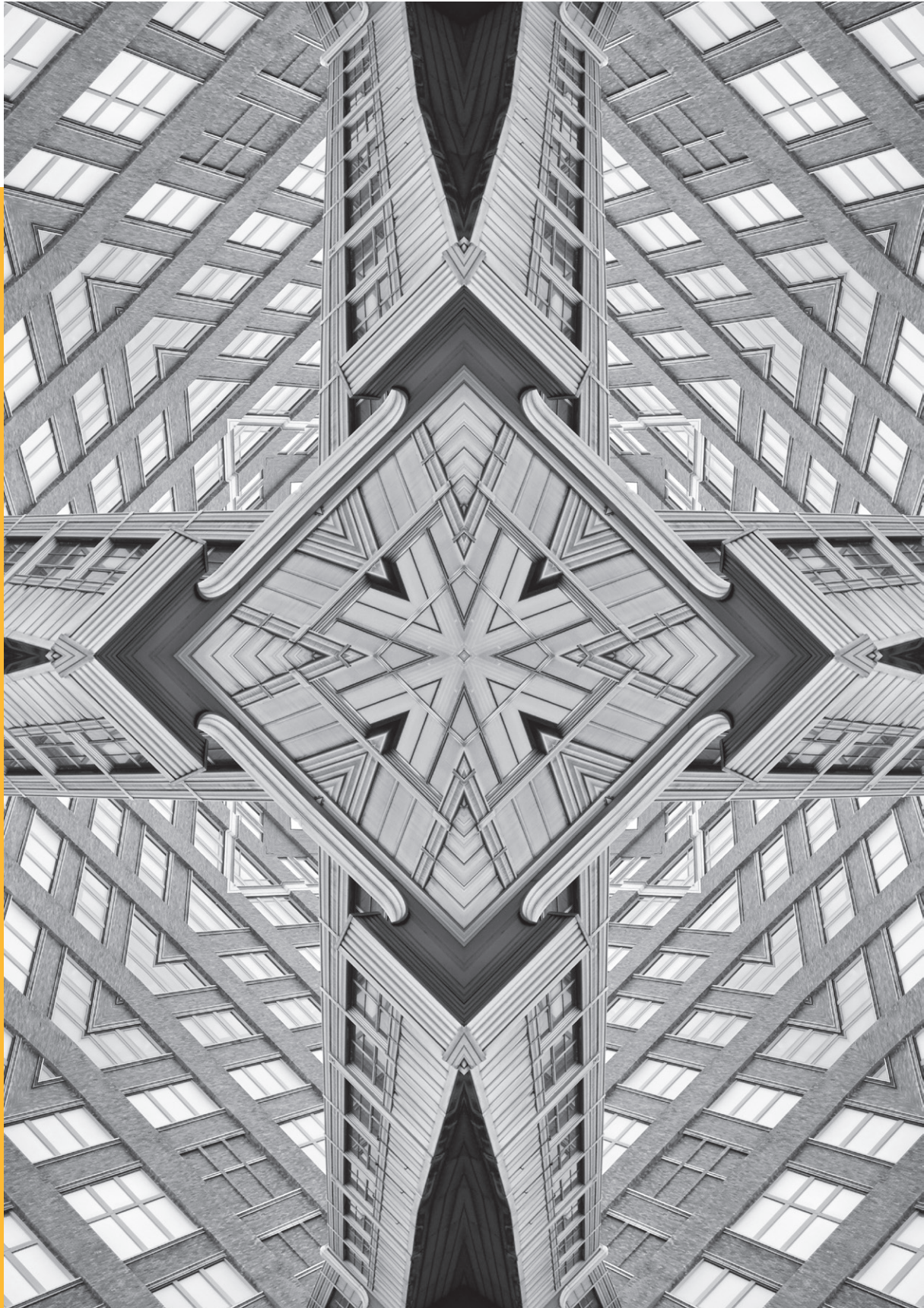


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Quantum Sensing and its Applications in Indian Military Navigation Systems

