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Artigos Dossiê

Artificial intelligence in SAR imagery: new frontiers for National Defense

Inteligência artificial em imagens SAR: novas fronteiras para a Defesa Nacional

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Abstract

This study examines the strategic application of Artificial Intelligence (AI) to Synthetic Aperture Radar (SAR) imagery for monitoring and protecting critical areas of national interest. Focusing on the Brazilian Air Force (FAB), it employs a qualitative and exploratory approach grounded in systematic literature review and documentary analysis. The research evaluates SVM, CNN, GAN, and Transformer models according to accuracy, adaptability, and operational relevance. The findings identify three strategic pathways—incremental refinement, synthetic data generation, and hybrid integration—demonstrating that AI–SAR convergence strengthens situational awareness, supports decision-making in strategic domains, and enhances defense capabilities essential to technological autonomy and national sovereignty.

Keywords: Artificial intelligence; Synthetic Aperture Radar; Deep learning; Military innovation; National Defense

Resumo

Este estudo examina a aplicação estratégica da Inteligência Artificial (IA) em imagens de Radar de Abertura Sintética (SAR) para o monitoramento e a proteção de áreas críticas de interesse nacional. Com foco na Força Aérea Brasileira (FAB), a pesquisa adota uma abordagem qualitativa e exploratória, fundamentada em revisão sistemática da literatura e análise documental. O trabalho avalia modelos SVM, CNN, GAN e Transformer quanto à precisão, adaptabilidade e relevância operacional. Os resultados identificam três caminhos estratégicos — refinamento incremental, geração de dados sintéticos e integração híbrida —, demonstrando que a convergência entre IA e SAR fortalece a consciência situacional, apoia a tomada de decisões em domínios estratégicos e aprimora capacidades de defesa essenciais para a autonomia tecnológica e a soberania nacional.

Palavras-chave: Inteligência artificial; Radar de Abertura Sintética; *Deep learning*; Inovação militar; Defesa Nacional

INTRODUCTION

Synthetic Aperture Radar (SAR) is a remote sensing technology capable of producing detailed images of the Earth's surface regardless of weather or lighting conditions. This characteristic makes SAR essential for the continuous monitoring of large areas, with strategic applications in security, defense, and disaster response. In contemporary conflict scenarios, this technology has been widely employed to enhance situational awareness and support military decision-making (Meyer, 2019).

In Brazil, the Brazilian Air Force (FAB) has integrated SAR sensors into maritime patrol, reconnaissance, and search-and-rescue aircraft, as well as into satellites developed under the Strategic Space Systems Program (PESE) (Ministry of Defence, 2018). The Lessonia-1 project marks a milestone in this process, enabling the country to autonomously operate synthetic aperture radar satellites for the surveillance of strategic areas (Brazilian Air Force, 2025). Despite these advances, the interpretation of acquired images remains highly dependent on manual analysis, which requires significant time and specialized labor.

This limitation underscores the need to explore technological solutions that increase the efficiency and reliability of image processing. In this context, Artificial Intelligence (AI) emerges as a promising alternative for automating analysis, allowing for the rapid and accurate identification of relevant targets. Techniques such as Support Vector Machines (SVM), Convolutional Neural Networks (CNNs), Generative Adversarial Networks (GANs), and Transformers have already been applied to Automatic Target Recognition (ATR) in several countries, enabling the differentiation of vessels, vehicles, and clandestine airstrips in near real time. It is noteworthy that the FAB has already begun implementing some of these tools in the monitoring of strategic areas, achieving significant results in combating illicit activities—such as the detection of illegal mining dredges—although several other possibilities remain unexplored (Aerospace Operations Command, 2025).

Given this scenario, the present study seeks to answer the following research question: How can the application of Artificial Intelligence to SAR image processing enhance the Brazilian Air Force's capability to monitor strategic regions? The general objective is to analyze recent advances in the integration of AI with SAR sensors within the FAB, focusing on improving the monitoring of strategic areas. Specifically, the study aims to: (i) review the literature on AI applied to SAR imagery; (ii) map the current capacity of the Brazilian Air Force to acquire and process SAR images; and (iii) identify Artificial Intelligence techniques with the greatest potential for operational application in the national context. To achieve these goals, the study adopts a qualitative and exploratory approach, based on bibliographic and documentary review.

The strategic relevance of integrating SAR and AI can be observed in recent conflicts, such as the war in Ukraine, where SAR imagery, combined with deep learning algorithms, has been crucial for tracking troop movements, assessing infrastructure damage, and supporting humanitarian operations (Dietrich et. Al., 2024). These examples demonstrate that autonomous mastery of such technologies represents not merely an operational advantage, but a necessity for any modern air force.

The article is organized into five sections. Following this introduction, the second section presents the theoretical framework, addressing the fundamentals of SAR and AI techniques applied to SAR processing. The third section outlines the methodology, while the fourth presents the data analysis and results concerning the use of SAR by the FAB, highlighting the challenges and opportunities for strengthening national sovereignty. Finally, the article concludes by emphasizing the research contributions and suggesting potential directions for future work.

