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Quantum Technologies: Radio Frequency (RF) Systems

Quantum Remote Sensing Applied to National Defense

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Abstract

This work presents a study on quantum remote sensing applied to national defense using RADAR (Radio Detection and Ranging) and LIDAR (Light Detection and Ranging) technologies, which can be adopted in metrology and remote sensing processes, capable of detecting and intercepting targets in a given coverage area. In this context, the work presents a bibliographic research addressing concepts, principles of quantum mechanics, basic configurations, methods of photon entanglement, projects, experiments, and potential applications of RADAR and LIDAR systems, highlighting advantages and aspects, such as speed, greater precision, lower cost, greater security guarantee, higher sensitivity, and resolution of quantum remote sensing operation, as well as associated challenges: photon loss, technical difficulties, the phenomenon of decoherence, sensitivity to noise, and the need for integration of quantum remote sensing systems with quantum error correction modules.

I. INTRODUCTION

In an increasingly complex and rapidly evolving national defense scenario, cutting-edge military technologies, such as those utilizing principles of quantum mechanics, emerge to extrapolate and enhance classical capabilities and play a fundamental role in ensuring strategic advantage in security, intelligence, and counterintelligence. This new paradigm has the potential to revolutionize various defense sectors, from cybersecurity, communication, and cryptography, to metrology and remote sensing [1].

The field of remote sensing research, an essential tool in modern defense strategies, has made significant advances in range, resolution, and sensitivity with the advent of RADAR (Radio Detection and Ranging) and LIDAR (Light Detection and Ranging) systems, used to detect, locate, and classify objects at varying distances, providing valuable data for strategic and tactical decision-making in defense operations [2].

In the last decade, the integration of quantum principles, especially the phenomenon of quantum entanglement first presented in 1935 [3], in remote sensing has emerged as a promising research and development resource in RADAR and LIDAR system projects, aptly described as "quantum," since they enable the detection of targets in noisy environments with refined resolution and, at the same time, present potential resources against the eventual stealth capability of targets — highly desirable characteristics in defense applications [4].

The objective of this work is to present bibliographic research on quantum remote sensing as a quantum technology for defense through the consolidation, analysis, and synthesis of current references that address quantum adaptations and advances in quantum remote sensing systems, quantum adaptations and advances in quantum RADAR and LIDAR systems.

The expected outcome is a comprehensive research on concepts and principles of quantum mechanics, basic configurations, methods, projects, experiments, and potential applications associated, as well as the advantages and challenges pertinent, highlighting the state of the art and potential future directions in this promising and critical field for national security and defense.

II. RESEARCH METHODOLOGY

The methodology of this work was based on referenced research to guarantee a comprehensive, relevant, and updated view of the application of quantum technology in remote sensing for defense, in quantum adaptations and advances of RADAR and LIDAR systems, based on:

- Selection and exploration of research databases, including IEEE Xplore, Google Scholar, ScienceDirect, SpringerLink, and JSTOR, using customized query parameters and related terms;
- Filter criteria based on publication date (prioritizing the last decade), relevance (quantum remote sensing for defense), and peer review;
- Data extraction highlighting the main findings, contributions, challenges, limitations, and suggestions for future research;

- Systematic analysis of the extracted data and coherent synthesis in the consolidation, comparison, and structure of the results;
- Cross-validation of references to ratify the relevance and exploration of potentially overlooked works.

III. CONCEPTS AND COTEXTUALIZATION

Quantum mechanics is the theory that describes the behavior of matter and energy at the subatomic level and provides a rigorous foundation for principles such as superposition and entanglement [7]. Superposition postulates that a quantum system can exist in several states simultaneously, resolving only to a defined state immediately after measurement [6]. Entanglement, on the other hand, is a quantum phenomenon in which particles become correlated in such a way that the observation of the state of one particle implies establishing the state of the other instantaneously, regardless of the distance between them [7].

The organization and utilization of such principles in computational systems promise unprecedented information processing power [8].

While classical computers operate with bits — represented by the values 0 (zero) or 1 (one) —, quantum computers manipulate quantum bits or qubits (quantum bits, the units of quantum information), which can be in a superposition of both states simultaneously, allowing them to perform a large volume of calculations simultaneously [9].

