

The Effectiveness of Primary and Secondary Radar in the Malaysian Air Defence Mechanism

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DOI Link: <http://dx.doi.org/10.6007/IJARBSS/v16-i10/29042>

Published Date: 10 October 2026

Abstract

Radar surveillance constitutes a critical component of modern air-defence systems, enabling states to detect, identify, track and respond to aerial activities. This capability is particularly important for Malaysia due to its geographical separation, extensive maritime approaches, large airspace and increasing exposure to foreign military aircraft, unmanned aerial vehicles (UAVs) and unidentified aerial activities. Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR) perform complementary functions. PSR independently detects airborne objects through reflected electromagnetic signals without target cooperation. SSR relies on aircraft transponders to provide identification and other flight information. This distinction is significant for national air defence because non-cooperative targets may not provide information required by SSR. This study examines the effectiveness of PSR and SSR within Malaysia's air-defence mechanism through qualitative documentary and case study analysis of international standards, Malaysian aviation policies, surveillance infrastructure, parliamentary records, official defence documents and selected airspace incidents. The findings indicate that Malaysia possesses a credible and increasingly modern surveillance foundation comprising PSR, SSR, Automatic Dependent Surveillance-Broadcast (ADS-B) and dedicated military radar capabilities. However, effectiveness remains constrained by uneven geographical coverage, equipment availability, low-altitude surveillance challenges, dependence on cooperative systems and fragmented civil-military surveillance functions. The study argues that Malaysia's challenge extends beyond radar acquisition to the incomplete integration of sensors, surveillance data, institutional responsibilities, and decision-making processes. A layered national air-surveillance architecture integrating PSR, SSR, ADS-B, long-range military radar and complementary sensors within a common operational picture is therefore essential to strengthen situational awareness, response time, and the protection of national sovereignty and territorial integrity.

Keywords: Primary Surveillance Radar, Secondary Surveillance Radar, Air Defence

Introduction

Monitoring, identifying and responding to activities within national airspace are essential aspects of exercising state sovereignty and protecting national security. International law recognises the sovereignty of states over their airspace; however, the practical enforcement of this sovereignty depends upon adequate monitoring and response capabilities. Accordingly, in the contemporary security environment, airspace sovereignty is not merely a legal principle but also an operational capability, supported by radar surveillance that enables the continuous detection, tracking and classification of aircraft beyond the limitations of visual observation.

Although other surveillance technologies, including Automatic Dependent Surveillance-Broadcast (ADS-B), multilateration satellite surveillance and electro-optical systems, have emerged, radar remains particularly important to military air defence because it can detect targets without depending on information voluntarily transmitted by aircraft (Skolnik, 2008). This capability is especially relevant to unidentified, unauthorised or potentially hostile aircraft that may not cooperate with national surveillance systems.

Within this surveillance architecture, PSR detects targets by reflected electromagnetic energy and does not require a transponder signal to function. SSR is based on aircraft transponders that provide additional information, such as identification and altitude. Thus, SSR is of great value for cooperative air traffic, but PSR is still essential for non-cooperative targets (Bowes, 1982).

This distinction is particularly relevant to Malaysia. CAAM employs PSR, SSR and ADS-B within the Kuala Lumpur and Kota Kinabalu FIRs, supported by civil and military radar systems. Although surveillance coverage along established air routes in Peninsular Malaysia is extensive, certain lower-level gaps remain, particularly along the eastern coast. More importantly, civil aviation surveillance requirements differ from those of national air defence, which must also address unidentified and non-cooperative targets.

The 31st May 2021 incident involving 16 PLAAF aircraft near Sarawak was detected by the RMAF through its air-defence surveillance system, contributing to Malaysia's subsequent operational and diplomatic response. The incident therefore illustrates how radar detection can serve as the first stage of a broader national response to activities affecting Malaysian sovereignty.

Problem Statement

Three major gaps are identified in the existing literature. First, radar research predominantly emphasises technical performance, including detection range, accuracy and coverage, rather than its contribution to the effectiveness of national air defence. Second, Malaysian aviation studies largely focus on air traffic management and aviation safety, with limited attention to the integration of civil surveillance systems with military air-defence activities. Third, studies of Malaysian airspace security often examine specific incidents, legal sovereignty or defence procurement separately, rather than systematically assessing how surveillance systems support the complete detection-to-response process.

This study assesses the effectiveness of PSR and SSR within Malaysia's air-defence mechanism as system-level national security capabilities, focusing on detection, identification, tracking, information integration, threat assessment and timely response. It argues that although Malaysia possesses a legitimate surveillance foundation, effectiveness remains constrained by geographical, technological, operational and institutional factors. Therefore, radar's strategic value depends on integrating PSR, SSR, ADS-B, military radar and other surveillance assets into a coherent national air-surveillance and command-and-control architecture.

Literature Review

The literature review examines six key dimensions underpinning radar effectiveness within Malaysia's air defence mechanism. Six key dimensions are as follows:

Radar as an Air-Surveillance Capability

Radar is fundamental to airspace surveillance and defence, using electromagnetic energy to detect and locate objects while providing information on range, bearing, altitude and velocity. Technological advances have further improved detection, tracking and classification capabilities (Skolnik, 2008; Richards, 2014; Mahafza, 2013). The literature distinguishes PSR and SSR by their operating principles. This distinction creates an important limitation for both systems. PSR offers independent detection but provides comparatively limited information about target identity, while SSR provides more detailed information but may be ineffective when an aircraft fails to respond or disables its transponder. Consequently, neither system alone provides a complete surveillance picture.

The literature therefore supports an integrated approach in which PSR provides the independent detection layer, while SSR enhances the identification and classification of cooperative targets. Their effectiveness in air defence ultimately depends on how successfully these complementary capabilities are integrated to overcome their respective limitations.