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Abstract

India has made reasonable progress in terms of quantum sensing systems via its National Quantum Mission, but needs a more refined and coordinated approach led by the Ministry of Defence. Given the importance of Position, Navigation, and Timing (PNT) systems, their augmentation should be a priority for the Indian military. Quantum PNT systems offer a distinct advantage over classical systems as they do not rely on external signals, and hence, are immune to jamming or spoofing. This paper argues that the Indian military should undertake a comprehensive assessment of its current PNT capabilities and develop a long-term strategy for PNT resilience with a clear outline for augmentation. In addition to providing an advantage on the battlefield, this will go a long way in ensuring the timely commercialisation of quantum technologies within the country.

The defence sector is the primary site for the development of new, cutting-edge technologies, including the evolution of quantum technology. Developing control over individual particles at the quantum scale can be a paradigm shift for defence technology, offering new capabilities while augmenting existing ones.

Within the realm of quantum technology, quantum sensing has the most practical utility, with multiple working prototypes and commercially available quantum sensing systems already in place. With potential applications from enhanced Intelligence, Surveillance, and Reconnaissance (ISR) to electronic and space warfare, it is easy to see why many nations have invested heavily into the technology. However, their most viable application currently lies in the realm of augmenting classical Position, Navigation, and Timing (PNT) sensors.

PNT systems form the backbone of modern military systems, being widely employed for navigation, communication, ISR operations, and targeting. They were widely used in recent conflicts such as the Russia–Ukraine War, the Iran War, and Operation Sindoor. Moreover, given the increasing instances of Global Positioning System (GPS)-jamming and spoofing along the India–Pakistan and Indo–China borders, for India, they offer a viable alternative to the traditional Global Navigation Satellite Systems (GNSS), as they are an effective counter to navigation warfare.

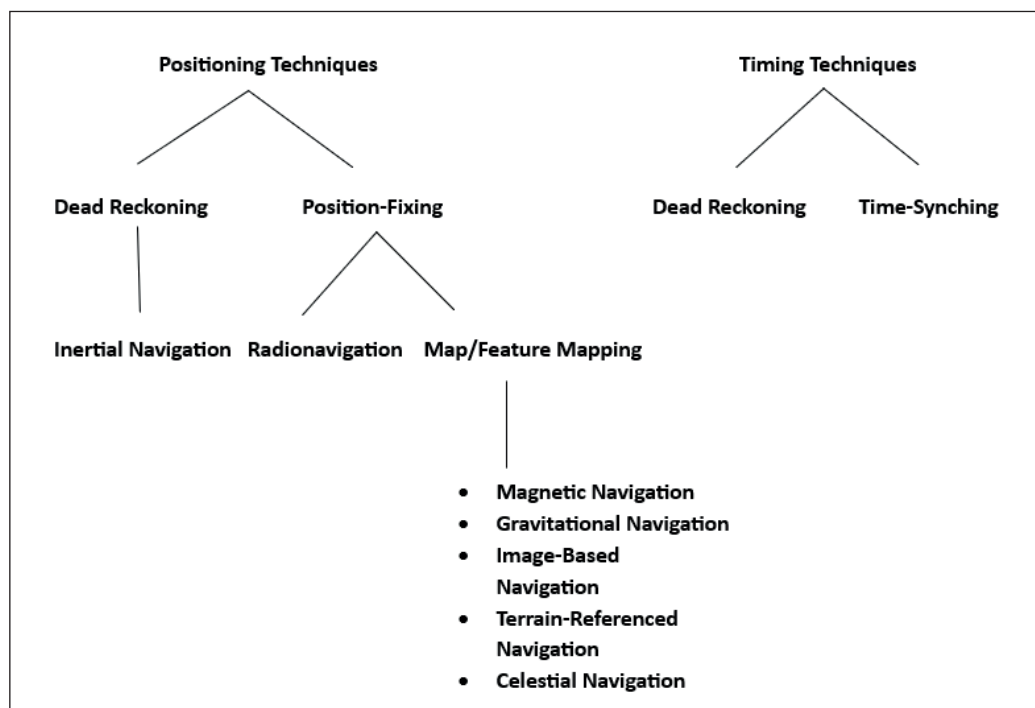
The Indian military has undertaken multiple initiatives to develop quantum sensing and PNT systems in collaboration with academia and start-ups working in the field, primarily under India’s National Quantum Mission. However, given the nascent and complex nature of the technology, several practical and strategic constraints will need to be overcome.

