engineering Significance*

Unlike AIS-only approaches, this method integrates physical-layer observations with communication data, improving reliability in vessel identification and reducing the likelihood of false situational interpretations in high-density navigation zones.

➢ *Case Study 3: Low-Visibility Maritime Activity Monitoring*

Night-time ship-to-ship (STS) operations present a challenge due to limited visibility and reduced effectiveness of optical surveillance systems.

- *Multi-Layer Coordination*

At the space layer, SAR detects abnormal vessel proximity patterns independent of illumination conditions. The aerial layer then performs thermal verification, identifying heat signatures and operational activity.

- *Communication Robustness*

Under congested communication conditions, the surface-layer delay increases:

$$T_{surface} \uparrow \text{ (as defined in Eq. 4)}$$

However, the aerial relay path maintains system connectivity, ensuring that the effective reporting delay remains bounded:

$$T_{sys} \leq T_{threshold} \tag{13}$$

- *Operational Outcome*

This layered redundancy ensures that situational awareness is preserved even when individual communication channels degrade, demonstrating the robustness of the proposed architecture under adverse conditions.

➢ *Case Study 4: Port Congestion and Collision Risk Management*

Port and nearshore environments are characterized by high vessel density, complex navigation patterns, and frequent maneuvering operations. Under such conditions, maintaining situational awareness and preventing collisions require timely and reliable information across multiple observation sources.

- *Operational Context*

In congested port areas, vessel movements are highly dynamic, and AIS communication may suffer from increased latency due to channel contention. Simultaneously, radar and visual monitoring may be limited by environmental factors and infrastructure constraints.

- *System-Level Assessment*

The proposed framework evaluates operational safety by monitoring cross-layer consistency:

$$\Gamma(t) = \| z_{obs}(t) - z_{rep}(t) \|$$

When inconsistencies exceed the operational threshold, the system identifies elevated collision risk and triggers adaptive verification mechanisms.

- *Response Improvement*

By integrating satellite context, aerial verification, and surface-level tracking, the system improves early warning capability:

$$\Delta T_{alert} > 10 \text{ minutes}$$

Compared with conventional monitoring approaches.

- *Operational Impact*

This enhanced response window allows port authorities to implement timely traffic control measures, reducing collision risk and improving safety in high-density maritime environments.

➢ *Discussion*

The results highlight a fundamental limitation in current maritime monitoring practices: the lack of integration between sensing systems and operational decision requirements. Existing solutions are often designed as independent subsystems—satellite observation, aerial inspection, and AIS monitoring—without explicitly considering their combined effect on system-level reliability.

From a maritime engineering perspective, the proposed HML architecture reframes surveillance as an integrated system in which sensing accuracy, communication delay, and verification timing are jointly optimized to support safety-critical operations.

A key insight derived from the case studies is that system reliability is governed primarily by cross-layer consistency rather than individual sensor performance. While satellite sensing provides extensive coverage, it lacks temporal resolution; conversely, aerial platforms offer high-fidelity verification but limited persistence. The proposed architecture resolves this trade-off through progressive verification, enabling uncertainty reduction through coordinated multi-layer interaction.

Furthermore, the introduction of a continuous identity reliability model allows vessel-state inconsistencies to be interpreted as graded risk levels rather than binary anomalies. This aligns with modern reliability-based engineering approaches, where probabilistic assessment supports more adaptive and robust decision-making.

Another important contribution is the explicit incorporation of communication delay as a safety-limiting factor. In real-world maritime environments, delays arising from satellite propagation, aerial relay, or AIS congestion directly influence the effectiveness of collision avoidance and emergency response. By linking delay models with operational response requirements, the framework provides a transparent mechanism for evaluating system adequacy under realistic conditions.

From an offshore engineering perspective, the proposed architecture also supports the transition toward digitalized lifecycle management. The same cross-layer consistency principles can be extended to structural monitoring of vessels and offshore installations, forming the basis for reliable digital twin systems. In such applications, temporal coherence and data integrity become essential for long-term condition assessment and predictive maintenance.

Overall, this study advances the state of maritime safety engineering by integrating communication modeling, sensing coordination, and operational decision support into a unified framework. The reliability-oriented design enables improved situational awareness, faster response, and more robust safety performance under complex and uncertain maritime conditions.

## VI. CONCLUSIONS AND ENGINEERING IMPLICATIONS

➢ *Summary of Technical Contributions*

This study presents a reliability-oriented Heterogeneous Multi-Layer (HML) maritime surveillance architecture to address critical limitations in existing maritime monitoring systems, including fragmented sensing coverage, vessel identity inconsistency, and delayed response caused by communication and observation constraints.

By adopting an operation-centric design and integrating cross-layer data fusion with consistency-based evaluation, the proposed framework enhances spatiotemporal coherence, verification efficiency, and communication robustness in both offshore and nearshore maritime environments.

From a system engineering perspective, the principal contributions of this work can be summarized as follows:

- *Reliability-Oriented Multi-Layer Architecture*

A coordinated three-layer architecture—comprising space-based observation, aerial verification, and surface-level sensing—was developed to support safety-critical maritime operations.