Primary Surveillance Radar and Non-Cooperative Targets

A key debate concerns whether modern airspace surveillance can rely predominantly on cooperative systems or whether independent detection remains necessary. PSR retains an important advantage because it can detect aircraft without requiring transponder responses, unlike SSR and ADS-B, which depend substantially on aircraft cooperation.

Although SSR and ADS-B provide richer information for identification and classification, their effectiveness decreases when targets are non-cooperative. Military aircraft may provide limited cooperative information, while unauthorised aircraft may deliberately withhold identification signals. Conti et al. (2013) similarly identify challenges in detecting non-cooperative, low-altitude and low-radar-cross-section targets.

For Malaysia, this debate reinforces the continuing importance of PSR. Cooperative surveillance can enhance the recognised air picture but cannot guarantee detection of all potential threats. PSR should therefore remain the independent detection layer, complementing rather than being replaced by SSR and ADS-B within an integrated national air-defence architecture.

Secondary Surveillance Radar and Identification

The literature regards Secondary Surveillance Radar (SSR) as an important advancement over PSR because aircraft transponders provide additional information. Mode A provides identification codes, Mode C provides pressure altitude, and Mode S provides improved data capabilities (ICAO, 2026). These features make SSR particularly valuable in dense civil aviation environments by improving aircraft identification, situational awareness and air traffic management.

However, SSR's principal strength also represents a limitation. Its effectiveness depends on aircraft cooperation. An unavailable, incompatible, malfunctioning or deliberately disabled transponder can significantly reduce the information available. This confirms the ongoing need of PSR where cooperative surveillance is not enough alone (CAAM, 2021).

This restriction is more important in national defense. While SSR is highly effective for cooperative traffic, its reliance on transponder responses creates vulnerabilities when confronting non-cooperative or unidentified targets. SSR should therefore enhance, rather than replace, PSR within an integrated air-defence system capable of addressing both cooperative and non-cooperative threats.

ADS-B and the Evolution of Surveillance

The literature identifies Automatic Dependent Surveillance-Broadcast (ADS-B) as a significant development in aviation surveillance because it continuously broadcasts aircraft-derived information, including position, identification and velocity. Compared with PSR, ADS-B can provide richer aircraft information and extend surveillance into areas where conventional radar coverage is limited or uneconomical. Unlike SSR, however, ADS-B broadcasts information rather than relying on interrogation. CAAM therefore recognises its value for extending surveillance coverage and providing redundancy alongside radar.

Despite these advantages, ADS-B differs fundamentally from PSR because it remains dependent on information transmitted by the aircraft. Where an aircraft does not transmit ADS-B, or its reported position cannot be independently verified, ADS-B alone cannot provide the independent detection capability offered by PSR. This distinction is particularly important for national air defence.

Accordingly, the comparison is clear. PSR provides independent detection, SSR enhances cooperative identification, and ADS-B extends and enriches cooperative surveillance. ADS-B therefore improves coverage and situational awareness but cannot replace PSR against non-cooperative or unidentified targets. A resilient Malaysian air-defence architecture should consequently integrate all three capabilities according to their complementary strengths.

Multi-Sensor Integration

The literature increasingly debates whether surveillance effectiveness should be attributed to individual sensor capabilities or to the integration of multiple sources. Hall and Llinas (1997) argue that multisensor data fusion improves estimates and situational

awareness by combining information from different sensors, while Waltz and Llinas (1990) similarly emphasise its value in complex surveillance environments.

This perspective is particularly relevant to air defence. PSR can establish the presence of an object, while SSR may provide its identity and ADS-B can contribute position and velocity information. Other sensors, like electro-optical systems and electronic intelligence, can provide visual and electronic evidence. The challenge, therefore, is not simply to detect an object, but to integrate these inputs to determine whether it represents routine traffic, an unidentified aircraft or a potential threat. Therefore, the literature suggests that effective air defense increasingly depends on information integration rather than sensor capability alone.

Situational Awareness and Decision-Making

The literature debates whether the effectiveness of a radar should be measured only by its capability of detection or by its contribution to situation awareness and decision-making. Endsley (1995) conceptualises situational awareness as the perception of relevant elements, comprehension of their meaning and projection of their future status. Applied to air defence, radar primarily supports perception by detecting an aircraft, but its value increases when the information enables identification, threat assessment and prediction of movement. Klein (1998) further argues that decision-making in complex environments depends on pattern recognition, experience and timely information. This means that the effectiveness of the radar cannot be distinguished from the speed and accuracy with which its information is converted into operational understanding. Consequently, a radar system is effective not merely when it detects a target, but when its information enables operators to understand the situation, anticipate potential threats and make timely decisions.

The previous studies have not sufficiently examined the effectiveness of an integrated evaluation of PSR and SSR that necessitates an examination of their contribution to the core surveillance functions of detection, identification, and tracking. The limited attention to geographical coverage, system availability, and technological constraints further requires an assessment of the operational limitations that may affect surveillance effectiveness. Finally, the insufficient examination of civil-military integration emphasizes the necessity to determine how surveillance information is coordinated and transformed into an integrated air picture and subsequent defense response. These gaps establish the need for a systematic assessment of radar effectiveness beyond the technical performance of individual systems. Accordingly, the present study, particularly the 2021 PLAAF incident, translates these identified gaps into three specific objectives:

- (1) To assess the effectiveness of PSR and SSR in detecting, identifying, and tracking aerial activities;
- (2) To examine the coverage, availability, and operational limitations affecting their effectiveness; and
- (3) To evaluate the extent to which civil-military integration of surveillance capabilities contributes to Malaysia's air-defence response and the protection of national airspace sovereignty.

