International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

Quantum Radar for Future Indian Air Defence: Comparative Evaluation and Implementation Prospects

(Bridging Quantum Physics and Defence Engineering - A Technical and Strategic Study on the Future of India's Air Defence Sensors)

Rajat Singha
Military Institute of Technology, Pune, India

***Abstract*— The aim of this paper is to evaluate the role of Quantum Radar in strengthening India's air defence architecture by addressing the limitations of classical radar systems against stealth and low-observable aerial threats. Air defence in the 21st century is characterised by a continuous contest between detection and evasion. While modern radars have evolved through digital beamforming, phased arrays, and frequency agility, stealth technology—through shaping, radar-absorbent coatings, and signature management—has reduced aircraft radar cross-section to unprecedented levels. For India, facing a two-front threat from technologically advanced adversaries, reliable detection of stealth aircraft, cruise missiles, and UAVs is a strategic necessity. Quantum Radar, based on Quantum Illumination principles, utilises photon entanglement and correlation to detect low-RCS targets even in high-noise and jamming environments. This paper presents a comparative evaluation of Quantum Radar with India's indigenous radar systems and examines engineering implementation prospects under the National Quantum Mission. A phased roadmap is proposed to integrate photonic and quantum sensing technologies within the Integrated Air Defence System, enabling future-ready, quantum-resilient surveillance and target acquisition capabilities for the Indian Armed Forces.**

Keywords*— *Quantum Radar, Quantum Illumination, Stealth Detection, Indian Air Defence, Low-Observable Targets, Photonic Radar, Quantum Sensing, DRDO, National Quantum Mission.

I. INTRODUCTION

Air defence in the 21st century is defined by a persistent contest between detection and evasion. Since the discovery of radar in the 1930s, the technology has evolved from mechanically scanned arrays to electronically steered, software-driven sensor systems operating across multiple frequency bands. Despite advancements such as Active Electronically Scanned Arrays (AESA), digital beamforming, and solid-state electronics, the evolution of stealth technology has significantly reduced radar effectiveness.

Stealth or low-observable (LO) design techniques—through airframe shaping, radar-absorbent materials, and signature management—minimize the radar cross-section (RCS) of platforms such as the Chinese J-20 and American F-35. These features complicate detection across most conventional frequency bands, thereby eroding the early-warning advantage of traditional radar systems. For India, this challenge is particularly acute. The induction of fifth-generation aircraft and precision strike systems by China, coupled with Pakistan's access to Chinese technologies, creates a two-front air threat that exploits radar vulnerabilities. Despite significant progress in indigenous radar systems like Rohini, Arudhra, Ashwini, and Surya VHF, classical radar physics impose inherent limits against low-RCS and electronically deceptive targets.

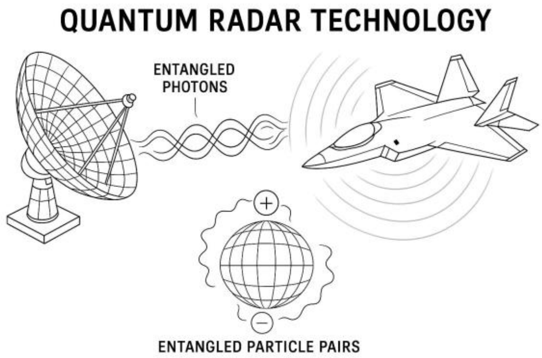

Fig.1. Basic Diagram of Quantum Radar Technology

In this context, Quantum Radar—a sensor concept leveraging Quantum Illumination (QI) principles—has emerged as a potential disruptor. By exploiting quantum entanglement and correlation between signal and idler photons, QI-based radar systems can theoretically distinguish targets within high-noise or jamming environments where classical radars fail. While still at low Technology Readiness Levels (TRLs), Quantum Radar holds the potential to redefine counter-stealth detection and situational awareness within India's Integrated Air Defence System (IADS).