This parallelism is fundamental for problems considered intractable for classical computers, such as algorithms for factoring large numbers or simulating complex quantum systems [5]. Quantum Technology (QT) is an emerging field of physics and engineering based on properties of quantum mechanics, especially entanglement, superposition, and tunneling, which develops practical applications with a dual purpose of commercial production and defense operations. Therefore, it is of interest to various actors, such as military organizations, governments, and peacekeeping organizations [1].

Due to its nature, technologies that explore and instrumentalize fundamental properties of quantum mechanics are susceptible to interference, noise, or falsification. In this sense, research and development efforts for procedures for the detection and correction of quantum errors, maintenance of coherence of quantum states, and guarantee of fidelity of quantum logic gates constitute the main challenges to improving the quality of qubits [5].

According to reference [10], the results from QT can be categorized into three areas of concentration:

a) Quantum computing (computers, simulators, cryptanalysis systems, and Artificial Intelligence systems that surpass their classical counterparts);

b) Quantum communication (quantum key distribution and entangled qubit distribution); and

c) Quantum sensing (measurement and monitoring of physical variables, such as magnetic or electric fields, gravity gradients, acceleration rotations, and time).

A. Quanntum Technologies for Defense

In the domain of National Defense, the greater the use of effective innovative technologies, the better the performance and the greater the preparation for achieving the expected objectives in military operations.

In this context, the potential implications of QT for national defense and security have been consolidating as one of the main emerging and disruptive initiatives that will bring new capabilities for both civilian and military purposes.

There are several research groups in universities worldwide committed to this theme, playing a leading role in developing groundbreaking research in quantum computing (hardware, algorithms, protocols, communication, etc.) and post-quantum (cryptography protocols, for example). Companies such as IBM, Google, Microsoft, D-WAVE, and Righetti, based in the United States, Canada, China, and Europe, serve the interests of the industry, companies, and governments worldwide through applied quantum research [9].

Reference [1] relates the low Technology Readiness Levels (TRL) — ranging numerically from 1 to 8 — with current quantum technologies and their time horizon, despite their emerging disruptive potential to drive and define success in achieving national defense objectives.

TABLE I. EXPECTATIONS OF TECHNOLOGY READINESS LEVELS (TRL) AND TIME HORIZON.

Technology	TRL	Time Horizon
Quantum computer (annealer)	4-5 (5-6)	2030
Quantum Key Distribution (QKD) via satellite	7-8 (6-7)	2025 (2030)
Post-Quantum Cryptography	7-8	2025
Quantum Communication Networks	1-3	2030-2035
Quantum Inertial Navigation	4-5	2025-2030
Quantum Clocks	4-6	2030
Quantum Radar	1-2	N/A
Quantum Radio Frequency Antenna	4	2025-2030
Quantum Sensing of Magnetism and Gravity	5-6	2025
Quantum Ghost Imaging	5	2025-2030

The concept of "quantum warfare" is conceived as the use of quantum technologies in military applications that encompasses intelligence, security, and defense capabilities in all domains of war, giving rise to new strategies, doctrines, and military scenarios, as well as ethical and peacekeeping issues [11].

The main stage for this concept is represented by quantum channels, defined as any flow of photons that carries qubits in a quantum network, quantum RADAR systems, or similar systems that use free space or fiber optic cabling as a communication medium [10].

However, given the lack of a precise notion of effectiveness or impact, but with imminent implementation in real-world applications, the authors highlight the relevance of discussing methods and techniques for falsifying, disabling, or destroying such artifacts, such as counter-attack (quantum hacking) or countermeasures in the context of field operations immersed in this new reality.

According to reference [1], "quantum warfare" can be enabled by:

a) war systems equipped with classical technologies enhanced by quantum antennas and quantum computers analyzing radio frequency spectra through the use of quantum machine learning and optimization techniques; and

b) pure quantum systems equipped with Signals Intelligence (SIGINT) and Communications Intelligence (COMINT) for detection, interception, identification, and location, as well as capabilities for quantum electronic attacks (jamming, deception, use of directed energy weapons).

Fig. 1 illustrates the concept of "quantum warfare" through the possible applications of defense systems based on quantum technologies in the context of military operations [10].