This paper gives an overview of the classical PNT systems and their limitations, discussing the need for PNT resilience and augmentation. It elucidates the basic concepts of quantum sensing and its applications in developing novel PNT systems for timing and inertial navigation, and details the global initiatives pursuing this technology. It discusses the Indian PNT scenario, along with the efforts made to develop quantum sensing systems. It concludes with policy recommendations that can aid in harnessing the technology for optimal military impact.

PNT systems have cemented themselves in the modern world, finding application across almost every domain, from civilian applications such as transportation, banking, energy grids, and air travel to military employment for aircraft, drone, and ship navigation, as well as missile guidance, and precision-guided munitions.

Positioning and timing techniques form the foundation of PNT systems. They can be broadly classified as given in Figure 1.

Figure 1: Position and Timing Techniques Employed in PNT Systems



Source: Author's own, based on quantum vs classical complementarity PNT.¹

Timing Techniques

Timing techniques can be divided into dead reckoning and time synchronisation. In dead reckoning, a timing sensor is employed to estimate time relative to a previously estimated time, such as logs from previous marine navigations.² Time synchronisation employs the more modern approach of estimating time relative to an externally defined time, such as Coordinated Universal Time (UTC).³ While the latter is the more accurate and reliable approach, dead reckoning is used in the absence of traditional timing systems like the Global Positioning System (GPS). Accuracy^a in dead reckoning tends to reduce over time due to error accumulation (or ‘drift’) by clocks.

Timing systems rely on clocks, which typically consist of an oscillator^b and a counter. Earlier oscillators were only made of quartz crystal, but now they are gradually being replaced by Micro-Electromechanical Systems (MEMS) that are more accurate.⁴

A counter consists of a circuit that counts or accumulates the periodic signals from an oscillator.⁵ Examples include binary ripple counters and decade counters.

Positioning Techniques

Similar to timing techniques, positioning techniques can be divided into dead reckoning and position-fixing. Dead reckoning employs inertial navigation to estimate position, based on a previously known or estimated position.⁶ Inertial navigation relies on inertial measurement units (IMUs), such as accelerometers and gyroscopes, to track acceleration and rotation respectively. This is done by monitoring a moving mass, such as a ball suspended from a spring, and integrating the measured accelerations and rotations at each measurement point to estimate position.⁷ Each subsequent estimation tends to accumulate measurement errors over time. Here, too, dead reckoning is reasonably accurate over short distances, but tends to accumulate errors over longer ranges due to sensor drift. Examples of mature IMUs include ring laser and fibre-optic gyroscopes.

a The degree to which measurements remain true to their actual value.

b Instruments that produce a stable and periodic signal, such as pendulums, pulsars, or piezoelectric crystals.

Position-fixing estimates position relative to one or multiple landmarks sharing a common reference frame (like GNSS satellites), terrestrial features, or features from a map. It can be broadly divided into radionavigation and map/feature-matching.⁸