II. PRINCIPLES OF QUANTUM RADAR AND QUANTUM ILLUMINATION

Quantum Radar operates on the foundational concept of Quantum Illumination (QI), wherein pairs of photons—known as the signal and idler—are generated in an entangled quantum state.

- The signal photon is transmitted toward the target area, while the idler photon is retained locally. When the reflected signal returns, the radar compares it with the stored idler to detect subtle correlations that survive even after environmental noise and scattering have destroyed full entanglement.
- Unlike classical radar, which measures echo amplitude and phase, QI exploits statistical correlation

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

between quantum photon pairs. This provides a measurable quantum advantage in detection probability, allowing targets with extremely low radar cross-sections (RCS) to be identified within clutter or jamming conditions.

- The theoretical benefit of Quantum Radar lies in its ability to maintain discrimination performance at low signal-to-noise ratios (SNRs), where traditional radars fail. However, practical realisation requires sophisticated photon sources, ultra-low-noise detectors, and quantum memories for idler storage—making engineering implementation the key challenge rather than the underlying physics.

III. Quantum Radar Architecture and Subsystem Functional Overview

A. Quantum Entanglement Source: This block generates pairs of entangled photons—known as the signal and idler—using nonlinear optical processes such as Spontaneous Parametric Down Conversion (SPDC) or quantum dot emitters. The quantum entanglement establishes a correlated state between the two photons in parameters such as polarization, phase, or frequency. The degree of entanglement directly influences detection fidelity in later stages.

B. Transmitted Signal Subsystem: The signal photon is directed toward the target through free-space propagation. Upon reflection from a stealth or low-observable object, the photon undergoes weak alterations in its phase or polarization due to interaction with the object's surface or coating. These small modulations encode the target's presence, range, and motion, even when the reflected energy is close to the noise floor.

C. Receiver Subsystem: The idler photon, entangled with the transmitted signal photon, is retained locally within the receiver for reference comparison. When the reflected signal photon returns, the receiver subsystem collects it and performs coincidence counting—a process of detecting simultaneous photon events to identify the correct signal–idler pair. This ensures that even extremely weak echoes buried in environmental noise can be distinguished from background interference.

D. Quantum Correlation and Measurement Unit: This subsystem performs joint detection between the returned signal and its retained idler. Quantum correlation analysis extracts key observables such as time delay, phase shift, and polarization coherence, forming the basis of Quantum Illumination (QI). The correlation function, typically represented as

$$\rho=|\psi_s \psi_i|$$

(where ψ_s and ψ_i denote the quantum states of signal and idler photons), quantifies the coherence between them. Even when entanglement is partially lost during propagation, residual correlation enhances detection sensitivity beyond classical radar limits.

E. Target Information Extraction: Processed data from the correlation stage is used to derive target range, velocity, and radar cross-section (RCS) signature. The quantum advantage manifests as a measurable improvement in signal-to-noise ratio (SNR) under identical power and bandwidth conditions compared to conventional radar. This makes Quantum Radar inherently resistant to stealth shaping, jamming, and clutter, enabling superior detection reliability in contested electromagnetic environments.

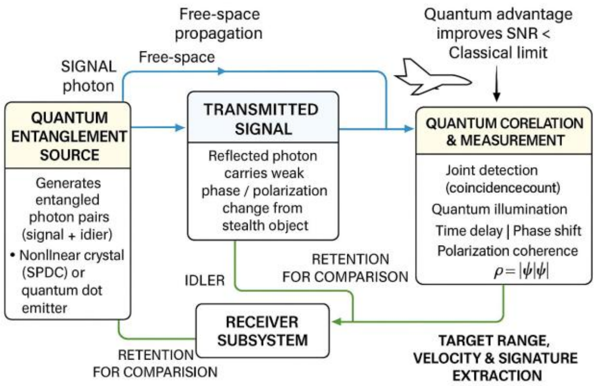

Fig.2. Functional Diagram of a Quantum Radar

IV. COMPARATIVE OVERVIEW OF INDIGENOUS RADAR SYSTEMS

Over the last three decades, India's radar ecosystem—spearheaded by DRDO, BEL, and private industry—has evolved into a layered and largely self-reliant network forming the backbone of the Integrated Air Defence System (IADS). These systems span multiple frequency bands and mission roles, reflecting steady progress under the Atmanirbhar Bharat initiative.