THEORETICAL FRAMEWORK

The present section aims to present the theoretical foundations underpinning this research, addressing the key concepts, technologies, and methodologies related to the use of SAR and AI in the context of Intelligence, Surveillance, and Reconnaissance (ISR) operations, with emphasis on their employment by the FAB.

Given the wide scope of Artificial Intelligence, this study focuses on data processing and analysis methodologies based on Machine Learning and Deep Learning, due to their relevance and growing application in complex operational scenarios. The purpose is to provide a solid conceptual basis to understand both the physical and operational aspects of SAR and the AI-based data processing and analysis methods that have been progressively incorporated by the FAB in complex operational environments.

Initially, this section addresses the fundamental concepts related to SAR functioning, including its technical characteristics, operational advantages, and limitations, highlighting its applicability in environments with dense vegetation cover, high cloudiness, or adverse conditions, where traditional optical sensors present constraints. Subsequently, it discusses the main Artificial Intelligence techniques applied to SAR image analysis, from classical methods such as SVMs to more advanced approaches such as CNNs, GANs, and Transformer-based models.

Characteristics and potential of Synthetic Aperture Radar

Monitoring large territorial areas—especially in contexts where meteorological conditions, dense forest cover, or lack of sunlight impose challenges on conventional optical sensors—demands technologies capable of providing accurate and continuous information. In this scenario, SAR emerges as one of the most advanced tools in the field of remote sensing, widely used for both civil and military applications (Bezerra, 2021).

Unlike optical sensors, SAR operates in the microwave region of the electromagnetic spectrum and is capable of generating detailed images of the Earth's surface regardless of climatic conditions (rain, clouds, or fog) or the diurnal cycle, since it does not depend on sunlight for data acquisition (NASA, 2025). More specifically, the technique involves pulse compression and signal processing to synthesize a large angular aperture—known as a synthetic aperture—simulating an antenna physically much larger than the real one, thereby producing high-resolution images (Bezerra, 2021).

The wavelength is a critical characteristic to consider when working with SAR, as it determines how the radar signal interacts with the surface and how deeply it can penetrate a medium. For example, an X-band radar, operating at a wavelength of approximately 3 cm, has limited penetration capacity in broadleaf forests and primarily interacts with the foliage at the top of the canopy. Conversely, an L-band signal, with a wavelength of about 23 cm, can penetrate deeper into the canopy and interact more significantly with large branches and tree trunks (NASA, 2025).

In addition to wavelength, another essential factor in characterizing SAR imagery is spatial resolution. According to the Glossário das Forças Armadas (2015), spatial resolution refers to the smallest portion of the terrain that a sensor is able to distinguish, which determines whether an object can be detected or recognized in the resulting image. In simpler terms, spatial resolution represents the level of detail that an image can display on the surface—that is, the minimum size of an object that can be visualized and differentiated.

However, there is an intrinsic relationship between higher spatial resolution and the amplification of the phenomenon known as speckle. This granular noise, characteristic of SAR images, results from the coherent interference of radar waves reflected by multiple scatterers located within the same resolution cell. When spatial resolution increases—meaning that each pixel represents a smaller ground area—the sensor begins to capture echoes from finer surfaces, making the interference effects, whether constructive or destructive, more pronounced. Thus, although higher resolution allows for more detailed observations, it also enhances speckle granularity, which can affect both the visual quality of the image and the accuracy of its interpretation (Saatchi, 2019).

Despite this challenge, one of the advantages of using SAR data goes beyond simple surface imaging. SAR technology also enables advanced analyses such as interferometry, a method known as Interferometric SAR (InSAR). This technique utilizes the phase information of the radar signal recorded by the sensor to calculate, with extreme precision, the distance between the sensor and the ground target. When two or more observations of the same area are taken at different times, these measurements can be compared to detect minute changes in surface topography, indicating phenomena such as ground deformation, slope displacement, subsidence, and the consequences of events like earthquakes, volcanic eruptions, or mass movements (Meyer, 2019).

Therefore, although speckle may represent a limitation for the visual aspect of SAR images, the same physical principle that generates speckle—the coherence of the radar signal—is what enables the extraction of phase information used in interferometric analyses (Meyer, 2019). This transforms SAR from a mere imaging instrument into a powerful tool for the precise monitoring of millimetric deformations in the Earth's crust, demonstrating its versatility and relevance for both environmental applications and defense and security purposes (Kellndorfer, 2019).

In summary, SAR stands out as a strategic tool for military applications, environmental monitoring, and geodynamic risk management, requiring a constant balance among spatial resolution, frequency band selection, and control of speckle effects.