Fig. 1. Concept of "Quantum Warfare". Scheme of the application of systems based on quantum technologies in military operations [10].

In quantum remote sensing research, phenomena such as quantum illumination explore entanglement to improve the detection of weak signals in noisy environments [4]. Similarly, the potential for LIDAR and RADAR systems with enhancements arises from leveraging these quantum principles [12], aiming to develop properties such as improved resolution, sensitivity, and security in detection and ranging applications [13].

B. Remote Sensing for Defense

Historically, remote sensing for defense has been predominantly dominated by reconnaissance aircraft and satellites, collecting visual and infrared images of various regions [14].

Remote sensing is a tool for defense and offers a combination of large-scale surveillance and detailed target recognition through the use of electromagnetic waves that enable object detection and classification, in addition to enhancing situational awareness, intelligence gathering, and strategic planning of national defense operations [12]. Traditionally, remote sensing is applied to defense under the following approaches:

- Surveillance and reconnaissance: continuous monitoring of areas of interest, providing data on enemy movements, installations, and activities;
- Target recognition: precise identification potential threats or targets based on their signatures;
- Terrain mapping: generation of detailed topographic maps that are crucial for mission planning, especially in unknown terrain; and
- Missile defense: tracking and interception of incoming threats using high-resolution detection.

Quantum remote sensing is one of the areas of quantum technology whose emergence was driven by advances such as the development of quantum clocks for GPS (Global Positioning System) and quantum sensors capable of producing precise information about electrical signals, magnetic anomalies, and data necessary for inertial navigation [14].

C. Quantum RADAR & LIDAR

The protocols of quantum optics that relate the entanglement of photons to enable noise suppression and object resolution are used in quantum RADAR systems to detect objects in optically opaque environments [4].

Therefore, this is a research field that has the potential to significantly leverage investments in defense resources, providing unparalleled advantages in detection, resolution, and security.

The advent of RADAR (Radio Detection and Ranging) and LIDAR (Light Detection and Ranging) systems marked a significant technological leap, as, using radio waves and light waves, respectively, these systems offer the advantage of day and night operation, with penetration through certain occlusions and the ability to capture specific types of data, such as speed through analysis of results from the Doppler Effect [1].

The application of quantum principles to RADAR and LIDAR systems promises a new frontier in remote sensing capabilities, such as:

- Enhanced sensitivity: quantum systems are inherently more sensitive than classical systems, allowing for the detection of low-signature targets in noisy environments [2].
- Enhanced resolution: quantum entanglement and specific quantum states (such as NOON states) can enable resolutions beyond the classical diffraction limit [15];
- Precision: as a consequence of the previous capabilities, in response to minimal changes in the considered environment, RADAR and LIDAR systems are ideal for detecting or tracking threats, such as chemical, biological, and nuclear weapons [11]; and
- Security: quantum signals can be inherently secure, and any attempt at interception or eavesdropping would disturb the quantum states, making detection evident [14].

Some key challenges and considerations in this field of research are outlined in [11], including:

- Photon loss: a significant issue in quantum RADAR and LIDAR systems, particularly over long distances or in challenging noisy environments;
- Technical challenges: creating, managing, and detecting specific quantum states of light, especially in an external environment, poses significant technical challenges closely tied to maintaining the quality of processed information;
- Decoherence: quantum states are delicate and can be easily corrupted by the environment, leading to a loss of quantum advantage; and

- Integration of quantum systems into established defense infrastructure requires careful consideration (temperature, error correction, etc.) due to the unique requirements and sensitivity levels of the information units being manipulated.

IV. RESULTS AND DISCUSSIONS

Fig. 2 displays two target detection schemes: classical and quantum [4].

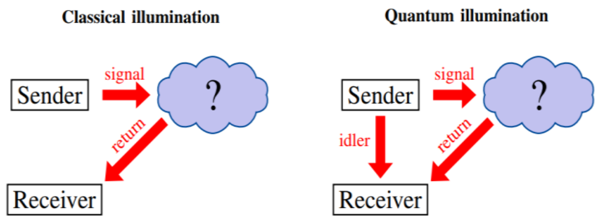

Fig. 2. Classical target detection schemes (Classical illumination) and quantum entanglement-based detection (Quantum illumination) [4].