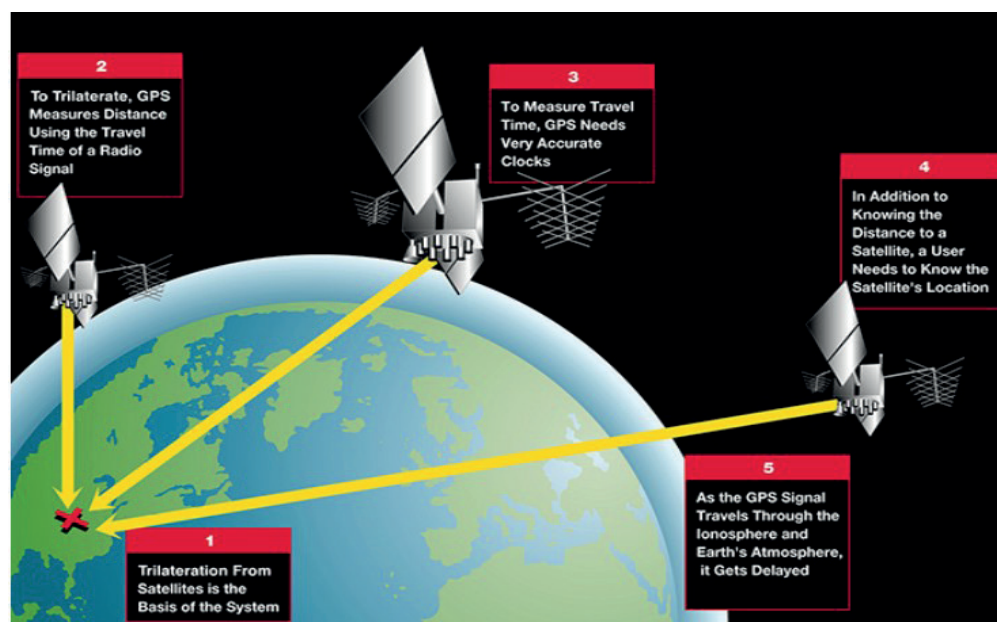
In radionavigation, radio signals from one or a network of transmitters are used to estimate the receiver's position. Depending on the transmitter, radionavigation can take on several forms:

- A. Satellite Navigation or GNSS:** GNSS such as GPS and the Russian Global Navigation Satellite System (GLONASS) consist of a constellation of Medium-Earth Orbit (MEO) satellites that transmit radio signals in the L-band frequency range (1–2 gigahertz) to the receiver, which uses the position data of the satellites contained therein to estimate its position (see figure in the box).⁹
- B. Terrestrial Radionavigation Systems:** These consist of ground-based transmitters such as Loran (Long-Range Navigation) and pseudolites,^c which provide regional coverage as opposed to global coverage provided by GNSS.¹⁰
- C. Signals of Opportunity:** These signals, such as LTE signals and broadband communication signals from Low-Earth Orbit (LEO) satellites like Starlink, are not typically meant for navigation.¹¹ But receivers can estimate their position using the Doppler Effect, or the change in the frequency of the signal caused by relative motion between the receiver and source.

c A ground-based RF transmitter which is typically used as an alternative to GPS in GPS-denied environments.

How Does GPS Work?

GNSS like GPS require a global constellation of satellites, which transmit radio frequency (RF) signals from MEOs. Some of the GNSS systems are GPS (US), GLONASS (Russia), Beidou (China), Galileo (Europe), QZSS (Japan), and NavIC (India). GPS, in particular, currently consists of a constellation of 31 operational satellites, though it requires a minimum of 24 to function effectively, and signals from four satellites to triangulate the receiver's position. GPS satellites carry extremely accurate atomic clocks that are used to broadcast a Pseudorandom Noise (PRN) code containing precise timing to the receiver. The time difference between the signal reception and broadcast can give the accurate receiver position after accounting for propagation delays caused by the earth's ionosphere.



Source: US Federal Aviation Administration.¹²

In map- or feature-matching, the user's environmental observations are matched with an existing map or database containing known man-made (such as streets and buildings) or geophysical (such as terrain, gravitational anomalies, or magnetic fields) features. A summary of map-/feature-matching techniques is given in Table 1.