Artificial intelligence and SAR imagery

In the defense sector, there is a growing need for automation, precision, and speed in interpreting large volumes of geospatial data—a scenario that has driven the adoption of AI techniques in the context of remote sensing. The automation of image processing through AI enables the efficient extraction of information and decision-making with minimal human intervention, resulting in faster and more reliable data outputs (NASA, 2025).

The relevance of this capability transcends efficiency gains; it is also a matter of national sovereignty. The incorporation of cutting-edge technologies such as AI and quantum technologies empowers a nation to develop autonomous solutions to its strategic challenges (Costa et. al., 2025). However, informational sovereignty is not consolidated merely through the possession of technology, but through the continuous ability to develop, adapt, and sustain it—an endeavor that demands persistent investment in research and development (R&D), infrastructure, and, crucially, in the training and retention of specialized human capital. The mere existence of scientific competence does not guarantee its application in defense; it is essential to overcome structural and cultural barriers that have historically limited collaboration and innovation within the sector (Franco-Azevedo et. al., 2021).

Therefore, the application of AI to SAR imagery exemplifies this technological race, in which success depends not only on technical excellence but also on the ability to articulate the innovation ecosystem. Against this backdrop, the present section aims to examine the evolution of Artificial Intelligence techniques applied to the analysis of Synthetic Aperture Radar imagery, with emphasis on their use in defense contexts.

In the field of target recognition in SAR images, different AI techniques have been progressively incorporated. Initially, more traditional machine learning methods, such as Support Vector Machines (SVMs), were employed (Zhao; Principe, 2001). SVMs are classification algorithms designed to separate datasets through a hyperplane that distinguishes data classes. In the case of SAR imagery, SVMs demonstrated strong performance on databases such as Moving and Stationary Target Acquisition and Recognition (MSTAR), although they faced challenges in more complex contexts involving high angular variation (Wang et al., 2006).

Even with these constraints, SVMs played a foundational role in the early automation of SAR image interpretation. Their performance on benchmark datasets established an important baseline for subsequent advances, and their conceptual simplicity facilitated widespread adoption in the initial phases of ATR research. Over time, more sophisticated approaches emerged, yet hybrid strategies that combine SVMs with deep learning models and synthetic data generation remain relevant, particularly in environments characterized by limited or imbalanced training samples. This historical contribution underscores the enduring significance of SVMs in shaping current methodologies in the field (Gomes et. al., 2015).

A turning point in image analysis—including that of SAR imagery—was the rise of deep learning, particularly CNNs, which include convolutional layers to extract relevant information, revolutionized Automatic Target Recognition in SAR imagery. By automatically learning complex hierarchical spatial patterns directly from raw data, this capability has substantially improved accuracy (Falqueto et. al., 2023) .

Studies conducted on the MSTAR dataset have reported accuracies frequently above 90%, in some cases reaching values close to 100% (Morgan, 2015). However, it is important to note that such high performance is typically achieved in controlled environments with specific datasets. Generalization to complex operational scenarios and unseen data remains a significant challenge, requiring robust and adaptable models. Thus, although CNNs have become one of the leading techniques for ATR in SAR imagery, their effectiveness depends heavily on the availability of large, labeled datasets—a critical constraint in defense contexts, where access to real operational data is limited.

To address this limitation, Generative Adversarial Networks have emerged as a promising solution. GANs can artificially expand training datasets by generating realistic synthetic samples, mitigating data scarcity and enhancing the performance of algorithms such as SVMs and CNNs. Studies have shown that models trained on GAN-generated data can achieve performance comparable to those trained on real data, while offering greater adaptability to new scenarios (Araujo et. al., 2022). Nevertheless, the effective application of GANs to overcome data scarcity is not trivial and requires careful consideration, particularly due to the domain shift problem—that is, discrepancies between synthetic and real data domains.

Although domain shift remains an intrinsic challenge when synthetic data are used to train models for operational contexts, recent literature has proposed several mitigation strategies. One possibility involves combining transfer learning with fine-tuning based on small sets of real samples, achieved through adjustments in GAN discriminators that incorporate additional representational layers to better handle unsupervised domains. Another line of research explores semi-supervised CNNs integrated with GAN architectures that employ multiple discriminators to enhance robustness against domain variations (Zhang et. al., 2019).

In addition, methods such as Progressive Growing of GANs (PGGAN) enable the synthesis of minority-class samples, balancing training datasets and reducing bias. Strategies involving pre-training on broader datasets followed by domain-specific fine-tuning, as well as adversarial learning frameworks integrated with operational validation processes, have also proven valuable in enhancing model fidelity under real operational conditions (Araujo et. al., 2022).

More recently, the field has advanced toward Transformer-based models. Unlike CNNs, which focus on local patterns through convolutions, Transformers use self-attention mechanisms to analyze entire images holistically, capturing complex spatial and contextual relationships (Dosovitskiy, 2021). This approach provides significant gains in classification and detection tasks and has emerged as one of the most promising directions in radar-based remote sensing. The Vision Transformer (ViT) architecture, in particular, has demonstrated superior performance to CNNs in classifying maritime geophysical phenomena (Xia, 2025). In specific contexts, Transformer-based models therefore represent the cutting edge of SAR image analysis, offering superior capacity to learn complex and contextual patterns with greater adaptability and generalization. Nonetheless, their high computational cost for both training and inference remains a limitation, especially for embedded or real-time applications (Xia, 2025).

