Towards Technological Sovereignty in Next-Generation Short-Wave Infrared (SWIR) Imaging Solutions for National Defence Applications

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India's ongoing defence reforms mark a decisive shift towards technological self-reliance amid an increasingly complex and contested security environment. Within this transformation, short-wave infrared (SWIR) imaging, operating in the 0.9–2.5 µm range, has emerged as a strategically significant capability for surveillance, reconnaissance and targeting under low-light and obscured conditions. However, continued dependence on foreign SWIR sensors and sub-systems creates operational, supply-chain and security vulnerabilities. This article examines the role of indigenous SWIR imaging in advancing India's defence modernisation and reform agenda. It proposes an end-to-end domestic ecosystem integrating research institutions, defence laboratories and industry to accelerate innovation, technology maturation and manufacturing. The article further examines critical defence applications and the role of policy incentives, R&D funding and strategic procurement in accelerating deployment. Indigenous SWIR capabilities can strengthen technological sovereignty, secure defence supply chains and enhance India's operational preparedness.

Keywords: *SWIR Imaging; Indigenous Sensor Fabrication; Quantum Dot Photodetectors; Secure Electronics; National Security*

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Introduction and Strategic Context

The rapid convergence of advanced sensing technologies, artificial intelligence (AI), autonomous platforms and network-centric warfare has transformed modern military operations, making electro-optical (EO) systems indispensable for Intelligence, Surveillance and Reconnaissance (ISR), precision targeting and situational awareness. Among these technologies, short-wave infrared (SWIR) imaging, operating in the 0.9–2.5 μm spectral range, provides high-resolution reflectance-based imaging with superior performance under low-light conditions, atmospheric obscurants and camouflage, complementing both visible and thermal imaging while enhancing object recognition and material discrimination.[1]

Although countries such as the United States (US), members of the European Union (EU) and Israel have established indigenous SWIR ecosystems, India continues to rely heavily on imported detector technologies, creating strategic vulnerabilities. Supported by various initiatives, including 'Atmanirbhar Bharat', 'Make in India', India Semiconductor Mission (ISM) and Innovations for Defence Excellence (iDEX), this article presents a holistic framework for developing an indigenous SWIR ecosystem. This ecosystem will encompass detector technologies, semiconductor manufacturing, AI-enabled ISR, civil–defence collaboration and sustainable innovation to strengthen India's technological sovereignty, defence preparedness and long-term global competitiveness in advanced EO systems.[2]

Indigenous Sensor Fabrication and Materials for SWIR Imaging

The SWIR imaging systems have increasingly become strategic priorities for modern defence applications, offering superior performance in obscured and low-light environments. At the heart of these systems lie photodetectors specifically those sensitive in the spectral range of 0.9–2.5μm. Traditionally, Indium Gallium Arsenide (InGaAs) has been the material of choice for SWIR photodetectors due to its high quantum efficiency and low noise characteristics.[3] However, the fabrication of high-performance InGaAs sensors is currently concentrated in a few technologically advanced nations, making India's defence sector reliant on imports for critical surveillance and targeting hardware.[4] Developing indigenous capabilities in sensor fabrication, therefore, is essential for achieving technological self-sufficiency and supply chain resilience.

InGaAs Photodetector Fabrication: Challenges and Opportunities

The InGaAs-based SWIR sensors operate by exploiting the material's bandgap properties, which align well with the SWIR spectral window. These sensors are typically grown on indium phosphide (InP) substrates using certain techniques, such as molecular beam epitaxy (MBE) or metal-organic chemical vapour deposition (MOCVD). However, these growth methods demand extreme precision, cleanroom facilities and access to rare materials, which collectively increase the cost and complexity of fabrication. Despite these challenges, recent advancements in nanostructure-enhanced InGaAs photodetectors provide a pathway towards viable domestic development. By integrating plasmonic nanostructures or metamaterials into the detector architecture, researchers have demonstrated significant improvements in quantum efficiency and responsivity.[5] Such enhancements reduce the reliance on high-purity materials and enable more flexible detector designs. Moreover, developments in low-cost wafer bonding and backside illumination techniques offer a means to integrate InGaAs with conventional complementary metal-oxide semiconductor (CMOS) readout integrated circuits (ROICs), paving the way for mass production.[6]

India already possesses foundational capabilities in III–V semiconductor research, primarily through certain institutions, such as the Solid State Physics Laboratory (SSPL), Semiconductor Laboratory (SCL) and Indian Institute of Technology (IIT) Madras' Centre for Nanoelectromechanical Systems (NEMS) and Nanoelectronics. Expanding these facilities to include dedicated InGaAs fabrication lines and integrating them with Defence Research and Development Organisation (DRDO) funded research can catalyse the domestic production of focal plane arrays (FPAs) for military-grade SWIR systems.

Colloidal Quantum Dots (CQDs) as Emerging Alternatives

While InGaAs remains the benchmark, alternative material systems are gaining ground, most notably CQDs. These nanometre-sized semiconducting particles can be engineered to absorb in specific regions of the infrared spectrum by precisely controlling their size and composition. Lead sulfide (PbS) and lead selenide (PbSe) CQDs have shown particularly promising results in the SWIR range due to their tunable bandgap properties and compatibility with solution-phase processing. The CQD-based photodetectors present several advantages over traditional InGaAs systems:

1. *Low-cost manufacturing*: The CQDs can be deposited via spin coating or inkjet printing on various substrates, including flexible and curved surfaces.

2. *CMOS compatibility*: These detectors can be monolithically integrated with standard CMOS electronics,[7] reducing packaging complexity and improving scalability.
3. *Room-temperature operation*: Unlike some infrared detectors that require cryogenic cooling, CQD photodetectors can operate efficiently at ambient temperatures and are suitable for large-area flexible substrates.[8]
4. *Customisability*: Tailoring the quantum dot composition allows for wavelength-specific tuning, enabling multispectral and hyperspectral imaging applications. Recent advances have further improved noise performance and detectivity in the SWIR band.[9]

Efforts to establish CQD fabrication lines in India could offer a rapid path to SWIR detector self-reliance, particularly for applications in compact unmanned aerial vehicle (UAV) payloads, soldier-wearable vision systems and low-cost field sensors. The Centre for Nano Science and Engineering at the Indian Institute of Science (IISc) Bangalore, IIT Delhi and the National Centre for Flexible Electronics at IIT Kanpur are well-positioned to lead research and prototyping of CQD-based imagers, offering a parallel pathway to sensor self-reliance alongside InGaAs.

Indigenous Fabrication and Reform Linkages

While significant progress has been made globally in SWIR sensor technologies, India's domestic capability in photodetector fabrication has historically remained limited. This gap can be attributed to a combination of technological, economic and policy-related constraints. The development of high-performance SWIR sensors, particularly those based on InGaAs materials, requires access to advanced epitaxial growth facilities, high-purity material supply chains and precision fabrication infrastructure. Such capabilities involve substantial capital investment and long gestation periods, which were traditionally met through imports rather than indigenous development. In addition, earlier procurement models prioritised off-the-shelf acquisition of proven foreign systems to meet immediate operational requirements. While this approach enabled rapid capability induction, it inadvertently limited the growth of domestic fabrication expertise and ecosystem development. The absence of sustained industry participation, coupled with fragmented collaboration between research institutions and manufacturing entities, further constrained the evolution of a robust indigenous sensor fabrication base. The current phase of defence reforms has begun to address these structural limitations by shifting the focus from import dependency to capability creation within the country.