In the classical illumination scenario (as a detection procedure), a coherent state is sent to the target region, so the returned light is measured, which is in a strong thermal configuration or a combination of a very weak coherent state and a much stronger one. In this scheme, the discrimination process between the two hypotheses corresponds to distinguishing between a broad Gaussian distribution and an identical one but slightly offset.

A two-mode squeezed vacuum state is generated in the context of quantum illumination for target detection. One signal (idler) is retained at the sender, while the other is transmitted to the target region. To determine which of the hypotheses is true, a joint measurement is performed on the returned and retained idler signal. By joint measurement, we mean a detection scheme that treats the signal and idler together as a single quantum system capable of measuring their correlations. Measuring the returned signal and idler individually is not sufficient to reconstruct their correlations in post-processing.

Fig. 3 shows a commercially available and widely used LIDAR scheme where a laser pulse (light amplification by stimulated emission of radiation) is divided into a large number of narrow beams that propagate towards the target and a set of detectors records the return signal, allowing for the collection of statistical data on the object's characteristics, which can be inferred. [2].

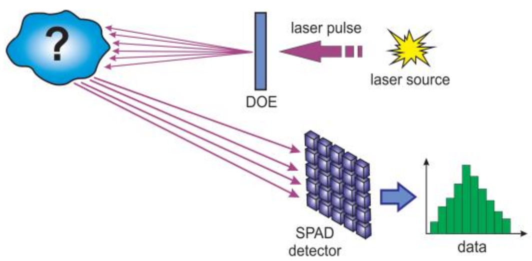

Fig. 3. LIDAR scheme with single-photon detector array: the laser beam is divided into beams by a diffractive optical element (DOE) and the return signal is detected using single-photon avalanche diodes (SPADs)[2].

This scheme offers advantages such as high sensitivity, the possibility of using weaker laser sources, eye safety, low cost, potentially larger area coverage performance, enhanced depth resolution, and accuracy [13]. However, it requires high computational power and advanced methods for object reconstruction and noise removal, especially if the goal is to capture real-time images of moving targets. Single-photon LIDAR systems are estimated to be capable of achieving a two-fold increase in spatial resolution above the diffraction limit for distances over 8 km [2].

Another possible application of quantum RADAR is quantum radio transmissions on underwater vessels by manipulating the magnetic field of the chemical element Rubidium (Rb) in order to send digital signals [9].

In the context of the Brazilian military scenario, where strategic and operational planning outlined by the National Defense Policy (NDP) and the National Defense Strategy (NDS) are guided, as per efforts of the Ministry of Defense with the three Armed Forces, by the Capability-Based Planning (CBP) methodology, budgetary considerations in the face of restrictions and policy guidelines for the use of Military Power form the methodological basis for strategic planning, such as that of the brazilian Aeronautics Command (COMAER) [16].

Indeed, some phases of this process, such as prospective intelligence, technological and industrial analyses, and financial and budgetary resource assessments, aim to support, among other actions, the allocation of resources to acquisitions or development of strategically diagnosed capabilities [16]. Therefore, for the defense sector, market trend analyses regarding quantum sensors, illustrated in Fig. 4, and price research, exemplified in Table II, are activities inseparable from purely tactical and operational initiatives and actions or strictly technical approaches previously discussed.

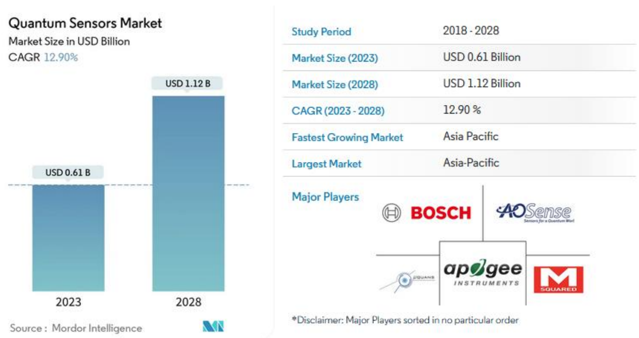

Fig. 4. The quantum sensor market size is estimated to be $0.61 billion in 2023 and is expected to reach approximately $1 billion by 2028, growing at a compound annual growth rate (CAGR) of 12.90% during the forecast period (2023-2028). A significant portion of such investments comes from the defense sector due to the precision and sensitivity in detecting submarines, underground structures, and nuclear materials [17].