These objectives provide a direct analytical pathway from the identified shortcomings in the existing literature to the empirical assessment undertaken in this study.

Conceptual Framework

The conceptual framework conceptualises radar effectiveness through detection, identification, tracking, coverage and availability, and operational integration. These dimensions assess radar's ability to transform surveillance information into meaningful, timely and actionable outcomes for national airspace surveillance and defence. Detection refers to identifying airborne objects within the surveillance area and forms the foundation of the air-defence process. Identification defines what an object is, its identity and characteristics, enabling the distinction between lawful civilian traffic and unidentified, unauthorized or potentially hostile activity. Tracking is the ability to maintain constant awareness of a target's movement, direction and behavior, allowing assessment of the target's trajectory and intent. Coverage and availability refer to the adequacy of the geographical coverage and the reliability of the operations, including limitations imposed by maintenance, technical failures and other constraints, especially important for Malaysia's large and dispersed airspace. Finally, operational integration links radar surveillance to the wider air-defence system by facilitating information sharing, data fusion and assessment among relevant agencies to support effective command decisions and timely responses. Taken together, these dimensions form a sequential, yet interdependent process as follows:

Detection → Identification → Tracking → Coverage/Availability → Operational Integration → Action.

Thus, radar effectiveness should be measured not simply by whether a radar can detect an aircraft, but by whether surveillance information can be reliably transformed into actionable information that supports the protection of Malaysia's national airspace.

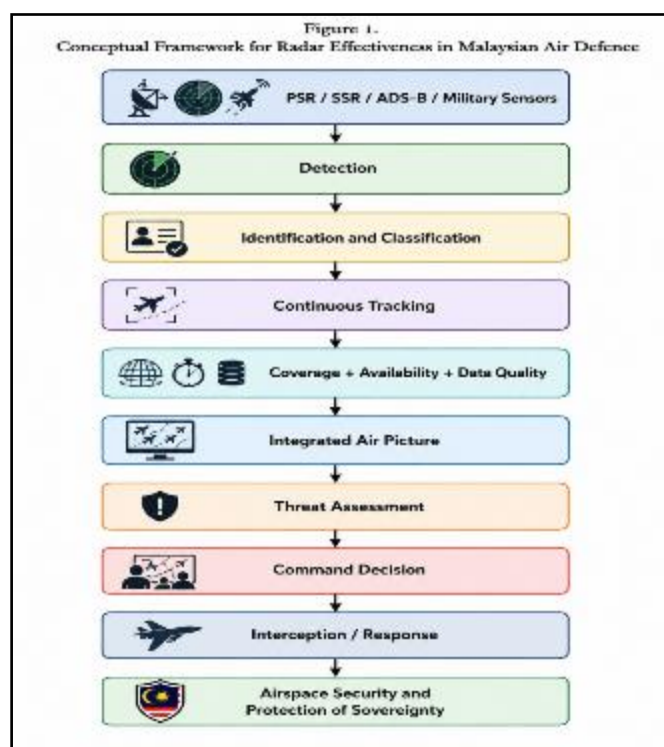


Figure 1. Conceptual Framework for Radar Effectiveness in Malaysian Air Defence Mechanism

Sources: Researcher's own illustration

Figure 1 conceptualises radar effectiveness as being integrated and communicated to relevant authorities to enable timely decision-making and response. Accordingly, the proposed formulation is expressed as follows:

$$\text{Radar Effectiveness} = \text{Detection} \times \text{Identification} \times \text{Tracking} \times \text{Coverage/Availability} \times \text{Operational Integration}$$

The multiplicative formulation reflects the interdependence of these dimensions, whereby weakness in any single component can constrain overall radar effectiveness. Thus, the framework provides a holistic basis for assessing radar contribution to Malaysia's national air defence.

Research Methodology

The research methodology comprises four key subtopics outlining the research design, documentary sources, case selection, and data analysis employed to examine radar effectiveness.

Research Design

This study adopts a qualitative research design based primarily on documentary analysis and case-study analysis. Qualitative research is appropriate because the study seeks to understand how radar capabilities operate within the broader institutional and strategic context of Malaysian air defence rather than to calculate engineering performance under controlled experimental conditions.

The study follows the logic of qualitative case study research, in which a contemporary phenomenon is examined within its real-world context (Yin, 2018). Documentary analysis is particularly appropriate for defence and airspace-security research because a substantial proportion of operational information is contained within government documents, aviation publications, parliamentary records, official statements, and policy documents (Bowen, 2009).

Documentary Sources

The research draws upon five principal categories of documentary evidence:

- a) ICAO standards and guidance;
- b) CAAM aviation publications and regulatory documents;
- c) Malaysian Ministry of Defence policy and procurement documents;
- d) Malaysian Parliamentary Hansard records; and
- e) official statements and reports concerning airspace incidents.

The analysis also incorporates selected scholarly literature concerning radar technology, surveillance, sensor fusion, situational awareness and decision-making.

Case Selection

The principal Malaysian case examined is the 31 May 2021 incident involving 16 People's Liberation Army Air Force (PLAAF) aircraft near Sarawak. The case was selected because it provides a clear empirical illustration of how radar detection contributes to Malaysia's air-defence response. The Royal Malaysian Air Force (RMAF) reported that its air-defence radar

detected the aircraft while they were approaching Malaysian airspace (Bernama, 2021). The study also examines Malaysia's radar-modernisation efforts, particularly the deployment of the GM400 long-range air-defence radar at Bintulu and the expansion of surveillance capabilities in East Malaysia (Ministry of Defence Malaysia, 2023; Civil Aviation Authority of Malaysia [CAAM], 2024).