Policy frameworks promoting indigenous design, development and manufacturing have created new opportunities for establishing domestic semiconductor and photonics fabrication capabilities. Increased emphasis on public–private partnerships, startup-driven innovation and targeted funding mechanisms is enabling the gradual development of specialised fabrication ecosystems relevant to SWIR technologies. Parallel advancements in materials research, particularly in areas such as CQD and two-dimensional materials, are also lowering entry barriers for sensor development. These emerging technologies offer the potential for cost-effective and scalable fabrication processes compared to conventional epitaxial systems, making them well-suited for a growing domestic manufacturing ecosystem. When supported by reform-driven initiatives that encourage technology transfer, infrastructure development and skill creation, these advancements can accelerate the transition towards indigenous SWIR sensor fabrication. Furthermore, the integration of fabrication capabilities with system-level design, including optics, electronics and AI-based processing, reflects a broader shift towards end-to-end capability development.

This approach aligns with national priorities of achieving technological sovereignty and reducing vulnerabilities associated with external supply chains. As reforms continue to mature, the development of a self-sustaining SWIR sensor ecosystem is likely to play a pivotal role in strengthening India's defence preparedness and enabling long-term strategic autonomy.

Roadmap to Domestic Sensor Sovereignty

Achieving domestic sensor sovereignty in SWIR imaging is a strategic imperative for India's defence and technological autonomy. A structured, phased roadmap is essential to systematically reduce dependency on foreign sources, while building indigenous capabilities across the entire sensor value chain. This roadmap should begin with short-term import substitution and evolve towards advanced, next-generation sensor technologies tailored for both defence and dual-use applications.

Phase 1 focuses on immediate capability enhancement through the local integration of foreign InGaAs dies with domestically developed optics, electronics and packaging. This approach enables rapid deployment of SWIR systems while nurturing expertise in system-level design, assembly and testing. It also creates a foundation for local value addition and builds momentum for deeper technology development.

Phase 2 involves establishing domestic epitaxy and wafer processing capabilities for InGaAs photodetectors. Strategic investments in cleanroom infrastructure, material growth technologies and fabrication facilities will enable India to produce high-quality SWIR sensors at scale. This phase is critical for building a resilient supply chain and fostering research and development (R&D) partnerships between research institutions and industry.

Phase 3 envisages the development of full-stack SWIR sensors using cutting-edge materials, like CQDs and two-dimensional semiconductors. These technologies offer tunable spectral response, lower manufacturing costs and compatibility with CMOS integration, making them ideal candidates for scalable defence and commercial applications.

By investing concurrently in mature InGaAs technologies and emerging material platforms, India can diversify its sensor base, future-proof its capabilities and assert global leadership in infrared imaging. This multi-phase approach lays the groundwork for a self-reliant, innovation-driven ecosystem that secures strategic advantages across defence and beyond.

Optical, Mechanical, Electronics and Firmware Integration for Advanced SWIR Imaging Systems

Optical System Design

The performance of SWIR imaging systems is intrinsically linked to the quality and precision of their optical and mechanical components. In defence applications, where environmental conditions can be extreme and operational demands are high, the development of ruggedised, high-performance optics is essential. Specialised optics tailored for the SWIR spectrum (0.9–2.5 μm) must deliver high resolution, thermal stability and mechanical durability to ensure mission-critical reliability.

Optical integration in SWIR systems involves the design and fabrication of lenses, filters and coatings specifically optimised for SWIR wavelengths. Unlike visible optics, SWIR optics require materials, such as germanium, chalcogenide glass and specialised infrared-grade coatings, that offer high transmission and minimal aberration[10] in the target spectral range. Continuous zoom lens assemblies, such as the FireAnt SWIR lens, exemplify the ruggedised solutions necessary for tactical deployment. These assemblies provide seamless variable focal lengths, superior image stability and precision autofocus mechanisms, all while withstanding shocks, temperature variations and moisture exposure.

Mechanical Integration

Mechanical integration plays an equally critical role. The SWIR optics must be housed in enclosures that not only protect internal components but also maintain strict alignment and focus tolerances under varying physical stresses encountered in military platforms.[11] Vibration-damping mounts, sealed housings and thermally adaptive materials are essential in ensuring that SWIR imaging systems function reliably in real-world military scenarios, such as airborne reconnaissance, armoured vehicle targeting and unmanned aerial surveillance. Domestic development of these advanced optical assemblies will drastically reduce India's dependence on foreign suppliers and unlock the potential for mission-specific customisation. This includes compact optical designs for portable systems, wide-aperture lenses for long-range targeting and adaptive optics for precision-guided applications. Moreover, indigenous capabilities will allow rapid prototyping and iterative improvements based on operational feedback, significantly enhancing agility and innovation in defence imaging. Establishing a robust optical manufacturing ecosystem requires collaboration between optical engineers, materials scientists, defence laboratories and private industry. Investments must be directed towards R&D in infrared materials, high-precision computer numerical control machining and testing infrastructure for environmental simulation and optical performance benchmarking.

Additionally, workforce development through specialised training programmes in infrared optics design and mechanical integration will ensure a sustainable talent pipeline. Parallelly, local industry should be encouraged to co-develop with defence agencies, creating modular and scalable SWIR optics platforms that can be integrated across multiple platforms, ranging from handheld devices to satellite payloads. This modularity not only enhances system versatility but also streamlines maintenance and logistics in the field. Ultimately, the domestic production of ruggedised, high-performance SWIR optical and mechanical components will strengthen India's strategic autonomy in defence imaging technologies, where Japan currently takes the lead. It will empower the nation to tailor solutions for its unique operational needs, while contributing to the global frontier of infrared optical innovation. This integration of specialised optics and robust mechanical engineering marks a foundational step in the journey towards a self-reliant and technologically sovereign defence ecosystem.

Embedded Electronics

In the realm of defence technology, ensuring the security and integrity of electronics and firmware in SWIR imaging systems is critical. These

systems play a pivotal role in surveillance, targeting and reconnaissance missions, making them high-value targets for cyber and electronic warfare. Vulnerabilities in the hardware or firmware layers can compromise system functionality, expose sensitive data and create backdoors for adversaries. Thus, developing indigenous, secure electronics and firmware is not only a technological necessity but a strategic imperative.

Secure Firmware Infrastructure

The firmware that governs SWIR imaging systems manages everything from image acquisition and processing to communication protocols and control algorithms. If compromised, it can allow unauthorised access, data manipulation or even remote disablement.[12] By establishing a secure firmware development lifecycle, including code signing, secure boot mechanisms, encryption and access control, India can ensure that only trusted, verified firmware runs on its imaging platforms. This prevents tampering and unauthorised updates, reinforcing operational integrity.

Equally important is the localisation of electronic components, including printed circuit boards (PCBs), microcontrollers and interface modules. Relying on imported electronics increases the risk of embedded hardware trojans and supply chain attacks. A domestic electronics ecosystem, supported by secure foundries and vetted manufacturing practices, provides greater oversight and reduces exposure to foreign interference. Implementing robust supply chain risk management practices, such as component provenance tracking and security auditing, will further safeguard the integrity of SWIR systems. Collaborative frameworks between defence agencies, cybersecurity experts and indigenous tech companies can accelerate the development of secure hardware–software co-design methodologies.

By investing in secure, indigenous electronics and firmware, India can achieve greater control over its critical defence systems, enhance cybersecurity resilience and establish trust in its SWIR imaging platforms. This foundational security ensures reliability in field operations and strengthens the country's broader digital defence infrastructure.

Supply Chain Assurance and Cyber Resilience in Defence Electronics for SWIR Imaging Systems

The development of secure electronics for SWIR imaging systems must be understood within the broader context of supply chain security and cyber resilience, both of which have emerged as critical concerns in modern defence planning. Increasing digitisation of military systems has expanded the attack surface, making hardware and firmware integrity as important as

functional performance. Imaging systems, which are a key component of ISR architectures, are particularly vulnerable to issues arising from compromised components or unverified software.