In summary, the evolutionary trajectory of AI techniques applied to SAR imagery can be outlined as follows: SVMs marked the beginning, introducing the first stage of automation; CNNs significantly increased accuracy by autonomously learning visual features; GANs addressed data scarcity through realistic synthetic generation; and Transformers now represent the state-of-the-art frontier, offering enhanced adaptability and robustness in specific scenarios. Each technique has contributed in distinct ways, consolidating AI as a central component in advancing ATR for SAR imagery and strengthening operational defense capabilities.

However, this scientific evolution translates into national sovereignty only when coupled with consistent long-term innovation policies, since these technologies require sustained investment, continuous training, and integration with institutional strategies. They are not merely resources that can be purchased or freely accessed but represent scientific, technological, and operational competencies whose consolidation is decisive for enhancing national security and defense capabilities. This consolidation embodies the true essence of informational sovereignty, achieved through full mastery of the technological life cycle.

METHODOLOGY

This study adopts a qualitative and exploratory approach, grounded in bibliographic and documentary research as its primary tools for data collection and analysis. The exploratory nature of the research is justified by the scarcity of prospective studies addressing the use of AI techniques applied to the analysis of Synthetic Aperture Radar imagery within the Brazilian Air Force. Although widely discussed in international literature, this topic still lacks systematic examination in a national context (Creswell, 2018). The choice of a qualitative method enables interpretive analysis of both technical and contextual data, allowing the identification of operational nuances that would hardly be captured through purely quantitative approaches (Patton, 2014).

Data collection was structured in two complementary stages. In the first stage, a literature review was conducted between January and February 2025 using national and international academic databases, including Scopus, Web of Science, IEEE Xplore, arXiv, Wiley Online Library, Google Scholar, and the Digital Library of Intellectual Production of the Brazilian Air Force. The review considered works published between 2006 and 2025, in Portuguese and English, that addressed the application of AI to SAR image processing. Exclusion criteria included documents lacking thematic relevance, opinion-based publications without technical or scientific grounding, and works with restricted access that prevented content validation.

In the second stage, documentary research was carried out to collect institutional regulations and technical reports from the FAB, such as the Basic Doctrine of the Brazilian Air Force, documents from the Lessonia Project, and reports from the Aerospace Operations Command (COMAE). This procedure was essential to ensure dialogue between academic literature and current operational practices. The articulation between these two categories of data made it possible to integrate academic and operational perspectives, aligning the study with both the international state of the art and the institutional context of Brazil.

Data analysis was conducted using content analysis techniques, allowing for the comparative categorization of the selected AI approaches (Bardin, 2011). To ensure methodological rigor and reliability, four central evaluation metrics were established: accuracy, computational performance, generalization capability, and reduction of false positives and false negatives. Based on these metrics, four main classes of algorithms were analyzed: Support Vector Machines , Convolutional Neural Networks , Generative Adversarial Networks , and Transformer-based models, including the Vision Transformer (ViT).

Although the research is primarily bibliographic and documentary in nature, a data triangulation strategy was adopted, whereby different sources—academic books, official documents, and scientific articles—were systematically cross-referenced. This procedure aimed to enhance the validity of the findings and minimize biases that could result from relying on a single source (Lincoln; Guba, 1985).

ANALYSIS AND DISCUSSION

Current capabilities of the Brazilian Air Force in SAR and AI

The current capabilities of the Brazilian Air Force in employing Synthetic Aperture Rada and Artificial Intelligence reflect a gradual modernization process that has been consolidated across both aerial and space-based platforms. This evolution strategically positions the FAB within the field of Intelligence, Surveillance, and Reconnaissance (ISR) operations, while also highlighting the importance of integrating emerging technologies to enhance situational awareness in complex environments.

At the aerial level, the FAB has incorporated a set of aircraft equipped with multimode SAR sensors, thereby consolidating a technological capability of high strategic value. As noted in the theoretical framework, the main advantage of these systems lies in their ability to operate under adverse weather conditions and in low-light environments—factors that limit the effectiveness of conventional optical sensors. This feature grants the FAB greater operational flexibility and enhances its situational awareness, a particularly relevant aspect in the Amazon region, where dense forest cover and climatic instability pose persistent challenges to aerial monitoring.