Data Analysis

The documentary data were analysed thematically using five categories derived from the conceptual framework, which is detection, identification, tracking, coverage and availability, and operational integration. This approach enabled recurring patterns, relationships and areas of convergence to be systematically identified across the selected documents (Braun & Clarke, 2006). Given the classified and operationally sensitive nature of certain Malaysian military information, the analysis was deliberately confined to publicly accessible sources. Accordingly, the study does not speculate on classified radar performance, precise deployment patterns, or sensitive operational procedures, thereby maintaining appropriate research boundaries and analytical integrity.

Malaysia's Radar Surveillance Architecture

Malaysia's contemporary surveillance architecture combines multiple technologies and institutional capabilities to support national airspace monitoring. CAAM's current AIP identifies PSR, SSR and ADS-B within the Kuala Lumpur and Kota Kinabalu FIRs, demonstrating the use of complementary surveillance systems for different operational requirements.

CAAM documentation also points to civil and military ATC radar systems, including 200-nautical-mile SSR and 60-nautical-mile PSR at several locations. The co-location of PSR and SSR shows the complementary roles of PSR and SSR in that PSR provides independent detection and SSR provides identification and altitude information to provide a more comprehensive surveillance picture.

This integrated approach is also demonstrated in Malaysia's National Air Navigation Plan which outlines a framework to modernise communication, navigation and surveillance infrastructure in accordance to ICAO and Asia-Pacific requirements (CAAM, 2025b). These trends suggest a move toward integrated surveillance, where air-defence effectiveness depends not only on expanding individual systems, but also on integrating them to produce timely and reliable situational awareness.

Table 1

Summary of Malaysia's Radar Surveillance Architecture

Surveillance Element	Primary Function	Contribution to Airspace Surveillance	Role in Malaysia's Architecture
PSR	Independent detection	Detects aircraft without requiring cooperation	Provides an independent detection layer
SSR	Identification & altitude	Provides aircraft identity and altitude information	Complements PSR and enhances target identification
ADS-B	Position, identity & velocity	Provides aircraft-derived surveillance information	Extends surveillance and provides redundancy
Integrated Surveillance	Information integration	Combines multiple surveillance inputs	Supports a more comprehensive air picture
National Air Navigation Plan	Strategic modernisation	Guides CNS infrastructure development	Aligns Malaysia with ICAO and Asia-Pacific requirements

Case Study: The 2021 PLAAF Incident

The 31 May 2021 PLAAF incident, in this case, is a significant case to evaluate Malaysia's radar capability within the framework of the national air-defence mechanism. The RMAF said its Air Defence Center in Sarawak detected 16 PLAAF aircraft flying in a tactical formation at about 23,000 to 27,000 feet as they approached the Malaysian Maritime Zone at about 11.53am. The incident is of particular importance when considering the study of the role of radar surveillance in Malaysia's air-defence response in that it entailed the presence of foreign military aircraft in a sovereignty-sensitive area.

The results show three dimensions of radar effectiveness. First, the aircraft was independently detected by RMAF air-defence radar, which demonstrates the value of non-cooperative surveillance. Secondly, early warning for assessment and operational response was provided by detection of them before reaching the Malaysian mainland. Third, information from radar fed into broader governmental action, with the Ministry of Foreign Affairs later lodging a diplomatic protest against China, showing radar's role in both military and diplomatic responses. Taken together, the incident illustrates the broader response chain as follows:

Radar detection → Military assessment → Aircraft response → Government assessment → Diplomatic action

The case therefore supports the central proposition that radar effectiveness is a system-level capability, whereby timely surveillance information is transformed into coordinated operational and national action that contributes to the protection of Malaysian sovereignty.

The Effectiveness of Primary Radar in Malaysia

The 2021 PLAAF incident provides important evidence of the continuing operational significance of Malaysia's primary military surveillance capability. The successful detection of 16 PLAAF aircraft demonstrates that military radar can provide an independent surveillance source when foreign military aircraft operate within Malaysia's surrounding maritime

environment. Unlike cooperative surveillance systems, PSR does not depend on aircraft transmitting identification information or responding to transponder interrogation (ICAO, 2007).

This independence is a key strength of PSR in air-defence operations. Commercial aviation generally operates within a cooperative surveillance environment, where aircraft submit flight plans, communicate with air traffic control, and transmit identification and positional information through systems such as SSR and ADS-B. Foreign military aircraft, however, may not provide comparable cooperative information. PSR consequently enables Malaysia to establish the presence of an aircraft within a particular area regardless of whether cooperative surveillance data are available.

The importance of this capability is further reinforced by Malaysia's geographical environment. Aircraft approaching Malaysian territory may originate from the South China Sea or neighbouring states, creating a need for surveillance beyond immediate national airspace. Early PSR detection can provide additional time for identification, assessment and response, thereby extending its contribution from basic detection to the broader early-warning function of air defence.

Nevertheless, PSR is not a complete surveillance solution. ICAO notes that PSR does not inherently provide aircraft identity or altitude information, and that its effectiveness may be affected by terrain, obstacles, ground clutter and radar-site characteristics (ICAO, 2007). These shortcomings are especially important for low-altitude targets, for which the detection may be complicated by radar horizon limitations and clutter. PSR effectiveness therefore depends not only on technical capability but also on geographical deployment and operational conditions.

Coverage and availability further determine its practical value. Radar can contribute to national surveillance only where sufficient coverage exists and while the system remains operationally available. Maintenance requirements, technical failures and readiness issues may consequently affect surveillance continuity. Moreover, successful PSR detection does not by itself establish identity, intent or threat level. Its information must therefore be correlated with SSR, ADS-B, visual observations, and other intelligence sources. As ICAO (2025) recognises, PSR is particularly valuable when integrated with other surveillance systems. Thus, its greatest operational contribution arises from integration with identification, tracking, coverage, availability, and broader air-defence decision-making.