Historically, dependence on imported electronic subsystems has introduced risks associated with opaque supply chains, including the possibility of hardware trojans, embedded malware and unauthorised backdoor access. Such vulnerabilities can undermine system reliability, compromise sensitive data and, in extreme cases, disrupt mission-critical operations. In the context of network-centric warfare, where imaging systems are tightly integrated with communication and command infrastructures, even minor compromises can have cascading operational consequences. Recognising these risks, ongoing defence reforms have placed increasing emphasis on the development of trusted and verifiable electronics within the country, ensuring verified firmware runs on its imaging platforms.[13] Indigenous design and manufacturing of control electronics, ROICs and embedded firmware enable greater oversight of system architecture and behaviour. Secure development practices, including hardware-level validation, cryptographic authentication, secure boot mechanisms and end-to-end encryption, contribute to ensuring the integrity and confidentiality of imaging data.

From a cyberwarfare perspective, secure electronics also play a defensive role against adversarial attempts to exploit or degrade sensing capabilities. Imaging systems operating in contested environments must be resilient not only to physical threats but also to electronic interference, spoofing and cyber intrusion. The integration of security features at the design stage, rather than as an afterthought, aligns with emerging best practices in defence system engineering. Reform-driven initiatives supporting domestic semiconductor development, trusted electronics programmes and secure communication frameworks are gradually enabling the creation of a resilient supply chain ecosystem. By reducing dependence on external vendors and establishing end-to-end control over critical subsystems, India can enhance both the reliability and survivability of its EO systems. In this context, secure electronics are not merely a technical requirement but a strategic necessity, forming a key pillar of technological sovereignty in defence imaging systems.

Ecosystem Development for Indigenous SWIR Capability

Achieving technological sovereignty in SWIR imaging systems is a multidimensional challenge that extends well beyond laboratory-based research and prototyping. It necessitates the establishment of a robust,

collaborative and well-funded national ecosystem that spans the full innovation pipeline, that is, from fundamental research and material development to system integration, testing, certification and mass manufacturing. Such an ecosystem must leverage the strengths of government institutions, academia and private enterprises to ensure that indigenous SWIR imaging solutions are not only technologically competitive but also deployable at scale for defence and dual-use applications, while academic research drives advances in materials, device physics and nanophotonics. Private sector participation is critical for scaling fabrication, optics manufacturing and system integration, supported by national semiconductor and defence manufacturing missions.[14] Centralised testbeds for spectral calibration, environmental qualification and electromagnetic interference/electromagnetic compatibility validation are essential to reduce deployment timelines and ensure operational reliability.[15]

Semiconductor Ecosystem

A semiconductor ecosystem comprises the integrated network of research institutions, semiconductor materials, fabrication facilities, chip design capabilities, packaging and testing infrastructure, skilled human resources, industrial supply chains and supportive policy frameworks required to develop, manufacture and sustain advanced semiconductor technologies. In the context of indigenous SWIR imaging, such an ecosystem forms the technological foundation for achieving long-term sensor sovereignty, reducing import dependence and enabling sustained innovation across defence and civilian applications.

Civil–Defence Collaborative Innovation Model for Indigenous SWIR Ecosystem

The development of an indigenous SWIR ecosystem requires a paradigm shift from isolated, defence-centric research programmes towards an integrated innovation framework that leverages the complementary strengths of civilian industry, academia and defence organisations. Given the multidisciplinary nature of SWIR technology, encompassing semiconductor materials, photonics, microelectronics, AI and precision manufacturing, no single institution possesses the capability to independently develop and sustain the complete technology value chain. A collaborative civil–defence innovation model, therefore, offers the most viable pathway for accelerating technological maturity while ensuring long-term strategic autonomy. Such a framework enables the civilian sector to focus on foundational technology development and commercial scalability, while defence organisations concentrate on

mission-specific adaptation, qualification and operational integration of indigenous SWIR systems.[16]

Under this model, civilian-led foundational technology development should form the cornerstone of India's SWIR innovation ecosystem. Universities, national laboratories, semiconductor startups and commercial photonics companies are better positioned to undertake long-term research in advanced detector materials, quantum dot photodetectors, ROICs, integrated photonics and low-cost manufacturing techniques. These organisations operate within a competitive innovation environment that encourages rapid experimentation, technology diversification and continuous product improvement. Furthermore, civilian markets, such as industrial inspection, precision agriculture, medical diagnostics, autonomous mobility and environmental monitoring, generate commercial demand that sustains investments in SWIR technologies beyond defence procurement cycles, thereby improving economies of scale and reducing unit costs.[17]

While the civilian sector drives technology creation, defence organisations should assume responsibility for mission-specific system integration and operational validation. Military applications demand stringent requirements relating to environmental survivability, electromagnetic compatibility, cybersecurity, secure firmware, reliability and interoperability with existing command-and-control networks. Consequently, organisations, such as the DRDO, the armed forces and defence public sector enterprises, should focus on integrating commercially developed SWIR subsystems into specialised ISR payloads, weapon seekers, surveillance platforms and soldier systems while ensuring compliance with military standards. This division of responsibilities enables rapid technology transition without compromising national security or operational reliability.

An equally important pillar of this framework is the establishment of academia–industry–defence collaborative research clusters. Joint centres of excellence, dedicated to infrared imaging, semiconductor devices and computational imaging, should be created to facilitate multidisciplinary research, doctoral programmes, technology demonstrators and prototype validation. Such collaborative ecosystems promote continuous knowledge exchange, reduce duplication of research efforts and accelerate the translation of laboratory innovations into deployable defence capabilities. Structured funding mechanisms under various initiatives, such as the iDEX, the ISM and collaborative public–private partnerships, can further strengthen this innovation pipeline by encouraging participation from startups and medium, small and micro enterprises (MSMEs).

The creation of shared fabrication and characterisation facilities represents another critical requirement for developing indigenous SWIR capabilities. Establishing advanced semiconductor fabrication lines, wafer processing facilities, cleanrooms, epitaxial growth laboratories and detector characterisation centres demands substantial capital investment that may not be economically viable for individual organisations. Shared national infrastructure accessible to academia, industry and defence laboratories would optimise resource utilisation, reduce technology development costs and accelerate prototype fabrication. Simultaneously, common semiconductor process development should be encouraged to establish standardised fabrication workflows for infrared photodetectors, ROICs and hybrid FPAs, thereby improving interoperability, manufacturing consistency and future scalability.

Finally, defence qualification of commercially developed technologies must become an integral component of the innovation ecosystem. Instead of independently developing every subsystem within defence establishments, commercially mature technologies should undergo structured military certification involving environmental testing, reliability evaluation, electromagnetic compatibility assessment and field validation under representative operational conditions. Such an approach significantly shortens development timelines while preserving strategic control over sensitive defence applications. International experience demonstrates the effectiveness of this collaborative innovation model. In the US, defence agencies, such as the Defense Advanced Research Projects Agency (DARPA) and the Department of Defense, routinely leverage commercially developed semiconductor and photonics technologies before integrating them into specialised military systems through collaborative partnerships with industry and research universities.

Similarly, the EU promotes dual-use photonics and semiconductor innovation through coordinated research programmes involving academia, industry and defence stakeholders. Israel's defence technology ecosystem also illustrates the benefits of close interaction between universities, high-technology enterprises and defence organisations, enabling rapid transition of commercially developed innovations into operational military capabilities.[18] Adopting a comparable civil–defence collaborative framework would enable India to accelerate indigenous SWIR development, improve economies of scale, strengthen technological resilience and establish a globally competitive EO ecosystem, while maintaining sovereign control over strategically sensitive defence technologies.

SWIR within an Integrated Multi-Sensor ISR Architecture

Modern military operations increasingly rely on integrated multi-sensor ISR architectures to overcome the limitations of individual sensing technologies under diverse operational conditions. Within this framework, SWIR imaging occupies a unique position by providing high-resolution reflectance-based imagery with enhanced performance in degraded visual environments, complementing visible, thermal, radar and hyperspectral sensors. Recent advances in AI, edge computing and sensor fusion have further strengthened SWIR's role in network-centric warfare. Consequently, indigenous SWIR technology should be viewed as a critical component of India's integrated, AI-enabled ISR ecosystem, supporting technological sovereignty and enhanced defence capability.