Table 1: Map-Matching Techniques

Map-Matching Technique	Description
MAGNAV	Measurements of the earth's magnetic field are matched with existing maps of the field configuration to estimate position.
GRAVNAV	Measurements of the earth's gravitational field are matched with existing maps of the field configuration to estimate position.
Image-Based Navigation	Images taken using aerial platform cameras or synthetic aperture radars are matched with existing maps to estimate position.
Terrain-Referenced Navigation	Height measurements using altimeters, cameras, radars, lidars, and sonars are matched with existing databases on terrain elevation to estimate position.
Celestial Navigation	Images of celestial objects, like stars, are matched with an existing catalogue to estimate position.

Source: Author's own, based on *Classical vs Quantum Complementarity PNT*.¹³

In general, estimating position or time for most applications involves using dead reckoning in conjunction with position-fixing and time-synching techniques to rectify the error caused by drift. Some techniques such as Simultaneous Localisation and Mapping (SLAM) inherently involve using multiple methods like dead reckoning and map-/feature-mapping.¹⁴ The respective accuracies for different techniques are given in Table 2.

Table 2: Accuracies and Limitations of Positioning Techniques

Method Type	Accuracy (Metres)	Limitations	Best-Use Cases
GNSS	0.01 to 5	Signals are susceptible to jamming and spoofing. They cannot penetrate underground, underwater, or places with substantial obstacles.	Highest in terms of performance, provided signals are available.
Inertial Navigation	Time Dependent	Suffers from sensor drift. The best classical IMUs can last about one day before accumulating errors over 2 kilometres (km).	Any vehicle, either for short-term intervals or in conjunction with another PNT system to limit drift.
MAGNAV	100 to 1,000	Accuracy is dependent on velocity, altitude, platform corrections, and the magnetic anomaly map quality/resolution. Navigation will deteriorate in a space with minimal anomaly features.	Aircraft, guided munitions, drones (altitudes > 300 metres [m]). Possible applications: Ships, underwater vehicles.
GRAVNAV	2,000 to 10,000	Limited by gravitational anomaly map quality/resolution. Performance will also deteriorate in places with minimal gravitational anomaly features.	Ships, underwater vehicles. Possible applications: Land vehicles if no other landmarks/signals are available.
Celestial Navigation	25 to 2,000	Requires a clear view of the sky; accuracy improves in the absence of clouds or at high altitudes.	Aircraft and ships. Possible applications: Land vehicles if no other landmarks/signals are available.

Classical PNT Systems

Method Type	Accuracy (Metres)	Limitations	Best-Use Cases
Image-/Terrain-Based Navigation	1 to 30	Cannot be used over featureless terrain. Light-/laser-based methods have degraded performance in bad weather. Requires access to a terrain database to match signals.	Guided munitions, aircraft, submarines (sonar), airborne and underwater drones.
Radio Frequency Navigation	10 to 500	Requires costly and extensive infrastructure, impossible to build on enemy territory. Signals are still susceptible to jamming/spoofing and require a moderately clear path to a receiver.	Ships and underwater vehicles at shallow depths (when using very low-frequency signals).
Low-Earth Orbit Satellites	20 to 200	Will require a mega-constellation (such as a completed Starlink) to achieve global coverage. Signals are still susceptible to jamming/spoofing. May have incomplete PNT information, paywall barriers, or require decoding.	All above-water and above-ground vehicles.

Source: Author's own, based on How Quantum Sensing Will Help Solve GPS Denial in Warfare¹⁵

Limitations of Classical PNT Systems

The efficacy of classical PNT systems can be curtailed by a variety of factors:

Warfare

Given their pivotal importance for military operations, attacking PNT systems like GPS has become a focal point in modern warfare. These attacks are conducted using counterspace weapons which can be broadly classified into four categories:¹⁶