A. Ground-based radars

- Rohini / Revathi (S-Band): 3D surveillance radars with digital beamforming and solid-state modules, effective for medium-range detection (~150 km). However, stealth-optimised platforms exploit S-band limitations.
- Ashwini / Bharani (L- and S-Band): Mobile, low-level radars designed for mountainous and semi-urban terrain; provide coverage for low-flying aircraft and UAVs up to ~200 km.
- Arudhra (S-Band AESA): Medium-Power Radar (~300 km range) with ECCM features and high mobility, forming the IAF's mid-tier layer.
- LRTR / Swordfish (L-Band): Long-range tracking radar (>500 km), adapted for BMD but also capable of detecting air-breathing targets; limited tactical deployability due to size and power needs.

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B. Counter-Stealth and Emerging Technologies

- Surya (VHF Counter-Stealth): Detects stealth targets through resonance scattering; limited angular accuracy but valuable as an early cueing sensor.
- Photonic Radar (Prototype): Uses optical waveform generation for ultra-stable, deception-resistant signals—acts as a bridge between classical and quantum radar.
- Multi-static and Passive Radars: Experimental systems exploiting distributed geometry and civilian signal reflections; resilient to jamming and suitable for urban or coastal surveillance.

C. Airborne and Fusion Systems

- Uttam AESA (X-Band): Indigenous fighter radar with agile beam steering and ECCM, contributing to both offensive and defensive roles.
- Netra Mk-II AEW&C: Airborne early-warning platform (350–400 km range) improving low-altitude coverage and contributing to Recognised Air Picture integration.
- AkashTeer BMS: AI-enabled fusion system that integrates radar tracks from multiple sensors, enhancing continuity against stealth or low-RCS threats.

In summary, India possesses a robust and diversified radar network. However, most indigenous systems remain constrained by classical detection physics—monostatic operation, limited low-RCS sensitivity, and susceptibility to deception. Quantum Radar, therefore, represents the logical next step to augment these capabilities with correlation-based detection and enhanced resilience under contested electromagnetic environments.

V. ENGINEERING AND IMPLEMENTATION CHALLENGES

A. While Quantum Radar promises decisive advantages in counter-stealth detection, its realisation faces formidable engineering barriers. The transition from theoretical Quantum Illumination to deployable systems demands breakthroughs in photon generation, storage, and environmental resilience.

- Decoherence and Loss: Entangled photons are extremely sensitive to atmospheric absorption, scattering, and thermal noise. Maintaining useful correlation over operational ranges requires ultra-low-loss optics and precise environmental control.
- Idler Storage and Synchronisation: Correlation measurements depend on accurately matching the returned signal with its retained idler. This calls for quantum memories or long optical delay lines with nanosecond timing precision.
- Cryogenic Operation: Current superconducting detectors and quantum receivers need milli-Kelvin cooling. Achieving such temperatures in mobile, rugged military platforms remains a major integration challenge.
- Photon Flux Scaling: Laboratory sources generate microwatt-level quantum signals, far below the power required for long-range radar. Bridging this energy gap without destroying entanglement is a key research frontier.
- Ruggedisation and EMI Shielding: Quantum subsystems must endure shock, vibration, and electromagnetic interference typical of field deployments in deserts, coasts, and high-altitude terrain.
- Signal Processing and Data Fusion: Quantum detection produces probabilistic outcomes. Integrating these into deterministic radar displays and existing IACCS fusion systems requires new algorithms and operator training.