Comparative Sensor Capability Matrix

The increasing complexity of modern military operations has reinforced the need for a diversified sensing architecture capable of providing persistent and reliable intelligence under varying environmental and operational conditions. Each sensing modality operates on different physical principles and consequently, exhibits unique strengths and limitations. While visible EO sensors provide intuitive, high-resolution imagery under favourable illumination, their effectiveness rapidly diminishes during adverse weather or low-light conditions. Thermal infrared sensors operating in the mid-wave infrared (MWIR) and long-wave infrared (LWIR) regions detect emitted radiation from objects and therefore, remain effective during complete darkness; however, they often provide limited surface detail required for positive target identification. Similarly, Synthetic Aperture Radar (SAR) offers unparalleled all-weather imaging capabilities, but produces imagery that demands specialised interpretation and lacks the intuitive visual information available through optical systems. Hyperspectral imaging (HSI) extends target discrimination through spectral signature analysis, whereas light detection and ranging (LiDAR) contributes precise three-dimensional spatial information for terrain modelling and autonomous navigation. Within this diverse sensing ecosystem, SWIR occupies an intermediate position by combining high spatial resolution with enhanced performance in degraded visual environments, making it an important complementary sensing modality rather than a standalone ISR solution.[19]

The operational value of each sensor, therefore, depends not only on its intrinsic performance characteristics but also on the mission profile,

environmental conditions, platform constraints and the desired level of situational awareness. Consequently, defence organisations worldwide are increasingly adopting multi-sensor payloads that exploit the complementary strengths of different sensing technologies to improve target detection, identification and tracking, while minimising the limitations associated with individual sensors.[20]

Table 1 Comparative Capability Matrix of Major ISR Sensors

Sensor Type	Operating Principle	Major Strengths	Major Limitations	Typical Defence Applications
Visible EO	Reflected visible light (0.4–0.7 μm).	High spatial resolution; natural colour representation; and intuitive interpretation.	Performance deteriorates in darkness, fog, smoke and haze.	Day surveillance; target recognition; battlefield monitoring; and weapon aiming.
SWIR	Reflected short-wave infrared radiation (0.9–2.5 μm).	Superior imaging in haze, smoke and twilight; camouflage detection; material discrimination; and passive night imaging.	Dependent on reflected illumination and comparatively higher detector cost.	Border surveillance; UAV reconnaissance; target identification; and navigation in degraded visual environments.
MWIR	Thermal emission (3–5 μm).	Excellent long-range target detection; high sensitivity to hot objects; and missile warning.	Requires cooled detectors and increasing system complexity and cost.	Missile seekers; airborne targeting pods; aircraft surveillance; and fire control.
LWIR	Thermal emission (8–12 μm).	Effective day/night imaging; excellent thermal contrast; and passive operation.	Reduced capability for material discrimination and lower spatial detail than SWIR.	Night vision; vehicle observation; perimeter security; and thermal weapon sights.

SAR	Active microwave imaging.	All-weather capability; penetration through clouds; and wide-area surveillance.	Complex image interpretation; limited visual detail; and electromagnetic emissions may reveal platform presence.	Strategic reconnaissance; maritime surveillance; terrain mapping; and moving target indication.
HSI	Hundreds of contiguous spectral bands.	Precise material identification; camouflage and anomaly detection; and chemical analysis.	Large data volumes; computationally intensive processing; and sensitive to atmospheric conditions.	Camouflage detection; intelligence gathering; environmental monitoring; and target classification.
LiDAR	Active laser ranging.	High-resolution three-dimensional terrain mapping; accurate distance measurement; and obstacle avoidance.	Performance affected by dense fog, heavy rain and aerosols; and limited long-range coverage.	Autonomous navigation; terrain modelling; route planning; and precision targeting.

Source: Compiled by the author.

The comparison presented in Table 1 clearly demonstrates that no individual sensing modality possesses universal operational superiority across all mission scenarios. Instead, each technology contributes unique information that complements other sensors within an integrated ISR architecture. For instance, visible EO imagery provides detailed scene interpretation in daylight, whereas LWIR sensors excel at thermal target detection in complete darkness. The SWIR occupies a unique intermediate position by simultaneously offering high-resolution reflectance-based imaging and improved performance under degraded visual conditions, thereby bridging the capability gap between visible and thermal imaging systems. Likewise, SAR contributes persistent surveillance irrespective of cloud cover or adverse weather, while HSI facilitates material identification beyond conventional spatial imaging. The LiDAR further enhances situational awareness by generating precise three-dimensional representations of terrain and infrastructure, supporting both manned and autonomous operations.[21]

From an operational perspective, the greatest advantage is realised when these complementary sensing modalities are integrated through intelligent sensor fusion frameworks rather than deployed independently. Such architectures enable commanders to exploit the strengths of each sensor while compensating for their individual shortcomings, thereby improving detection probability, reducing false alarms and enhancing confidence in target identification across the tactical, operational and strategic levels of warfare. Consequently, indigenous development efforts should focus not only on achieving self-reliance in SWIR technology but also on ensuring interoperability with the broader EO and non-EO ISR ecosystem that will define future network-centric military operations.

Platform Deployment Matrix

The effectiveness of an ISR system is determined not only by the capability of individual sensors but also by the suitability of their deployment across different operational platforms. Each platform imposes distinct constraints on size, weight, power (SWaP), endurance, communication bandwidth and mission objectives, necessitating customised sensor configurations rather than a universal sensing solution. Consequently, modern ISR architectures are increasingly adopting modular payload designs that combine complementary sensing technologies to maximise mission effectiveness while maintaining operational flexibility. Such integrated payloads enable commanders to acquire persistent, multidimensional intelligence under diverse environmental conditions and evolving threat scenarios.

Recent advances in multi-sensor remote sensing further demonstrate that feature-level fusion of optical, thermal, radar and LiDAR data consistently improves target detection and situational awareness over single-sensor deployments. Among the various sensing modalities, SWIR is particularly well-suited for integration across multiple defence platforms because of its favourable balance of imaging performance, compactness and power consumption. Its ability to generate high-resolution reflectance-based imagery under twilight, haze, smoke and other degraded visual environments makes it an effective intermediate sensing layer between conventional visible EO systems and thermal infrared imagers. However, the operational value of SWIR is maximised only when deployed in conjunction with complementary sensors that collectively provide spectral, thermal, geometric and all-weather information. This integrated approach enhances mission resilience by reducing the likelihood of performance degradation resulting from environmental variability or adversary countermeasures.

Table 2 Platform Deployment Matrix for Integrated Multi-Sensor ISR Operations

Operational Platform	Primary Mission	Recommended Sensor Combination	Operational Rationale
Soldier-mounted systems	Surveillance; target recognition; and navigation.	Visible EO + SWIR + LWIR	SWIR enhances low-light imaging and camouflage discrimination, while LWIR improves night-time target detection.
Static surveillance posts	Border monitoring and perimeter security.	Visible EO + SWIR + MWIR/ LWIR + Radar	Continuous all-weather surveillance with improved intrusion detection and reduced false alarms.
Armoured vehicles	Driver vision; battlefield awareness; and target engagement.	Visible EO + SWIR + LWIR + Laser Range Finder	Enables navigation through fog, smoke and dust while supporting accurate target identification and range estimation.
Tactical UAVs	ISR; reconnaissance; and battle damage assessment.	Visible EO + SWIR + LWIR + AI-based Onboard Analytics	Multispectral imagery improves detection of concealed targets while maintaining low payload weight.
Helicopters	Low-altitude surveillance and target acquisition.	Visible EO + SWIR + MWIR + Laser Designator	Supports navigation in degraded visibility and precision engagement during day and night operations.
Fixed-wing aircraft	Wide-area reconnaissance and strategic ISR.	EO + SWIR + MWIR + SAR	Combines high-resolution optical imagery with all-weather radar surveillance for persistent intelligence collection.
Low Earth Orbit (LEO) satellites	Strategic surveillance; border monitoring; and disaster assessment.	Multispectral EO + SWIR + Hyperspectral + SAR	Enables continuous regional monitoring, with complementary spectral and radar observations, irrespective of weather conditions.