The Effectiveness of Secondary Radar in Malaysia

SSR performs a complementary function by enriching information about detected targets. CAAM's surveillance infrastructure includes long-range SSR and co-mounted PSR/SSR systems, confirming that secondary surveillance is an established component of Malaysia's wider aviation surveillance architecture (CAAM, 2024). The combination of these systems reflects an important principle of effective surveillance. Detecting an aircraft is only the first step; understanding its characteristics is equally important.

The main advantage of SSR is its capacity to provide information in addition to the physical presence of a target. In transponder mode, SSR can provide identification and

altitude information, thereby improving the accuracy and quality of the recognised air picture (ICAO, 2025). This capability is particularly valuable in civil aviation, where identifying and continuously monitoring cooperative aircraft supports safe and efficient air traffic management.

However, this strength also creates an important limitation for national air defence. SSR depends substantially on target cooperation. When an aircraft transmits a valid and compatible transponder response, SSR can significantly enhance identification and classification. Conversely, when an aircraft does not provide an appropriate response, the information available through SSR may be limited. This is particularly relevant to military surveillance, where aircraft cannot always be assumed to operate within the same cooperative environment as commercial aviation.

This limitation does not reduce the importance of SSR, but it clarifies its appropriate role. SSR should be understood as an identification-enhancing surveillance layer that complements independent detection rather than replacing it. Accordingly, PSR and SSR address different but interconnected requirements. PSR establishes that a target is present, while SSR provides additional information to determine what the target is.

For Malaysia, the objective should therefore not be to choose between PSR and SSR but to integrate their respective strengths. Combining PSR's independent detection with SSR's identification and altitude information can produce a more complete surveillance picture and directly supports the conceptual framework, in which detection and identification are interdependent dimensions of radar effectiveness. Ultimately, SSR provides greatest value when integrated with PSR and other surveillance sources to support timely air-defence assessment and decision-making.

Radar Coverage and the East Malaysian Challenge

Geography is a fundamental determinant of radar effectiveness, as the ability to detect and monitor aircraft depends substantially on the location, distribution and coverage of surveillance systems. This challenge is particularly significant for Malaysia because Peninsular and East Malaysia are separated by the South China Sea, creating extensive surveillance requirements across maritime approaches and highlighting the need for coverage beyond areas of concentrated civil aviation activity.

According to CAAM, Peninsular Malaysia has a fairly extensive radar and surveillance coverage along established air routes, but coverage is still uneven, with some lower-level areas along the eastern coast being an exception (CAAM, 2024). These limitations may be acceptable for civil aviation but are more significant for national air defence which needs monitoring of areas outside of existing routes and controlled airspace. Civil surveillance is mainly used for a safe and efficient management of cooperative air traffic. National air defence, however, also has to deal with unidentified, non-cooperative and possibly low-altitude targets in the vicinity of maritime or less frequently used areas.

This challenge is particularly felt in East Malaysia, where the large maritime approaches and geographically separated strategic areas of Sabah and Sarawak are involved. Malaysia has therefore enhanced the regional surveillance network through efforts such as

the replacement of ageing PSR/SSR systems, installation of a new PSR/SSR radar at Sandakan, and deployment of ADS-B sensors across Sabah and Sarawak, including Bario, Kapit, Sematan and Tawau (CAAM, 2025a). These developments demonstrate that effective surveillance requires not only technological upgrades but also the reduction of geographical and operational gaps. Accordingly, radar effectiveness ultimately depends on sufficiently wide, persistent and strategically positioned coverage across both Peninsular and East Malaysian approaches.

The GM400 and the Strengthening of Military Radar

The acquisition of the GM400 long-range radar for Bintulu represents an important development in Malaysia's air-defence architecture. The radar will enhance border control and Malaysia's ability to track aerial activity, particularly over the South China Sea (Bernama, 2023). Its importance does not lie solely in the modernisation of equipment but rather in an attempt to reinforce surveillance in a strategically important area of East Malaysia.

The strategic importance of the GM400 becomes clearer when the latter's position in relation to Malaysia's geographical surveillance needs is taken into account. Having a long-range radar at Bintulu brings surveillance capability closer to the approaches into East Malaysia and its maritime domain around it. Compared with relying predominantly on surveillance infrastructure in Peninsular Malaysia, a radar located in Borneo has greater potential to provide earlier awareness of aerial activity approaching Sabah and Sarawak. This illustrates an important principle of radar deployment. Surveillance architecture should be shaped by strategic geography rather than by existing concentrations of infrastructure.

This positioning also supports the concept of forward surveillance, whereby potential threats are detected as early as practicable before approaching or entering the defended area. Earlier detection provides additional time for operators to identify, assess and track a target before determining an appropriate response. This is particularly relevant to Malaysia because important approaches to its strategic airspace extend across maritime areas, where greater surveillance depth can provide valuable reaction time.

However, the advantages of increased surveillance range and forward positioning should not be equated with comprehensive surveillance capability. Like any radar system, the GM400 remains subject to operational and environmental limitations. Its actual contribution can be influenced by terrain, radar horizon, target altitude, environmental conditions, and system availability. Furthermore, detection alone cannot establish an aircraft's identity, intentions, or threat level. Thus, while the GM400 strengthens Malaysia's detection and early-warning capabilities, its effectiveness ultimately depends on the wider surveillance system within which it operates.

Accordingly, the GM400 should be assessed not as an isolated equipment capability but as part of a broader surveillance network. Integrating its information with other radar systems, ADS-B, electro-optical sensors, command-and-control infrastructure, and response aircraft can maximise its operational value. Consistent with the conceptual framework, the GM400 should therefore be regarded as one layer within a wider architecture in which coverage, availability and operational integration determine how effectively radar capability contributes to national air defence and the protection of sovereignty.