Among the aircraft equipped with SAR, the R-99 stands out for its multispectral sensor suite, which includes both SAR and ISAR systems and has proven its relevance in search and rescue missions—such as in the case of the Air France Flight AF447 accident and in the search for the wreckage of GOL Flight 1947, which crashed in the Amazon. This experience, although it revealed inherent limitations of the technology—such as the occurrence of "false alarms" due to limited understanding of SAR potential in maritime search and its inability to provide visual identification of located targets—also demonstrated the radar's versatility and its capacity to deliver critical data in emergency situations. These outcomes opened pathways for future enhancements through integration with Artificial Intelligence techniques (Leite; Habermann, 2013).

In addition to the R-99, other aircraft such as the P-3AM, SC-105, P-95BM, and KC-390 have expanded the range of SAR sensors available to the FAB, each contributing specific detection, mapping, and reconnaissance capabilities (Mesquita, 2021). The Gabbiano T-20N radar, developed by Leonardo Company for the KC-390, exemplifies this versatility: capable of operating in multimode configurations, it supports maritime surveillance, high-resolution ground mapping (Spot SAR and Strip SAR), Ground Moving Target Tracking (GMTT), and terrain mapping for navigation (Leonardo Company, 2025). These platforms demonstrate that, although the FAB already possesses high-performance systems, there remains considerable potential for expanding applications and integrating automation solutions based on AI.

At the space level, the Lessonia Project, part of the Strategic Space Systems Program (PESE), represents a milestone in the pursuit of national autonomy in remote sensing (Ministry of Science, Technology and Innovation, 2022). The launch of the Carcará I and II satellites, both equipped with SAR sensors, marks a major strategic step—not only in expanding territorial surveillance but also in establishing a solid foundation for technological independence. These satellites are capable of producing very high-resolution imagery at any time of day or night, regardless of weather conditions, directly addressing Brazil's defense and security requirements (Ministry of Science, Technology and Innovation, 2022). The effectiveness of this technology for monitoring illicit activities in the Amazon, such as selective logging, has been validated by studies employing Convolutional Neural Networks (CNNs) on X-band radar data, achieving accuracies exceeding 90% in detecting changes in forest cover (Kuck et. al., 2021).

In summary, the set of capabilities currently available allows it to be demonstrates that the FAB possesses a technological architecture capable of monitoring vast areas under adverse conditions—such as the Amazon region—while ensuring informational superiority and reducing operational costs.

Turning specifically to the use of Artificial Intelligence in SAR imagery, its incorporation into the Brazilian Air Force has been gradual and directly tied to operational needs. According to the 2025 Report on the Development of Computer Vision at the Joint Intelligence Operations Center (CCOI), in 2021 the analysis of SAR images was still conducted manually, without automated support—an approach that limited accuracy and significantly increased response times to threats and disasters (Aerospace Operations Command, 2025). In this context, a military researcher engaged in ISR missions, affiliated with the Aeronautics Institute of Technology (ITA) and supported by the Aerospace Operations Command (COMAE), requested access to imagery from the Lessonia Project with the goal of developing vessel-detection techniques to overcome the limitations identified at that time.

This initiative marked the beginning of the incorporation of AI techniques into SAR image processing within the FAB. After the academic work concluded in 2021, the head of the Production Division (DIVPROD) at the CCOI requested the implementation of the SAR image analysis tool developed during the postgraduate research, aiming at automated vessel identification in real support operations for the State (Aerospace Operations Command, 2025).

By recognizing the potential impact of this research, the CCOI demonstrated a paradigm shift—from manual analysis practices to deep learning-based approaches. This represented an important step not only at the technical level, by increasing intelligence production efficiency, but also institutionally, by signaling the FAB's commitment to integrating advanced AI methods into its ISR operations (Aerospace Operations Command, 2025).

During the implementation phase in 2022, however, the DIVPROD encountered challenges that exemplify the barriers to innovation described by Azevedo, Borba, and Araujo (2021). The realization that the deployment of AI techniques required specialized expertise not yet available internally—such as suitable infrastructure, specialized libraries, and advanced programming—exposed not only a shortage of human capital but also reinforced the need for intersectoral cooperation. As the authors emphasize, innovation depends on physical, human, and organizational conditions that foster creativity and learning. Overcoming this barrier, enabled through collaboration with COMAE's Information Technology departments, reinforces a central point of this study: innovation rarely occurs in isolation, and interaction among diverse actors is essential. This episode demonstrates that the incorporation of AI is not merely a scientific leap but a process requiring the construction of an enabling ecosystem—aligning technological development with organizational capacity and promoting a collaborative culture to ensure large-scale institutional implementation. Such complex coordination is fundamental for building robust and autonomous technological sovereignty.

The initial results of the AI tool, although promising, revealed limitations that motivated a new training cycle. This refinement process—focused on improving the model's precision in identifying vessels and distinguishing false targets, such as dredges and barges—culminated in a significant reduction in false positives, illustrating the iterative nature of deep learning development. As the literature suggests, successive training and validation cycles are essential to achieving robust and reliable models in complex operational scenarios (Araujo et. al., 2022). The FAB's experience thus materializes the practical application of this fundamental deep learning principle, allowing a reduction in the need for continuous aerial overflights (Aerospace Operations Command, 2025).