- A. Kinetic Weapons:** These include direct ascent as well as orbital anti-satellite (ASAT) weapons. Additionally, traditional kinetic weapons like bombs and missiles can also be used to damage terrestrial PNT infrastructure.
- B. Non-Kinetic Weapons:** These employ radiated energy to destroy or damage space-based systems like GNSS. They include nuclear detonation and directed energy weapons like lasers.
- C. Electronic Warfare:** In general, electronic warfare (EW) refers to the use of the electromagnetic spectrum to conduct an attack. When it comes to GNSS, EW is confined to jamming and spoofing, as the low-power nature of GNSS signals makes them susceptible to interference and prime candidates for navigation warfare.¹⁷ Jamming uses an RF transmitter/jammer to overpower GNSS signals on a particular frequency band, preventing nearby receivers from distinguishing true signals from the noise. In spoofing, the adversary creates fake signals bearing the appearance of GNSS signals but containing misleading data.
- D. Cyberattacks:** The reliance of GNSS systems on software and the internet also renders them susceptible to cyberattacks. For instance, in 2016, an unintentional software-based disruption created a data upload problem, leading to a timing error across the GPS system.¹⁸

Adversarial attacks on PNT systems can have severe ramifications for a nation's military. For instance, in the Russia–Ukraine conflict, Russian EW systems designed to jam GPS signals have had a marked impact on the effectiveness of typically reliable US-made satellite-guided weapons used by Ukraine, such as Excalibur shells, JDAM-ER missiles, and HIMARS launchers, reducing their hit rate from over 50 percent to less than 10 percent.^{19,20} EW has also been employed by Israel in its conflict with Hamas and Hezbollah, and led to at least one civilian aircraft nearly entering enemy airspace as it was following a spoofed signal.²¹ GPS jamming has been employed during the Iran War, too, increasing the risk of collision in vessels travelling along the Strait of Hormuz due to widespread Automatic Identification System (AIS) malfunction.²²

Furthermore, due to increasing commercial availability of jamming and spoofing technologies, EW is also being employed by non-state groups and terrorists in countries such as Ukraine, Syria, Afghanistan, South Korea, and India.²³

GPS-Denied Environments

Location is a critical factor in determining GPS signal reception. GPS signals become significantly weaker and inaccurate in remote areas or areas under dense foliage.²⁴ They cannot penetrate underground or underwater. Hence, alternative techniques are required for navigation in these areas.

Natural Events

Natural events such as solar flares and Coronal Mass Ejections (CMEs)^d can significantly degrade GNSS performance.²⁵ Terrestrial events like hurricanes can also damage or nullify alternative PNT systems like the Loran.

Other Factors

Other inadvertent factors like negligence, space debris, and GNSS technical failure can also severely handicap PNT capabilities.²⁶

In the absence of PNT systems, precision-guided munitions are essentially reduced to regular artillery shells. Tasks requiring precision timing and navigation, such as encrypted communication and preventing friendly fire, would be affected. Therefore, every nation's military relies on a combination of PNT techniques, depending on the situation, with each technique involving a trade-off between accuracy and availability, leading to the concept of PNT resilience. However, no classical PNT system is completely free of vulnerabilities and any of them can, in principle, be disrupted. On the other hand, quantum PNT systems are not susceptible to these disruptions, since they are passive and do not rely on external signals.²⁷

^d A Coronal Mass Ejection is a massive cloud of plasma ejected by the sun, which can accelerate charged particles creating a heightened risk of radiation storms.

Quantum Technology and Quantum Sensing

The formulation of quantum physics at the beginning of the twentieth century laid the foundation for most of the technologies that are now considered indispensable. These include semiconductors, lasers, nuclear energy, and nuclear magnetic resonance (NMR). In modern parlance, though, quantum technology refers to any technology with the ability to control and manipulate individual quantum particles such as electrons, photons, neutrons, and atoms. This has become increasingly feasible thanks to rapid technological advancements in recent decades, referred to as the “second quantum revolution.”²⁸

Quantum technology comprises three primary avenues: quantum computing, quantum communication, and quantum sensing. Quantum sensing, in particular, refers to any quantum technology that measures physical variables, such as electric and magnetic fields, acceleration, rotation, and gravitational fields. While traditional or classical sensor systems are also capable of measuring these variables, quantum sensors have an unparalleled level of accuracy thanks to the properties of individual quantum systems, such as energy quantisation and quantum entanglement.