Equipment Availability and Radar Effectiveness

A significant finding from Malaysian parliamentary records concerns the relationship between radar acquisition and operational availability. Parliamentary material on the Coastal Surveillance System indicates that radar systems were deployed across 13 locations in eastern Sabah. However, the same records also identified significant equipment problems including five AESA SPEXER 2000 radar systems rated as damaged beyond economical repair (Parliament of Malaysia, 2023). This evidence suggests an important difference between the physical presence of surveillance infrastructure and its actual operational contribution to national air defence.

In this regard, an installed radar is not necessarily an operational radar. Acquisition and deployment represent only the initial stages of developing surveillance capability. Its actual value depends on whether the system remains available and capable of providing reliable surveillance when required. A radar undergoing prolonged maintenance, lacking critical components or otherwise unavailable, cannot support real-time detection regardless of its nominal technical specifications. Radar availability should therefore be regarded as a core capability indicator rather than merely a logistical concern.

This distinction shifts attention from equipment procurement towards lifecycle capability management. Radar effectiveness is ensured by continuous maintenance, availability of spare-parts, technical expertise, software support, infrastructure, and trained personnel. It also requires planned replacement when systems become obsolete or uneconomical to maintain. These issues become particularly important for geographically dispersed radar networks, where logistical difficulties and long downtimes may directly impact surveillance continuity.

Redundancy and system resilience also strongly influence availability. Depending on individual radar sites too much can create significant surveillance blind spots whenever a system is down or becomes unavailable. Radar coverage may overlap, mobile surveillance assets and complementary sensors may provide alternative sources of information and decrease the operational impact of individual equipment failures.

Taken together, the parliamentary evidence demonstrates that radar effectiveness cannot be measured simply by the number of systems acquired or installed. A more meaningful assessment considers whether systems remain operationally available, adequately supported, and integrated within a resilient network. This directly supports the conceptual framework, in which coverage and availability constitute a distinct dimension of radar effectiveness. Malaysia's radar modernisation should therefore extend beyond procurement to encompass maintenance, technical sustainability, training, redundancy, and lifecycle management to achieve persistent and reliable air-defence surveillance.

Low-Altitude and UAV Surveillance

The proliferation of unmanned aerial vehicles (UAVs) presents a growing challenge to radar-based air defence, as conventional surveillance systems are primarily designed for manned aircraft. UAVs are often smaller, slower and capable of low-altitude flight, making consistent detection and tracking difficult, particularly in environments affected by terrain, buildings and ground clutter (Choi et al., 2019). This challenge is compounded by Malaysia's reliance on

cooperative surveillance technologies, as SSR and ADS-B depend on aircraft-transmitted information that small or unequipped UAVs may not provide (Patel et al., 2018). PSR therefore remains important as an independent detection capability, although small radar cross-sections, low-altitude operations and ground clutter can also limit its effectiveness (Choi et al., 2019). These limitations highlight the need for a layered counter-UAS surveillance architecture integrating PSR with complementary technologies, including electro-optical and infrared systems, passive sensors and other appropriate surveillance capabilities. For Malaysia, future radar modernization should address not only conventional aircraft but also small, low-altitude and potentially non-cooperative aerial systems. Consequently, surveillance effectiveness will increasingly depend not solely on radar detection range but on the integration of multiple sensors to support persistent and reliable low-altitude airspace awareness, including the detection, identification and tracking of UAVs that individual sensors may not consistently observe.

Civil-Military Coordination

One of the most significant findings of this analysis is that radar effectiveness should be understood as an institutional as well as a technological issue. Although Malaysia possesses surveillance capabilities distributed across different organizational settings, the availability of sophisticated sensors does not, in itself, guarantee effective airspace surveillance. The operational value of these capabilities ultimately depends on the extent to which surveillance information can be shared, correlated, and transformed into actionable knowledge across institutional boundaries.

This is especially so in the respective roles of the Civil Aviation Authority of Malaysia (CAAM) and the Royal Malaysian Air Force (RMAF). CAAM's surveillance and air traffic management framework acknowledges the importance of civil-military coordination, while the National Air Navigation Plan seeks to modernize surveillance infrastructure and enhance interoperability with regional and global air navigation systems (CAAM, 2025b). However, formal recognition of coordination needs should not be mistaken for real operational integration. The fact that coordination mechanisms exist does not necessarily show that information can be exchanged and processed fast enough in the course of an evolving security incident.

This is a crucial distinction as civil and military surveillance follow different institutional priorities. Whilst CAAM is mainly focused on civil air traffic management in a safe and efficient manner, the RMAF is responsible for air defence and protection of national sovereignty. These functions increasingly converge when an unidentified or suspicious aircraft is detected. What initially constitutes a routine air traffic management matter may rapidly acquire national security significance depending on the aircraft's identity, behaviour, trajectory, or proximity to sensitive areas.

Consequently, radar effectiveness cannot be assessed solely by whether a target is detected. It must also consider whether relevant information reaches the appropriate decision-making authority in sufficient time to support identification, threat assessment, and response. Fragmented information across agencies can therefore create an operational gap even when the underlying surveillance data are available. This reinforces Hall and Llinas'

(1997) argument that the integration of information from multiple sources enhances situational awareness.

The central institutional challenge, therefore, is not necessarily information scarcity but the capacity to convert distributed surveillance information into a coherent national air picture. Operational integration consequently represents a critical determinant of radar effectiveness, linking technological detection capabilities with timely and informed air-defence decision-making.