Initially, YOLOv4 convolutional neural networks were employed for real-time detection, followed by VGG16 and VGG19 architectures for pattern classification—demonstrating the FAB's transition into the second generation of AI techniques for SAR (Aerospace Operations Command, 2025). This generation is characterized by the predominance of CNNs, which overcame the limitations of traditional machine learning methods such as Support Vector Machines (SVMs), marking the beginning of automation (Zhao; Principe, 2001). The combined approach—using a CNN as a feature extractor and a machine learning classifier for the final task—has proven robust in military applications, such as the recognition of oil platforms in Sentinel-1 SAR imagery, where classifier parameter optimization resulted in significant performance improvements (Falqueto et. al., 2023) .

Beyond the >90% accuracy already achieved in detecting forest cover changes, the CCOI's use of CNNs produced even more significant operational gains in specific scenarios. In refinements completed in 2022, the AI achieved accuracy above 95% in identifying illegal mining dredges in remote areas covering regions comparable in size to European countries. This result demonstrates not only the technical robustness of the model but also its applicability in large-scale remote sensing operations (Aerospace Operations Command, 2025).

From an operational agility standpoint, the impact was equally significant. Recognition processes that previously required up to five working days of manual analysis were completed in approximately two hours of computational processing—a drastic reduction in response time. In terms of cost and logistical efficiency, the results are even more striking: coverage of 33,000 km² by satellite with AI support required only 20 minutes of orbital time, at a contractual cost equivalent to 8.5 hours of P-95B aircraft operation (Aerospace Operations Command, 2025). In practice, this represented an over 65% reduction in operational costs, considering that achieving the same coverage would have required approximately 25 flight hours in traditional aerial operations.

Additionally, the report indicates that average processing time decreased by about 40%, reinforcing AI's capability not only to deliver faster results but also to optimize the use of available computational resources. These quantitative indicators confirm that the adoption of AI extends beyond academic accuracy gains—it translates into tangible benefits: faster decision-making, more economical operations, and greater reliability in alerts generated to support monitoring missions (Aerospace Operations Command, 2025).

The experience of the Joint Intelligence Operations and Computing Center (CCOI) underscored the importance of continuous model training, with systematic retraining incorporating new imagery and target samples (Aerospace Operations Command, 2025).This process led to a significant increase in result reliability. Continuous retraining, by integrating updated data, not only improved model performance but also demonstrated the practical overcoming of the critical challenge posed by labeled data dependency—a key factor for the effectiveness of CNNs. The consolidation of this capability was intrinsically tied to the creation of a robust database, whose organization and labeling demanded substantial specialized human effort, grounded in

Ground Truth and expert validation. This rigorous categorization and labeling process is indispensable for the success of supervised learning models such as CNNs, ensuring the quality and precision of training data (Falqueto et. al., 2023) .

In conclusion, the trajectory of the FAB in applying Artificial Intelligence to SAR imagery illustrates a maturation process that transcends technology and enters the institutional sphere. The evolution—from manual analysis to the use of Convolutional Neural Networks—confirms global trends and marks a milestone in Brazil's modernization, supported by interdepartmental collaboration, continuous refinement, and adaptation to operational demands. However, this journey also reveals a fundamental truth about defense innovation: it is inseparable from consistent financial investment, the allocation of time for research and development, and, fundamentally, the training and retention of highly specialized human resources. It becomes evident, therefore, that maintaining technological leadership and consolidating informational sovereignty require not only strategic vision but also a long-term commitment to the resources that sustain it—reinforcing the Air Force's vocation for continuous and sustainable advancement.

Innovation and the future of AI applications in SAR processing

Despite the advances achieved by the Brazilian Air Force (FAB) in integrating Artificial Intelligence (AI) with Synthetic Aperture Radar (SAR) systems, technical and operational bottlenecks persist that limit the full exploitation of these technologies. Among the main challenges are: speckle noise, the scarcity of large labeled datasets, the complexity of SAR image interpretation, the demand for high computational power, the significant initial investment required, and the need for visual target validation, which necessitates confirmation by other means. This procedure increases response times and operational costs, while also contributing to a degree of skepticism among some decision-makers regarding information derived exclusively from SAR imagery (Ramsey, 2024).

In light of this scenario, enhancing the application of Artificial Intelligence represents a fundamental transformation in how SAR data can be processed and exploited by the FAB. AI can be integrated into operational systems to enable real-time data analysis, providing crucial information for rapid decision-making in defense and security contexts. Accordingly, this subsection shifts the perspective from "what has already been achieved" to "what can yet be attained," seeking to anticipate potential advancements and innovations in the combined use of SAR and AI within the national context.