Naval platforms	Maritime surveillance and coastal security.	EO + SWIR + MWIR + Maritime Radar	Improves detection of small vessels, floating objects and coastal activities under varying atmospheric conditions.

Source: Compiled by the author; with comparative characteristics synthesised across sensing modalities.

The deployment matrix, shown in Table 2, highlights that the composition of sensor payloads must be tailored to operational requirements rather than standardised across all platforms. Tactical soldier systems, for example, prioritise compactness, low power consumption and rapid target recognition, making the combination of visible EO, SWIR and LWIR particularly effective. Conversely, airborne and spaceborne platforms possess greater payload capacity and therefore, benefit from integrating SAR and hyperspectral sensors alongside SWIR to achieve persistent, all-weather intelligence collection. Similarly, naval platforms require radar-assisted maritime surveillance, complemented by SWIR imaging, to improve detection of low-signature vessels during twilight, haze and coastal atmospheric disturbances.

From the perspective of India's defence modernisation, indigenous development of modular multi-sensor payloads offers significant strategic advantages. Instead of pursuing isolated sensor technologies, future indigenous EO systems should adopt an open architecture that permits seamless integration of SWIR imagers with visible cameras, thermal sensors, radar, LiDAR and AI-enabled processing modules. Such modularity simplifies technology upgrades, facilitates platform interoperability and reduces lifecycle costs while preserving technological sovereignty. Moreover, common sensor interfaces and indigenous processing architectures would enable the same SWIR payload to be configured across soldier systems, unmanned platforms, armoured vehicles and space-based ISR assets with minimal redesign.

The transition towards platform-centric sensor integration also aligns with the broader evolution of network-centric warfare, wherein every sensing platform contributes to a common intelligence architecture rather than functioning as an isolated observation system. Within such an ecosystem, SWIR should be regarded not as an independent imaging technology but as an enabling component of an integrated multi-domain ISR network, capable of supporting persistent surveillance, rapid threat assessment and informed operational decision making across tactical, operational and strategic levels.

Sensor Fusion Concepts, Processing, Data Fusion and AI-enabled Exploitation of SWIR Intelligence

Modern ISR has evolved from a sensor-centric activity into an information-centric capability in which operational superiority depends not on individual sensor performance, but on the ability to integrate, process and exploit information from multiple heterogeneous sensing modalities. No single imaging technology can provide reliable situational awareness across the diverse operational environments encountered in contemporary warfare, where illumination variations, atmospheric obscurants, complex terrain, camouflage and electronic countermeasures frequently degrade sensor performance. Consequently, modern defence systems increasingly employ multi-sensor fusion architectures that combine complementary information from visible EO, SWIR, LWIR, SAR, LiDAR and HSI systems to generate a more comprehensive and reliable representation of the battlespace than any individual sensor can provide (see Figure 1).[22]

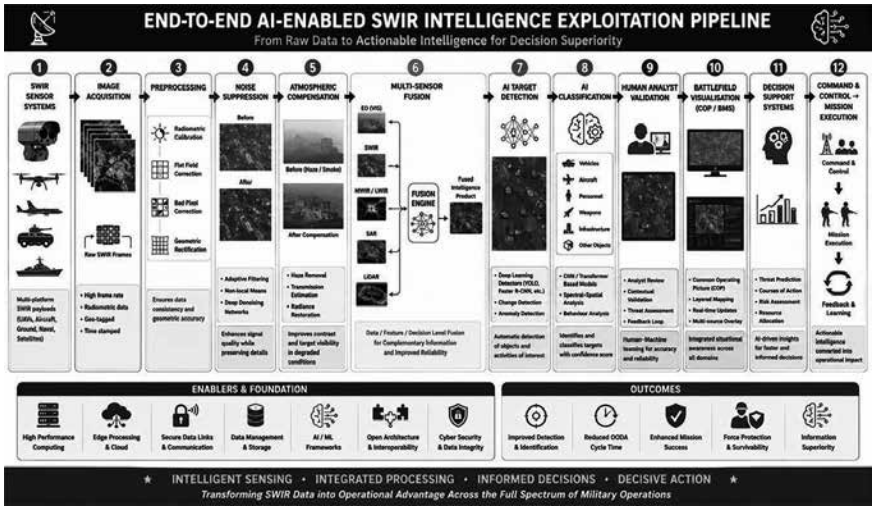


Figure 1 End-to-End AI-enabled SWIR Intelligence Exploitation Pipeline
Source: Author's conceptualisation; visualisation generated using ChatGPT (OpenAI), 2026.

The SWIR complements these modalities by producing high-resolution reflectance-based imagery that preserves fine spatial detail while maintaining superior performance under twilight, haze, smoke and light

fog. The integration of SWIR with visible, thermal, radar and spectral sensors significantly enhances target detection, camouflage discrimination, material identification and environmental perception, thereby improving the robustness and reliability of ISR operations under diverse operational scenarios.[23]

The effectiveness of such integrated sensing systems depends on a structured ISR exploitation chain that transforms raw sensor outputs into actionable intelligence. The initial stage involves image pre-processing, including radiometric calibration, flat-field correction, bad-pixel replacement, geometric rectification, atmospheric compensation and advanced de-noising techniques, which minimises sensor artefacts and environmental distortions while preserving radiometric and spatial fidelity. The enhanced imagery subsequently undergoes automated target detection, feature extraction and object classification using conventional image-processing techniques and machine-learning algorithms. Multi-level sensor fusion further improves information quality by integrating heterogeneous data at the data, feature and decision levels, thereby enhancing scene interpretation, reducing redundancy and improving confidence in operational assessments under uncertain or degraded conditions.[24]

Recent advances in AI have fundamentally transformed ISR exploitation by enabling automated interpretation of large, heterogeneous datasets generated by distributed sensing platforms. Deep learning architectures, including convolutional neural networks, transformer-based vision models and multimodal learning frameworks, can identify complex spatial, spectral and temporal relationships that are often difficult to detect with conventional analytical methods. These techniques support automated target recognition, anomaly detection, object tracking, behavioural analysis and confidence estimation while continuously adapting to evolving operational conditions. Rather than replacing human judgement, AI facilitates effective human–machine teaming by automating repetitive analytical tasks, reducing cognitive workload and accelerating intelligence generation, allowing operators to focus on mission-critical decision making.[25]

The growing adoption of edge computing further enhances operational responsiveness by performing image processing, AI inference and sensor fusion directly on the sensing platform, thereby reducing communication latency, minimising bandwidth requirements and maintaining operational capability in contested electromagnetic environments. Processed intelligence from distributed ISR assets is subsequently integrated into common operating pictures (COPs) and Battlefield Management Systems (BMSs),

where geospatial information, command-and-control networks and decision-support tools provide commanders with a unified and continuously updated representation of the operational environment. This integrated architecture significantly shortens the observe–orient–decide–act cycle, enabling faster, more accurate and better-informed operational decisions. Consequently, the development of indigenous SWIR capability should encompass the complete ISR exploitation ecosystem, integrating advanced detector technologies with image processing, sensor fusion, AI-enabled analytics, secure edge computing and decision-support architectures, to realise scalable, intelligent and interoperable EO systems for future multi-domain operations.[26]