The architecture enables progressive information refinement, where large-scale uncertainty is reduced through targeted verification. The system response behavior can be expressed as:

$$T_{sys} = T_{space} + T_{air} + T_{surface} + T_{proc}$$

Demonstrating how cross-layer coordination directly influences operational response capability.

This structure provides a systematic foundation for integrating heterogeneous sensing resources into a unified decision-support framework.

- *Vessel Identity Reliability Modeling*

A consistency-based vessel identity reliability model was introduced to evaluate the credibility of AIS-reported information. Instead of binary anomaly classification, the model quantifies identity inconsistency as a continuous risk metric:

$$R_{id} = \sigma\left(\alpha\delta_p + \beta\delta_v + \gamma\delta_t\right)$$

Where spatial, kinematic, and temporal inconsistencies are jointly considered.

This formulation enables adaptive decision-making by translating heterogeneous discrepancies into interpretable risk levels, thereby improving the reliability of navigation safety assessment and operational planning.

- *Analytical Modeling of System Responsiveness*

Analytical models were established to characterize delay propagation and communication constraints across heterogeneous maritime links. The framework explicitly links system latency and communication capacity to operational performance:

$$C_{eff} = B\log_2(1 + \gamma)$$

These formulations provide a quantitative basis for evaluating whether the system can satisfy the temporal requirements of safety-critical tasks, such as real-time verification and emergency response.

- *Scenario-Based Validation under Operational Constraints*

The proposed architecture was validated through representative maritime scenarios, including environmental hazard response, vessel identity inconsistency, low-visibility operations, and navigation safety monitoring.

The results demonstrate that cross-layer coordination reduces uncertainty and improves response timeliness, achieving an effective warning gain:

$$\Delta T_{alert} \approx 5\text{–}15 \text{ minutes}$$

Compared with conventional monitoring approaches.

This confirms the capability of the framework to enhance situational awareness and support timely decision-making under realistic operational conditions.

➢ *Limitations and Future Research Directions*

Despite the improvements achieved by the proposed framework, several practical constraints remain that require further investigation.

At the space layer, satellite sensing is affected by environmental attenuation and revisit limitations, which restrict its temporal resolution. The aerial layer is constrained by platform endurance, deployment logistics, and regulatory requirements, while the surface layer remains vulnerable to communication congestion, particularly under SOTDMA-based channel access in high-density traffic environments.

Future research will focus on the following directions:

- *Integration with Next-Generation Non-Terrestrial Networks*

The incorporation of High-Altitude Platform Stations (HAPS) and emerging 6G Non-Terrestrial Networks (NTNs) is expected to reduce end-to-end latency:

$$T_{sys} \downarrow$$

While increasing communication capacity and coverage continuity. This will enhance system responsiveness in offshore and remote maritime regions.

- *Edge Intelligence and Distributed Processing*

Deploying edge-based intelligence on UAVs and satellite platforms can significantly reduce processing latency:

$$T_{proc} \rightarrow T_{proc}^{edge}$$

Thereby enabling faster data interpretation and decision-making. Techniques such as federated learning and onboard multimodal fusion will further improve system autonomy and scalability.

- *Digital Twin-Enabled Maritime Systems*

The extension of cross-layer data fusion into digital twin frameworks will enable real-time virtual representation of maritime environments. In this context, system reliability can be expressed as:

$$\Gamma(t) \rightarrow \min$$

Where minimizing cross-layer inconsistency improves predictive accuracy and long-term system stability.

Such developments will support advanced applications, including structural health monitoring, environmental prediction, and proactive risk management.

## FINAL REMARKS

This study establishes a reliability-oriented framework for maritime surveillance by integrating heterogeneous sensing, communication modeling, and operational decision support into a unified architecture.

By shifting from isolated sensing systems toward a coordinated multi-layer design, the proposed approach enhances verification reliability, reduces response latency, and improves overall system resilience.

The results indicate that cross-layer consistency, rather than individual sensor performance, is the dominant factor in achieving reliable maritime situational awareness.

This work provides a scalable engineering foundation for next-generation maritime safety systems, enabling maritime authorities to maintain operational safety, environmental protection, and security assurance under complex and uncertain conditions.

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➢ *Conflict of Interest*

The author declares that there is no conflict of interest regarding the publication of this article.

➢ *Author Contributions*

The author solely contributed to the conceptualization, methodology development, formal analysis, case study design, writing, and revision of the manuscript.

➢ *Ethical Statement*

This study did not involve human participants, human data, or animal subjects, and therefore did not require ethical approval.

➢ *Data Availability Statement*

The data supporting the findings of this study are publicly available in the Zenodo repository at https://doi.org/10.5281/zenodo.18634908 (reference number: 18634908).

➢ *Generative Artificial Intelligence (AI) Disclosure*

Generative artificial intelligence tools were used solely for the creation and visual refinement of schematic figures in this manuscript. The use of AI was limited to graphical illustration purposes, such as layout optimization and visual enhancement, and did not involve the generation, analysis, or interpretation of research data. All scientific content, engineering models, analytical results, and conclusions presented in this study are entirely the work of the author.

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