The first direction involves the consolidation of already implemented technologies and incremental improvements aimed at enhancing efficiency without requiring major structural changes. The FAB already possesses a robust foundation composed of SAR sensors embedded in platforms such as the R-99, P-3AM, SC-105, and P-95BM, alongside the operational use of AI models such as YOLOv4, fine-tuned with real data collected during surveillance missions in the Amazon region—demonstrating positive outcomes, as presented in the 2025 CCOI Computer Vision Development Report (Aerospace Operations Command, 2025). This existing structure can be maintained and gradually optimized.

This framework reinforces that Convolutional Neural Networks are currently essential tools for monitoring strategic areas. However, as previously discussed, they still face limitations that reduce their efficiency in complex contexts. The main challenges include speckle noise, which degrades image quality and compromises model accuracy, and the need for adaptation to specific scenarios such as the Amazon, where dense vegetation cover, complex hydrography, and high humidity create unique conditions that demand locally tuned models. Added to this is the shortage of labeled data required to train models capable of recognizing a wide range of targets.

This challenge becomes even more critical in view of the growing volume of data to be analyzed. For instance, in November 2017, the Sentinel-1 satellite recorded a daily average of 3.79 TB of imagery, while the NISAR mission projected to reach

85 TB/day (Falqueto et. al., 2023) . This irreversible expansion of informational flow demonstrates that the limitation lies not in data generation, but rather in the lack of labeled datasets of adequate scale. Without extensive and diversified training bases capable of properly representing target and environmental variety, the informational potential of orbital missions remains underexploited, constraining the effectiveness of CNN models in complex scenarios.

Among the incremental improvements suggested, key measures include expanding existing SAR image databases using AI-assisted curation tools to accelerate labeling processes. Another effective strategy is the incorporation of post-processing algorithms to reduce false positives through temporal and geospatial pattern analysis. Additionally, adopting lightweight models capable of operating efficiently in limited-resource environments and continuously training operators for AI-assisted interpretation would strengthen the human-technological interface.

The second pathway proposes the systematic integration of Generative Adversarial Networks into the FAB's current SAR image analysis framework, aiming to expand the available dataset through the generation of high-fidelity synthetic imagery (Araujo et. al., 2022). In this way, GANs offer a promising approach to address the current bottlenecks, particularly the issue of data scarcity. As discussed, GANs can simulate various operational scenarios by altering parameters such as riverine patterns, vegetation density, geometry of clandestine airstrips, and types of illegal vessels (Araujo et. al., 2022). By complementing real data with well-calibrated synthetic imagery, the FAB can substantially enhance the training of its AI models, improving detection and automatic target recognition in remote or low-visibility regions. Furthermore, this approach allows for algorithm testing in rare or difficult-to-capture conditions, anticipating failures and fine-tuning parameters before operational deployment—directly influencing situational awareness and decision-making speed.

It must be noted, however, that despite their vast potential, the large-scale implementation of GANs imposes significant operational and structural challenges.

GAN training is computationally intensive, requiring access to robust processing power. This not only raises hardware acquisition costs but also the continuous operational expenses of energy and maintenance. Additionally, the effectiveness of a GAN depends directly on the availability of a substantial volume of high-quality training data, whose collection, storage, and curation constitute ongoing logistical and financial commitments. Another critical challenge is domain shift—the discrepancy between synthetic and real-world data—which can compromise model performance if not mitigated through appropriate techniques. Finally, orchestrating this ecosystem demands highly skilled human capital, making personnel costs one of the most critical factors in the viability of GAN-based projects. Thus, the successful adoption of this technology depends on strategic, long-term investment in computational, data, and human resources.

The cutting edge of Artificial Intelligence for SAR imagery analysis, however, lies not in the adoption of a single architecture, but in the synergistic integration of CNNs, GANs, and Transformers into an adaptive hybrid system. This third pathway represents the most comprehensive approach—designed to capitalize on the strengths of each model while mitigating their individual weaknesses. As established, Transformer-based models such as the ViT, employ self-attention mechanisms to analyze images holistically, capturing complex contextual relationships crucial in dynamic operational environments (Dosovitskiy, 2021).

In such a system, the architectures would operate in a logical sequence: CNNs for extracting local and textural patterns; GANs for expanding datasets through synthetic imagery; and Transformer-based models, such as the ViT, for contextual and global image analysis with enhanced precision and adaptability. This methodological combination would enable the FAB not only to improve accuracy in target and anomaly detection but also to adapt model parameters automatically according to mission type (surveillance, reconnaissance, or interdiction), terrain (rivers, dense forests, clandestine airstrips), and environmental conditions (rain, fog, darkness).

Nevertheless, implementing such a system represents a substantial leap in complexity and cost, surpassing by several orders of magnitude the requirements of previously discussed models. The challenges are multifaceted, beginning with the structural investment needed to establish a heterogeneous hardware infrastructure capable of supporting the simultaneous training and inference of three distinct architectures. Added to this are operational costs driven by high energy consumption and the need to maintain a complex software ecosystem. Perhaps the most critical obstacle lies in integration complexity, as orchestrating efficient and latency-free data flow among different models is an advanced software engineering task. Moreover, the system's validation and interoperability planning with existing FAB frameworks, along with extensive testing and regular updates to ensure real-world performance, must also be considered. Ultimately, the feasibility of such a project depends on developing a multidisciplinary expert workforce capable of designing, building, and sustaining a system of this sophistication.