Radar Integration and the Common Operational Picture

The development of a Common Operational Picture (COP) should therefore become a central objective of Malaysia's airspace-security modernisation. Building on the need for stronger institutional integration, the COP should bring together relevant information from PSR, SSR, ADS-B, military long-range radar, maritime surveillance, electro-optical sensors, UAV systems, communications networks and appropriate intelligence sources. The purpose, however, should not necessarily be to merge every sensor into a single technical system but to ensure that authorised decision-makers receive a coherent, timely and integrated representation of the airspace.

Achieving this objective requires effective multisensor data fusion. The literature indicates that integrating information from multiple sources can reduce uncertainty and improve situational awareness by allowing the strengths of one sensor to compensate for the limitations of another (Hall & Llinas, 1997). This is particularly important in air defence, where no single surveillance technology can provide complete and continuous awareness of all aerial activity.

The practical value of such integration can be illustrated through a layered surveillance process as follows:

PSR detects → SSR identifies → ADS-B provides cooperative information → electro-optical sensors verify → command systems evaluate.

Each layer contributes different information, allowing operators to develop a more reliable assessment of an aircraft's identity, location, and behaviour. Consequently, the effectiveness of the surveillance architecture lies not simply in the capability of individual sensors but in how effectively their information is combined to support decision-making. A well-integrated COP would therefore provide Malaysia with a more resilient basis for detecting, assessing, and responding to both conventional aircraft and emerging aerial threats.

Radar Effectiveness and the Air-Defence Decision Cycle

The ultimate test of radar effectiveness is its contribution to operational decision-making. In an air-defence context, the decision cycle can be represented as follows:

Detect → Identify → Track → Assess → Decide → Respond.

Although radar primarily supports detection, identification and tracking, the quality and timeliness of this information directly influence the subsequent stages of assessment and response.

Building on this relationship, early detection provides decision-makers with greater time to assess and respond to a potential threat. Radar range is therefore relevant because earlier detection can increase the available decision window. But range alone doesn't determine operational effectiveness. A long-range radar may have little practical value if the information it provides is poorly integrated or the target cannot be tracked continuously. In contrast, multiple overlapping sensors can increase the operational value by maintaining a reliable track across the surveillance area (Hall & Llinas, 1997).

This distinction points up the significance of ongoing surveillance. Instead of focusing only on the maximum nominal detection range, Malaysia's air-defence architecture should emphasise the ability to maintain continuous awareness of relevant aerial targets throughout the decision cycle. Persistent surveillance reduces uncertainty by ensuring that detected targets stay visible for identification, tracking and threat assessment. In contrast, intermittent tracks that reappear and disappear repeatedly may complicate assessment and may delay a proper response.

Accordingly, radar effectiveness should be understood not simply as the ability to detect targets at long range, but as the ability to provide timely, continuous and reliable information that supports the complete operational decision cycle.

Radar, Deterrence and Sovereignty

Radar possesses strategic value beyond its immediate surveillance function because its ability to detect aerial activity can contribute to the credibility of Malaysia's deterrence posture. From a deterrence perspective, Morgan (2003) emphasizes that deterrence depends not simply on possessing military capability but on whether that capability is perceived as credible by the potential challenger. Radar therefore contributes to deterrence by providing the surveillance capability necessary to demonstrate that activities approaching Malaysian territory can be detected and monitored.

Building on this theoretical relationship, however, detection alone does not constitute effective deterrence. The value of radar capability depends on whether it is connected to a credible capacity and willingness to respond. In this sense, the 31 May 2021 PLAAF incident provides an important illustration. The RMAF detected the 16 aircraft and initiated an operational response, and the Malaysian Government subsequently issued a diplomatic protest. The sequence demonstrates how surveillance capability can be translated into visible operational and diplomatic action, thereby reinforcing the credibility of Malaysia's response.

Consequently, radar contributes to deterrence by strengthening the connection between awareness, capability, and credible response. Its strategic significance therefore extends beyond identifying aircraft: effective radar enables Malaysia to demonstrate that its airspace is monitored, potential violations can be detected, and appropriate state responses can follow. In this respect, radar becomes an important supporting capability for the protection of national sovereignty and the credibility of Malaysia's deterrence posture (Morgan, 2003).

Findings

The evidence identifies five principal findings demonstrating both the strengths and structural limitations of Malaysia's radar-based air-defence mechanism. First, PSR remains indispensable as an independent means of detecting aircraft without relying on transponder cooperation, particularly for non-cooperative or unidentified targets (ICAO, 2007). Second, SSR remains essential as a complementary system, providing identification and altitude information from cooperative aircraft; however, its reliance on aircraft cooperation prevents it from replacing PSR. Third, radar coverage does not automatically equate to effectiveness, as geographical positioning, terrain, target altitude, system availability and maintenance influence operational performance. Fourth, Malaysia's radar architecture continues to evolve, as demonstrated by GM400 acquisition and ADS-B expansion, although capability enhancement cannot rely solely on individual systems. Fifth, integration represents the principal strategic challenge. Integrating PSR, SSR, ADS-B and other surveillance sources can enhance situational awareness and decision-making (Hall & Llinas, 1997). Collectively, the findings indicate that Malaysia's radar mechanism is functionally effective but structurally constrained, with overall effectiveness dependent on coverage, availability and, most importantly, the timely integration of information into an effective national air-defence response.

Strategic Recommendations

The findings indicate that Malaysia's radar capability is functionally effective but constrained by limitations in coverage, availability, and operational integration. The following recommendations therefore emphasise the need to strengthen surveillance resilience, information integration, and civil-military coordination.