Role of SWIR in Layered ISR Operations

Modern military operations increasingly rely on a layered ISR architecture, wherein information is collected simultaneously from multiple platforms operating across tactical, operational and strategic levels. Rather than operating independently, these layers continuously exchange information to build a comprehensive understanding of the battlespace, thereby enabling faster, more informed decision making. The effectiveness of such an architecture depends upon the complementary integration of diverse sensing technologies, each contributing unique operational information. Within this framework, SWIR imaging occupies a critical intermediate position by bridging the capability gap between conventional visible EO systems and thermal infrared sensors. Its ability to generate high-resolution imagery under degraded visual environments, while preserving material reflectance characteristics, makes SWIR an indispensable contributor to layered ISR operations rather than a standalone sensing solution.[27]

At the tactical level, ISR assets primarily support frontline military operations by providing immediate situational awareness to soldiers, armoured formations and tactical unmanned aerial systems. Operational environments at this level are characterised by rapidly changing conditions, limited decision-making time and frequent visibility degradation caused by smoke, dust, fog or low ambient illumination. Conventional EO sensors often experience significant performance degradation under these conditions, while thermal imagers may detect heat signatures without providing sufficient detail for reliable target identification. The SWIR addresses this capability gap by producing reflectance-based imagery that enhances target discrimination, camouflage detection and obstacle recognition under low-light and obscured conditions. When integrated with visible and thermal imaging systems, SWIR significantly improves battlefield awareness for infantry patrols,

special operations forces, border surveillance detachments and tactical UAVs, thereby reducing uncertainty during time-critical engagements.[28]

At the operational level, ISR focuses on theatre-wide surveillance, force manoeuvre, logistics support and persistent monitoring of areas of strategic importance. Platforms operating at this level include medium-altitude long-endurance (MALE) unmanned aircraft, helicopters, airborne early warning systems and fixed surveillance installations. The principal objective is to maintain continuous observation over large geographical regions while ensuring reliable target detection across varying environmental conditions. Multi-sensor payloads incorporating visible EO, SWIR, MWIR/LWIR and SAR provide complementary information that significantly enhances target tracking and activity monitoring (see Figure 2).

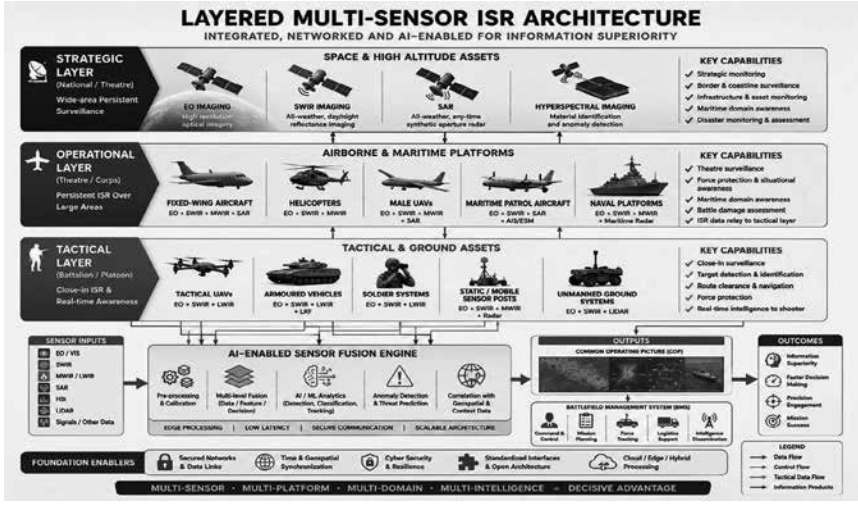


Figure 2 Layered Multi-Sensor ISR Architecture for Integrated Defence Operations

Source: Author's conceptualisation; visualisation generated using ChatGPT (OpenAI), 2026.

Within these payloads, SWIR delivers superior imaging performance in twilight, haze and light atmospheric obscurants, while simultaneously enabling material-based target discrimination that complements both optical and thermal observations. The integration of AI-enabled sensor fusion further improves detection confidence and enables automated identification of anomalous activities across extensive surveillance areas.[29]

At the strategic level, ISR extends beyond immediate battlefield operations to encompass national border management, maritime domain awareness, critical infrastructure protection and long-term intelligence collection. Space-based Earth observation systems, high-altitude platforms and strategic reconnaissance aircraft collectively provide persistent regional surveillance that supports national security decision making. In this domain, SWIR sensors are increasingly integrated with multispectral, hyperspectral and SAR payloads to exploit the complementary strengths of different spectral regions.

Spaceborne SWIR observations facilitate vegetation stress analysis, infrastructure monitoring, camouflage detection and environmental assessment, while hyperspectral and radar sensors provide additional spectral and all-weather information. Such integrated architectures improve the resilience of national ISR capabilities by ensuring continuity of surveillance irrespective of illumination or weather conditions. International Earth observation missions, such as Sentinel-2 and Landsat-8/9, demonstrate the operational value of combining SWIR bands with visible and near-infrared observations for terrain analysis, disaster response and strategic environmental monitoring, thereby illustrating the broader utility of integrated spectral sensing architectures beyond conventional military applications.[30]

The emergence of network-centric warfare has further strengthened the importance of layered ISR by enabling information collected from geographically distributed platforms to be fused into a single operational picture. Tactical observations acquired through soldier-mounted sensors and UAVs can now be correlated with airborne reconnaissance, satellite imagery and ground-based surveillance networks to provide commanders with near real-time situational awareness across multiple operational domains. Within this interconnected ecosystem, SWIR functions as a vital link that complements optical, thermal and radar observations by supplying additional spectral information essential for target verification and environmental interpretation. Rather than replacing existing sensing technologies, SWIR enhances their effectiveness by reducing ambiguity and improving confidence in multi-source intelligence products.

From an Indian perspective, the development of indigenous SWIR technology should therefore be viewed within the broader objective of establishing a self-reliant, integrated ISR ecosystem, rather than simply achieving import substitution for individual imaging sensors. Future surveillance platforms developed under different initiatives, such as 'Atmanirbhar Bharat', the iDEX, the ISM and the Defence Acquisition Procedure (DAP 2020), should adopt open-system architectures capable of

integrating SWIR with visible EO, thermal imaging, LiDAR, hyperspectral sensors and indigenous AI-based processing modules. Such modular architectures would facilitate interoperability across land, air, maritime and space domains, while reducing lifecycle costs and enhancing technological resilience against supply chain disruptions. Ultimately, India's technological sovereignty in advanced EO systems will depend not only upon indigenous SWIR detector fabrication but also upon its successful integration into a layered, multi-domain ISR architecture capable of delivering persistent, secure and actionable intelligence across the full spectrum of military operations.

Strategic Military Applications

The ability to see through obscured environments, whether due to darkness, smoke, haze or camouflage, confers a decisive advantage in modern warfare. The SWIR imaging fills critical gaps left by visible and thermal imaging systems. Traditionally reliant on expensive, imported InGaAs-based sensors, India's push towards indigenous SWIR technology holds the potential to revolutionise its defence readiness across multiple strategic domains. From reconnaissance and surveillance to smart weaponry and border security, domestically developed SWIR solutions can enable cost-effective, scalable and sovereign military capabilities.