Despite these implementation challenges, investing in a hybrid architecture integrating CNNs, GANs, and Transformers is justified as a strategic imperative for the Brazilian Air Force. The true value of this architecture lies in its ability to provide real-time situational awareness and rapid response, transforming massive and complex SAR datasets into actionable intelligence for critical security and disaster-response missions. In environmental crime and security scenarios—such as illegal logging and the expansion of gold mining in the Amazon—the system could deliver unprecedented precision. CNNs would identify early canopy disruptions; GANs would generate predictive models of activity expansion based on limited examples; and Transformers would analyze geospatial context to distinguish, for instance, deforestation linked to narcotrafficking (featuring clandestine airstrips) from that driven by livestock expansion. This capability would allow enforcement operations to be directed with maximum efficiency, optimizing resources and amplifying operational impact.

Similarly, in natural disasters such as major floods or landslides, rapid response can mean saving lives. The hybrid system could analyze SAR imagery—unaffected by clouds or smoke—to map the exact extent of affected areas, identify isolated villages, detect damaged critical infrastructure, and plan the safest routes for rescue teams or the delivery of supplies. Such speed and precision, surpassing the limits of optical sensors and large-scale human analysis, constitute a decisive advantage in consolidating informational sovereignty that transcends mere operational capability, ensuring strategic autonomy.

In summary, the technological options presented constitute a range of strategic pathways for the future of SAR-based intelligence in the Brazilian Air Force.

- Option 1 (CNN enhancement) represents the most conservative alternative, focused on gradual, low-risk improvements to a validated model.
- Option 2 (data augmentation with GANs) directly addresses the critical limitation of data scarcity but requires careful management to mitigate domain shift and preserve operational reliability.
- Option 3 (adaptive hybrid architecture) is the most transformative, integrating solutions that simultaneously overcome multiple limitations—albeit with higher cost and technical complexity.

The decision as to which pathway adopt is not merely technical; it is intrinsically linked to national sovereignty and the role of innovation as a pillar of defense. The contemporary technological race—driven by dual-use technologies such as artificial intelligence and quantum technologies—is redefining defense and security capabilities (Oliveira et. al., 2025). In this context, mastering disruptive technologies becomes a strategic differentiator for sovereignty, as it enables nations to develop autonomous capabilities to protect their territories and interests (Costa el. al., 2025).

Such advancement is a strategic imperative for a country of Brazil's dimensions and challenges, where the surveillance of vast territories such as the Amazon and the protection of resources within the Exclusive Economic Zone are matters of national security. Innovation, therefore, ceases to be an auxiliary goal and becomes a decisive element in strengthening situational awareness. The ability to develop and adapt algorithms to the Amazon's specific environmental conditions, or to generate predictive models to combat environmental crimes from minimal samples, are differentiators that strengthen the State's capacity to protect both its territory and its population.

Thus, the technological choice transcends operational efficiency—it becomes a declaration of the nation's ambition to position itself at the forefront of the technological revolution. Adopting a proactive and innovative posture, regardless of the chosen path, is what will ensure that Brazil not only responds to 21st-century security challenges but does so with autonomy, consolidating technology as a true vector of informational sovereignty.

CONCLUSION

This study has demonstrated that integrating Artificial Intelligence techniques into the processing of Synthetic Aperture Radar imagery constitutes a fundamental advance for national defense capabilities and sovereignty. Grounded in a systematic review and documentary analysis, the research confirmed that the transition from manual methods to Deep Learning algorithms—most notably Convolutional Neural Networks —yields substantial gains in the efficiency and accuracy of the Brazilian Air Force's Intelligence, Surveillance, and Reconnaissance operations.

The analysis revealed that, although the adoption of CNNs represents a consolidated step forward, the effectiveness of these models is constrained by the scarcity of labeled data and the complexity of operational scenarios, such as the Amazon region. In this context, the study underscored the strategic relevance of Generative Adversarial Networks as a means to mitigate data shortages through synthetic generation, and of Transformer-based models as the technological forefront, capable of performing complex contextual analyses. The investigation highlighted that the synergy among these architectures, within a hybrid system, offers the greatest transformative potential, despite high computational costs and implementation complexity.

The principal contribution of this work lies in systematizing technological options and articulating them with the operational challenges specific to National Defense, positioning AI-driven innovation not as an ancillary objective, but as a pillar of sovereignty. It concludes that the decision regarding which technological path to pursue—whether incremental enhancement of CNNs, data expansion via GANs, or the implementation of hybrid systems—transcends the technical sphere, constituting a strategic statement about the country's ambition to position itself at the frontier of knowledge in dual-use technologies.

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