Maintain PSR as the Independent Surveillance Layer

Malaysia should continue to regard Primary Surveillance Radar (PSR) as a fundamental component of national air defence because it provides an independent means of detecting aircraft without relying on transponder cooperation. Although the expansion of SSR and ADS-B can enhance identification, tracking, and situational awareness, these systems remain dependent on information transmitted by aircraft and therefore cannot fully substitute for PSR, particularly when dealing with non-cooperative or unidentified targets (ICAO, 2007). Malaysia should consequently maintain a complementary surveillance architecture in which PSR provides the independent detection layer, while SSR and ADS-B enhance the quality and depth of the recognised air picture.

Expand Layered Surveillance

Malaysia should further develop a layered surveillance architecture incorporating long-range, medium-range, and low-level radar, together with SSR, ADS-B, and complementary sensors. Such an architecture would allow different systems to compensate for their respective limitations, particularly where terrain, altitude, or target characteristics affect detection. Overlapping coverage would also reduce reliance on any single sensor and improve resilience when individual systems are unavailable or experience technical failures. This approach is consistent with multisensor fusion principles, whereby information from multiple sources can enhance surveillance reliability and situational awareness (Hall & Llinas, 1997). Layered surveillance would therefore provide a more resilient and persistent air-defence picture than reliance on individual systems alone.

Strengthen East Malaysian Coverage

East Malaysia should remain a priority for radar development because its geographical exposure, extensive maritime approaches, and proximity to the South China Sea generate significant surveillance requirements. These conditions make persistent early warning particularly important for protecting Malaysia's territorial airspace and maritime interests.

The installation of the GM400 radar at Bintulu is a major step in improving long-range surveillance in the area (Bernama, 2023). It should be seen, however, as part of a larger surveillance network rather than as an isolated contribution. The GM400 should be supplemented with overlapping radar coverage, ADS-B and complementary sensors to reduce surveillance gaps and to ensure continuity when individual systems are unavailable. This would strengthen the resilience and persistence of Malaysia's air defence surveillance architecture.

Establish a National Common Operational Picture

Surveillance information from CAAM, RMAF, and other relevant government agencies should be capable of integration into a secure national airspace picture. Such integration would provide authorised users with a more comprehensive and timely understanding of aerial activity by combining information from multiple surveillance sources.

This objective does not require the organisational merger of existing agencies. Rather, it requires effective system interoperability, agreed data-sharing procedures, and clearly defined authorities for accessing, assessing, and acting upon shared information. Consistent with multisensor data-fusion principles, integrating information from different sources can improve situational awareness and decision-making (Hall & Llinas, 1997). Institutional coordination should therefore prioritise the integration of information and decision processes while preserving the respective mandates of each agency.

Institutionalise Civil-Military Coordination

Malaysia should institutionalise a clear response sequence for interconnected airspace contingencies:

Detect → Verify → Identify → Assess → Coordinate → Respond → Escalate

An aircraft assessed as suspicious should first undergo verification; where identification remains unavailable, it should be treated as an unidentified aircraft. Loss of a transponder or communications should trigger alternative verification measures, while identification of a foreign military aircraft should activate established assessment, interception, and escalation procedures. Similarly, a UAV incursion should undergo enhanced detection and classification, while radar or communications failure should immediately activate alternative sensors and communication channels. Where civil and military incidents occur simultaneously, clearly defined authorities should determine prioritisation and coordination.

Regular multi-agency exercises should test the complete sequence rather than isolated procedures, ensuring that information, authority, and response remain connected under operational pressure (Endsley, 1995). This would strengthen Malaysia's ability to translate surveillance information into a timely and coordinated national response.

Introduce Radar Availability as a Capability Indicator

Future assessments of Malaysian air-defence capability should move beyond counting radar systems and instead evaluate how each system contributes to the wider surveillance network. A capability flow can be expressed as:

Availability → Coverage → Redundancy → Detection Performance → Operational Integration → Effective Surveillance

Each stage should incorporate measurable indicators. Operational availability rates, system downtime, and mean time to repair may be used to evaluate availability. Coverage is defined by the percentage of designated airspace that is monitored and the existence of persistent coverage gaps. Redundancy can be measured by overlapping coverage and the availability of alternative sensors, and the ability to continue surveillance following the failure of individual systems. Detection performance can be defined by detection probability, detection range and tracking continuity. The operational integration can be measured by the data-sharing reliability, sensor-fusion latency, common-air-picture availability, and response time. These indicators provide a more meaningful assessment of radar capability because they demonstrate whether installed systems are available, geographically effective, resilient, operationally capable, and integrated into decision-making (Hall & Llinas, 1997). An unavailable radar should therefore not be regarded as equivalent to a fully operational system.

Conclusion

This article examined the effectiveness of Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR) within Malaysia's air-defence mechanism. The findings confirm that both remain essential but serve complementary functions. PSR enables independent detection of non-cooperative targets, while SSR provides identification and flight information for cooperative aircraft. Together with ADS-B and military surveillance systems, they form key elements of Malaysia's surveillance architecture.

The 31 May 2021 PLAAF incident demonstrates the operational importance of independent radar capability. However, radar effectiveness is influenced by geography, coverage, altitude, availability, maintenance, and operational integration. Accordingly, effectiveness should be understood as a system-level rather than equipment-level concept, requiring detection, identification, tracking, information integration, and timely decision-making.

Malaysia should therefore pursue a layered surveillance architecture integrating PSR, SSR, ADS-B, long-range military radar, and complementary sensors into a common operational picture. Future capability assessments should emphasise availability, coverage, redundancy, detection performance, and integration, thereby strengthening persistent airspace awareness and Malaysia's capacity to safeguard national sovereignty and territorial integrity.

Acknowledgement

The author wishes to thank the National Defence University of Malaysia, University Malaysia of Sabah and University Science Islam of Malaysia for funding this research under the

Collaborative Research Grant (CRG/2020/SSK/5) and Short Research Grant (J0419 – UPNM/GPJP2025/SSI/8).

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