Spaceborne SWIR Sensors and Integrated Earth Observation Architectures

The strategic utility of SWIR imaging extends well beyond airborne and ground-based ISR platforms. Recent advances in Earth observation technologies have demonstrated that spaceborne SWIR sensors can significantly enhance persistent surveillance, environmental intelligence and strategic reconnaissance by providing high-resolution spectral information over large geographical areas. Unlike conventional visible imaging systems, SWIR sensors exploit reflected radiation in the 0.9–2.5 μm spectral region, enabling improved discrimination of vegetation, soil moisture, mineral composition, infrastructure materials and camouflage patterns under diverse illumination conditions. Although SWIR sensors remain dependent on reflected solar radiation, their superior atmospheric transmission characteristics allow improved imaging performance through light haze, smoke and thin cloud layers compared with visible-spectrum sensors. Consequently, modern Earth observation missions increasingly integrate SWIR payloads as an essential

component of multispectral and multi-sensor satellite architectures rather than deploying them as independent imaging systems.[31]

The operational capability of spaceborne SWIR systems is substantially enhanced through their co-deployment with complementary sensing modalities, including visible and near-infrared (VNIR), MWIR, LWIR, HSI and SAR. Each sensor contributes unique spectral or physical information that collectively improves target detection, environmental interpretation and change analysis. The VNIR imagery provides high-resolution visual representation of terrain and infrastructure; SWIR enhances material discrimination and moisture sensitivity; MWIR and LWIR enable thermal anomaly detection; hyperspectral sensors identify subtle spectral signatures associated with natural and artificial materials; and SAR ensures persistent all-weather imaging irrespective of cloud cover or illumination. The integration of these heterogeneous datasets through advanced processing algorithms enables a comprehensive Earth observation architecture, capable of delivering reliable intelligence under both peacetime and conflict scenarios.[32]

International satellite missions clearly illustrate the operational benefits of integrated SWIR architectures. The Sentinel-2 constellation of the European Space Agency incorporates dedicated SWIR bands that significantly improve land cover classification, wildfire assessment, vegetation monitoring and disaster response. Similarly, Landsat-8 and Landsat-9 employ SWIR channels alongside visible and thermal sensors to monitor agricultural productivity, water resources, urban development and environmental change over extended temporal scales. These missions demonstrate that the true value of SWIR lies not merely in independent image acquisition but also in its ability to complement visible and thermal observations, thereby generating richer geospatial intelligence products for a broad spectrum of civilian and strategic applications.[33]

From a defence perspective, integrated spaceborne SWIR payloads offer significant advantages for persistent surveillance and national security. Continuous satellite monitoring enables early detection of infrastructure development, military deployments and changes in strategic installations across vast geographical regions. The SWIR imagery is particularly valuable for border monitoring, where its sensitivity to surface reflectance and reduced susceptibility to atmospheric scattering improve the identification of temporary structures, concealed routes and disturbed terrain. In the maritime domain, SWIR sensors complement radar and optical observations by improving the detection of coastal activities, small vessels and floating objects under varying atmospheric conditions. Their capability to discriminate

between natural and man-made materials further enhances camouflage detection, allowing analysts to identify concealed military assets that may remain indistinguishable in conventional visible imagery.

Beyond conventional ISR, integrated SWIR observations contribute substantially to disaster management and national resilience. Rapid assessment of flood inundation, wildfire progression, landslide susceptibility and post-disaster infrastructure damage enables timely humanitarian assistance and resource allocation. In the agricultural sector, SWIR-based measurements of vegetation moisture, crop stress and soil conditions support food security assessments and drought monitoring. Likewise, continuous observation of strategic infrastructure, including transportation networks, energy installations, communication facilities and border logistics corridors, provides critical intelligence for both civilian planning and defence preparedness. Such dual-use capabilities significantly enhance the economic viability of indigenous SWIR technologies by expanding their applicability beyond military operations.

India's expanding space ecosystem presents a timely opportunity to develop indigenous SWIR payloads for future Earth observation missions. Building upon the country's demonstrated capabilities in satellite manufacturing, remote sensing and launch systems, future programmes should emphasise modular payload architectures that integrate SWIR with VNIR, hyperspectral and thermal imaging sensors, supported by indigenous onboard processing and AI-enabled analytics. Collaborative development involving the Indian Space research Organisation (ISRO), the DRDO, academia and domestic semiconductor industry would accelerate the maturation of indigenous detector technologies while reducing dependence on imported EO components. Such an integrated approach would not only strengthen India's sovereign ISR capability but also position the country as a globally competitive provider of advanced Earth observation technologies for defence, disaster management, agriculture and strategic infrastructure monitoring.

UAV-based Reconnaissance and Target Acquisition

The UAVs have become indispensable assets in modern military doctrine, particularly for ISR. While traditional EO sensors offer high-resolution imaging in daylight, they fall short under low-visibility conditions, such as dust storms, fog or night-time operations. The SWIR sensors, with their capability to penetrate haze and capture imagery using natural or minimal ambient illumination, offer superior target detection in degraded visual

environments. Indigenously developed SWIR payloads can significantly reduce costs associated with deploying such technology on tactical drones, like the Rustom and Nishant, and tactical quadcopters used by the Indian Armed Forces.[34] Moreover, lightweight and low-power SWIR modules can enable longer flight times, enhance area coverage and provide real-time geotagged video feeds for mission-critical decisions. Target acquisition can be further refined using hyperspectral SWIR capabilities, allowing for the discrimination of concealed or camouflaged threats based on material reflectance signatures.

Night Vision Systems for Infantry and Special Forces

Current night vision equipment employed by Indian infantry units predominantly relies on image intensification (I^2) or LWIR thermal sensors. While effective, these systems have inherent limitations. The I^2 devices are sensitive to sudden bright light and ineffective in total darkness, while LWIR sensors do not provide the level of scene detail needed for threat identification in complex urban or forested environments. The SWIR sensors offer a compelling alternative, bridging the performance gaps. Unlike visible light or I^2 systems, SWIR can leverage reflected light from stars or moonlight to render crisp images in complete darkness. More importantly, SWIR sensors allow identification of different materials, such as plastics, camouflage fabric and even human skin, which reflect light differently in the SWIR band. Integrating indigenous SWIR modules into monocular rifle sights and head-mounted displays can significantly enhance infantry night-fighting capabilities. Special Forces conducting counter-insurgency or hostage rescue missions in close-quarter environments will particularly benefit from high-resolution, passive and low-latency imaging, minimising exposure time and maximising mission success.

Fog-penetrating Vision for Armoured Vehicles and Border Patrol

Terrain obscurants, such as fog, smoke and dust, are significant impediments to visibility in armoured combat operations. Border patrols operating in mountainous regions, such as Sikkim and Arunachal Pradesh, or the Thar Desert face consistent challenges due to low visibility caused by environmental conditions. Traditional headlights and visible-spectrum cameras are largely ineffective in such scenarios. The SWIR imaging systems can 'see' through fog and haze by detecting scattered sunlight or ambient SWIR illumination reflected off terrain and obstacles. Integrating indigenously developed SWIR vision modules into the driver's vision enhancer systems

of tanks and armoured personnel carriers would provide safer mobility and better situational awareness during day–night and all-weather operations. Border surveillance platforms, such as the Long-Range Reconnaissance and Observation System (LORROS) and EO stations atop watchtowers, can incorporate SWIR sensors for uninterrupted monitoring. These systems could also support autonomous platforms, such as mobile sentry robots and vehicle-mounted observation units, where real-time fog-penetrating vision is critical.

Smart Munitions with Embedded SWIR-based Tracking

Smart munitions, ranging from guided bombs and loitering munitions to top-attack anti-armour missiles, require accurate terminal guidance to neutralise targets in cluttered, Global Positioning System (GPS)-denied or obscured environments. While laser or radiofrequency (RF) guidance is common, it is susceptible to jamming or loss of lock in smoky or dusty battlegrounds, creating tactical vulnerabilities. The SWIR-based imaging seekers[35] offer a robust solution, with enhanced target contrast and resistance to countermeasures. Indigenously developed SWIR seekers can be embedded in missile nose cones or glide-bomb guidance units, enabling lock-on-before-launch (LOBL) and lock-on-after-launch (LOAL) capabilities. These seekers can track heat-reflecting or spectrally distinctive features of enemy vehicles or infrastructure, even under concealment. For instance, SWIR-guided loitering munitions deployed in border skirmishes or surgical strikes can engage enemy bunkers or vehicular convoys with unprecedented precision and autonomy. Indigenous development of such sensors not only lowers unit costs but also ensures complete control over algorithmic logic, encryption and security, which is critical in today's AI-driven warfare.