While all three avenues present a plethora of potential military applications, quantum sensing ranks the highest in terms of Technology Readiness Levels (TRL) and is the first category of quantum technology to achieve practical utility.²⁹ It is the most viable avenue to pursue and is poised to pay maximum dividends in the near future.

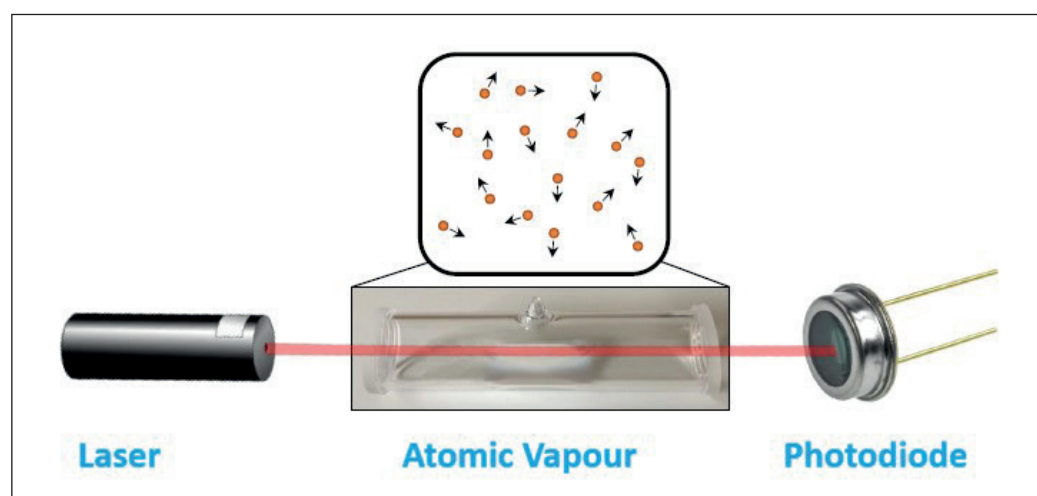
There are many potential avenues for the future development of quantum sensing such as PNT systems, RF receivers, and quantum imaging.³⁰ This paper will focus on its applications for PNT systems.

Types of Quantum Sensors

Quantum sensors use individual quantum particles to measure changes in physical variables, such as gravitational and electromagnetic fields.³¹ One of the main properties that makes this possible is energy quantisation—any particle (such as an electron) occupying a quantum system (an atom) exists in discrete, well-defined energy levels, which enables extremely precise measurement of the particle’s energy. As opposed to classical sensors, the particles used in quantum sensors remain identical regardless of the type of sensor, thereby enhancing reliability and alleviating the need for repeated calibration.³²

A quantum sensor typically consists of three fundamental components: a core quantum system comprising highly controlled particles, such as an atomic vapour in a specialised container; electronic components like lasers and photodiodes, which are needed to manipulate the particles and collect information; and specialised software needed to convert the collected data into useful information and for error correction.³³ A representation of a typical quantum sensor is given in Figure 2.

Figure 2: Representation of a Quantum Sensor



Source: *Perspective: Practical Atom-Based Quantum Sensors*³⁴

There are three basic categories of quantum sensors:

A. Atomic Sensors

Atomic sensors exploit the inherent stability, reproducibility, and sensitivity^e of atomic spectroscopy to make measurements of physical quantities, such as time, inertial inputs, and gravitational and electromagnetic fields.³⁵ They typically employ electromagnetic pulses (which can range from RF to microwave to optical frequencies) to probe the quantum states of vapour-state atoms whose energies are sensitive to the quantity of interest. Based on the quantity to be measured, atomic sensors can be further divided into various types.

^e Sensitivity is the smallest change in physical quantity that the sensor is capable of detecting.