B. In essence, the physics of Quantum Illumination are proven in principle; the challenge now lies in engineering scalability, mobility, and battlefield survivability to transform laboratory demonstrators into deployable defence assets.

VI. INDIAN CONTEXT AND TECHNOLOGICAL PATHWAY

A. India's pursuit of quantum technologies is being accelerated under the National Quantum Mission (NQM 2023), which identifies quantum sensing and communication as strategic priorities. Within this framework, DRDO, BEL, and academic partners such as IIT Delhi, IISc Bengaluru, and IIT Madras are exploring quantum-enhanced detection and photonic signal processing concepts relevant to radar applications. The country already possesses a robust radar manufacturing and integration base through DRDO's LRDE and BEL's production ecosystem. This industrial readiness provides a natural platform to transition from classical → photonic → quantum radar architectures. Photonic radars now under DRDO trials serve as bridge technologies, allowing the testing of optical waveform generation, high-stability clocks, and low-noise receivers—capabilities that directly feed into quantum illumination research.

B. To sustain progress, India requires a phased, mission-driven roadmap:

- Short Term (2025–2027): Demonstrate laboratory quantum illumination experiments and integrate quantum receivers with existing photonic radar testbeds.
- Medium Term (2027–2030): Develop hybrid quantum–classical demonstrators for limited field trials under IAF and BEL collaboration.
- Long Term (2030 onwards): Achieve system-level integration of quantum radar nodes within the

International Journal of Engineering Research & Technology (IJERT)
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Integrated Air Command and Control System (IACCS) for operational evaluation.

C. By leveraging existing radar expertise and aligning with the NQM's funding mechanisms, India can position itself among the earliest nations to field a quantum-ready counter-stealth capability suited to its diverse terrain and threat environment.

VII. POLICY AND STRATEGIC IMPLICATIONS

The evolution of Quantum Radar from concept to deployable capability carries significant policy and strategic implications for India's defence modernisation agenda. As adversaries invest in stealth aircraft, hypersonic systems, and electronic warfare, the ability to detect, track, and engage such threats defines the credibility of future air defence operations.

- From a policy perspective, Quantum Radar aligns with *Atmanirbhar Bharat* by fostering indigenous design, fabrication, and algorithm development in high-value technologies such as quantum optics, cryogenics, and superconducting sensors. Strategic investment through the National Quantum Mission and dedicated DRDO–academia joint testbeds would ensure focused, dual-use innovation applicable to both military and civilian domains.

- Operationally, Quantum Radar supports a layered detection philosophy, complementing VHF, photonic, and passive radar networks within the Integrated Air Defence System (IADS). Early prototypes can be deployed around high-value assets—airbases, missile sites, and command nodes—to validate real-world resilience against stealth and electronic counter-measures.

- At a strategic level, successful fielding of Quantum Radar will not only enhance India's defensive depth but also establish technological sovereignty in a domain where only a handful of nations are active. It represents a decisive step toward a quantum-enabled, network-centric battlespace, reinforcing India's position as a forward-looking military power in the Indo-Pacific region.

VIII. CONCLUSION

Quantum Radar represents a transformative advancement in the evolution of sensor technology—one that seeks to overcome the inherent physical limitations of classical radar through quantum illumination and correlation-based detection. For India, confronted with emerging stealth, hypersonic, and electronic warfare threats, this technology offers a credible pathway to restore detection superiority. While practical implementation remains constrained by challenges in photon generation, idler storage, cryogenic operation, and environmental hardening, the National Quantum Mission provides a structured framework to pursue these goals through coordinated DRDO, BEL, and academic efforts. A phased approach—progressing from photonic radar testbeds to hybrid quantum–classical demonstrators—can yield measurable results within the coming decade. Ultimately, Quantum Radar should be viewed not as a replacement for India's indigenous radar systems but as a strategic augmentation that enhances their resilience against stealth and deception. By investing early and systematically, India can position itself among the global leaders in quantum sensing and secure a decisive advantage in future air defence operations.

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