Surveillance and Intrusion Detection in Low-Visibility Conditions

Static and mobile surveillance networks form the backbone of border security, perimeter defence of sensitive installations and early warning systems in insurgency-prone zones. Current networks employ thermal and visual-spectrum cameras, which may fail to detect low-signature targets, such as camouflaged personnel, unmanned ground vehicles or small drones, under visually degraded conditions. The SWIR sensors, due to their sensitivity to naturally scattered light, can detect concealed objects and offer superior imaging fidelity at night or through smoke screens. They can also detect signatures that are invisible in other bands, such as specific reflective coatings or materials, making them ideal for intrusion detection and threat classification.

When integrated with AI-based video analytics, these sensors can enable automated tracking, pattern recognition and anomaly detection in real time. Deploying indigenous SWIR-based surveillance in complex terrains,[36] that is, high-altitude forward operating bases, coastal defence radars and critical infrastructure facilities, would drastically enhance operational readiness and counter-infiltration capabilities.

Economic Sustainability, Export Potential and Strategic Technology Diplomacy

In conclusion, the development of indigenous SWIR capability should be approached as the creation of an integrated technological ecosystem spanning the entire innovation and manufacturing value chain, rather than as an isolated effort focused solely on detector fabrication. Sustainable capability depends upon coordinated advances in compound semiconductor materials, FPA technologies, ROICs, precision optics, cryogenic packaging, embedded electronics, image processing, calibration infrastructure and complete EO system integration. Progress across these interconnected domains enables the transition from laboratory-scale research to reliable, field-deployable imaging systems that meet demanding operational and commercial requirements. Equally important, the establishment of shared fabrication facilities, standardised testing protocols and common design platforms can shorten development cycles, improve product reliability and reduce lifecycle costs by enabling technology reuse across multiple applications.[37]

The long-term sustainability of such an ecosystem also relies on strong interactions between defence requirements and civilian markets. Commercial applications in industrial inspection, autonomous mobility, environmental monitoring, precision agriculture, medical diagnostics and Earth observation provide continuous demand that supports manufacturing scale, encourages process optimisation and sustains industrial investment beyond defence procurement cycles.[38] At the same time, collaboration among research institutions, academia, startups, MSMEs, established industries and system integrators facilitates knowledge transfer, accelerates technology maturation and promotes innovation across the entire product development lifecycle.[39] As manufacturing capabilities and system integration mature, opportunities emerge to develop competitive EO products tailored to diverse operational and commercial requirements, including international markets seeking cost-effective imaging solution (as illustrated in Figure 3). Collectively, these technological, industrial and commercial interactions establish a self-

reinforcing innovation ecosystem in which advances in materials, device engineering, AI and system design continuously improve performance, manufacturability and application diversity. Such an ecosystem provides a robust foundation for sustained progress in advanced EO technologies, while supporting long-term competitiveness across both domestic and global markets.[40]

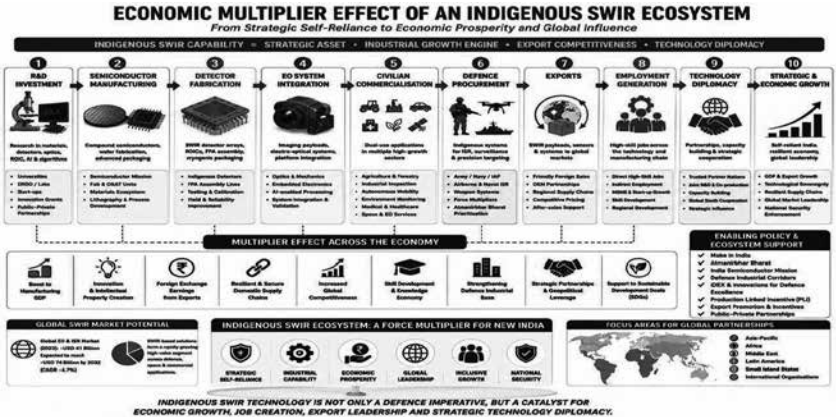


Figure 3. Economic Multiplier Effect of an Indigenous SWIR Ecosystem
Source: Author's conceptualisation; visualisation generated using ChatGPT (OpenAI), 2026.

Conclusion and Strategic Roadmap

The article demonstrates that SWIR imaging has evolved from a specialised EO technology into a key component of integrated ISR systems. Rather than functioning as an independent sensing modality, SWIR provides complementary reflectance information that bridges the capability gap between visible-spectrum and thermal infrared imaging, enabling improved target detection, material discrimination and environmental perception under degraded visual conditions. Its operational value is further enhanced when integrated with visible EO sensors, thermal imagers, hyperspectral systems, LiDAR and SAR through multi-sensor fusion frameworks supported by AI, edge computing and network-centric command-and-control architectures. The article, thus, highlights that future ISR capability will increasingly depend on the intelligent integration of complementary sensing technologies, rather than on continued improvements in individual sensors alone.

The analysis further indicates that the development of indigenous SWIR capability requires coordinated progress across the complete technology ecosystem. Advances in detector materials, FPAs, ROICs, precision optics, cryogenic packaging, embedded electronics, image processing, AI-enabled analytics and system integration must evolve simultaneously to achieve reliable operational performance. Equally important are common fabrication facilities, standardised testing and calibration infrastructure, system qualification methodologies and design platforms that facilitate technology reuse across multiple military and civilian applications. Such an integrated development approach shortens technology maturation cycles, improves manufacturability and supports continuous performance improvements through close interaction between research organisations, manufacturers and end users.

An equally important finding of this review is the increasing convergence of defence and civilian EO technologies. Commercial applications, including industrial inspection, precision agriculture, autonomous mobility, medical imaging, environmental monitoring and Earth observation, provide sustained demand that complements defence procurement and supports long-term industrial growth. Shared technology platforms, common semiconductor manufacturing infrastructure and dual-use innovation create opportunities to improve production efficiency, reduce lifecycle costs and accelerate technology maturation, while expanding the application space of SWIR imaging beyond conventional military systems. The interaction between research institutions, industry, startups and system integrators is, therefore, expected to play a central role in translating laboratory-scale innovations into deployable EO products.

The article also identifies several technological priorities that will shape the next generation of SWIR systems. Continued research is required in high-performance detector materials, low-cost compound semiconductor fabrication, advanced ROIC architectures, heterogeneous integration, uncooled and low-power detector technologies, compact optical systems, onboard AI processing and secure edge computing. Equally important are robust multi-sensor fusion algorithms capable of integrating optical, thermal, radar and spectral information in real time while maintaining reliable performance under complex operational environments. Progress in these areas will determine the scalability, affordability and operational adaptability of future SWIR-enabled ISR systems.

Based on these findings, a phased strategic roadmap extending towards 2040 is proposed. The first phase should focus on strengthening

fundamental research, indigenous detector technologies, semiconductor process development, workforce training and shared research infrastructure. The second phase should emphasise pilot-scale manufacturing, process standardisation, qualification of indigenous subsystems and validation across representative operational platforms. The third phase should prioritise system-level integration within AI-enabled multi-sensor ISR architectures that incorporate autonomous sensing, edge processing and distributed decision-support capabilities. The final phase should concentrate on large-scale manufacturing, technology diversification, continuous product innovation and broader commercial deployment across defence, space and civilian sectors, supported by internationally competitive EO products.

Overall, the review demonstrates that sustainable progress in SWIR technology depends not on isolated advances in detector fabrication, but on the coordinated evolution of semiconductor manufacturing, photonics, AI, precision engineering, system integration and scalable manufacturing within a unified innovation ecosystem. Such an integrated approach provides a practical pathway for advancing next-generation EO technologies that support diverse operational requirements, while fostering continuous technological innovation, broader commercial adoption and long-term competitiveness in advanced imaging systems.

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