Table II referentially compares the average value (in US dollars - USD) of classical and quantum sensors readily available for sale on the internet for civilian and general-purpose use [18]-[23]. This example demonstrates the fundamental relevance of this category of analysis in structuring the strategic potential of Brazilian military power from the perspective of capabilities that inevitably involve market prospecting activities for quantum sensing equipment in light of the country's budgetary reality.

TABLE II. EXPECTATIONS OF TECHNOLOGY READINESS LEVELS (TRL) AND TIME HORIZON.

Classical Sensor	*Value (US$)*	*Quantum Sensor*	*Value (US$)*
7210 Davis AirLink Professional Air Quality Sensor	215.00	Apogee Quantum Meter MQ-210	538.80
6450 Davis Solar Radiation Sensor	225.00	Apogee SQ-520 Quantum Sensor	653.25
Davis 6332 Solar-Powered Wireless Sensor Transmitter	235.00	SQ-515 Amplified 0-5 V Full-Spectrum Quantum Sensor	699.00

Therefore, in addition to the inherently technical challenges, the deployment of quantum sensors presents budgetary challenges. Despite their low operating costs compared to their classical counterparts, the acquisition costs of technological solutions for national defense and security can be prohibitive [11]. Furthermore, some quantum RADAR and LIDAR systems require operation near absolute zero (-273.15 °C or 0 K) to ensure correct precision and sensitivity in the detection process, a significant challenge for military operations.

V. RESULTS AND DISCUSSIONS

Despite the still incipient references on the application of quantum mechanics principles in remote sensors and their use of RADAR and LIDAR as quantum technology for national defense, it is a large area of research and innovations in the fields of quantum computing, photonics, and Artificial Intelligence will accelerate new interpretations, simulations, improvements and overcoming of the inherent challenges in its practical applicability, as predicted in recent works. [14].

Therefore, in the context of national security and defense, the main applications of this research area are in the fields of ISR (Intelligence, Surveillance, and Reconnaissance) and PNT (Positioning, Navigation, and Timing) [12]. Quantum RADAR could, in principle, increase the maximum range of its classical counterparts by 41% and be particularly effective against stealth aircraft [1].

In the short term, ghost imaging technology could improve ISR-related applications by overcoming atmospheric barriers such as clouds or smoke. Sensitive atomic clocks could improve GPS-based positioning, and magnetometers and radiometers could enable navigation in GPS-denied environments through the Earth's magnetic fields. Accelerometers could improve inertial navigation systems, including those integrated into guided missiles and other critical PNT applications [12].

As early as 2015, the US Air Force Scientific Advisory Board concluded - as noted in reference [12] - that only a sustained and intensive research and development effort can ensure the long-term maturation of these technologies for military applications.

It is also noteworthy that the concept of "quantum warfare" creates strategic, tactical, and doctrinal demands of a military nature, as well as technical challenges (new engineering applications in real environments, exponential data growth, new computational architecture and infrastructure, standardization issues, secure and reliable communication, education and workforce training, among others), in addition to ethical (direct threats to human DNA, new materials as weapons, etc.) and disarmament issues (generation and control of new weapons export and management of dual-use technology).

Global studies and discussions are necessary to assess the real implications, threats, and choices that arise from such a proposition.

As a proposal for future work, given the synergy between various Brazilian research areas, such as Meteorology, Physics, and Astronomy, as well as the exchange of experience with various sectors of Military Defense in Brazil (radars), hybrid civil-military projects can be conceived, creating quantum devices for detection and tracking of celestial bodies through gravimetry [14].

These systems can operate with optical systems (equipped with lasers) or with electromagnetic wave emission/detection systems in other spectra. Finally, research on applications of quantum RADAR and LIDAR systems in developing quantum radio transmission solutions, surveillance and data collection activities, anti-terrorist operations, and missile defense system design is also possible [11].

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