Table 3: Types of Atomic Sensors

Physical Quantity	Mechanism
Frequency (or Time)	Atomic Clocks
Magnetic Field	Magnetometer
Electric Field	Rydberg Atom
Acceleration and Rotation	Atom Interferometer
Gravitational Field	Atom Interferometer

Source: *Perspective: Practical Atom-Based Quantum Sensors*³⁶

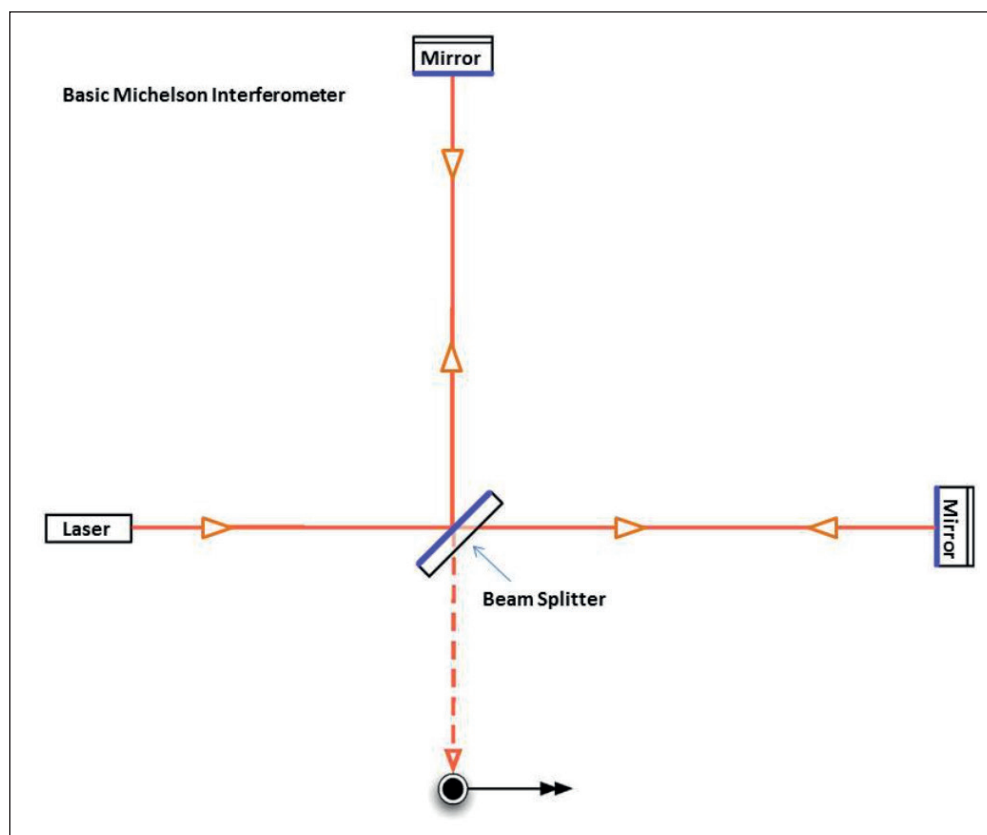
Atomic Clocks

Atomic clocks utilise direct measurement of an atomic Bohr frequency to produce a frequency reference that can be used for standardised timekeeping.³⁷ They are discussed in detail in the next section.

Atom Interferometer

An atom interferometer is based on a classical interferometer that functions by splitting a light source, such as a laser beam, into two, using a beam splitter, and thereafter recombining the two to form an interference pattern.³⁸ Analysing changes in this pattern induced by external objects or phenomena can enable precise measurements of various quantities.

Figure 3: A Classical Interferometer



Source: LIGO Caltech³⁹

Similarly, an atom interferometer uses lasers to separate an atomic cloud from a group of atoms. Depending on the system's subsequent acceleration or rotation, the behaviour (or phase) of the atomic cloud gets modified and can be measured after both parts are allowed to recombine or interfere.⁴⁰ Atomic interferometers can be based on warm or cold atoms, with the former offering enhanced bandwidth^f at the cost of lower precision^g and the latter, vice-versa.

Magnetometer

A magnetometer can detect even tiny variations in magnetic fields using atomic transitions resulting from exposing atomic vapours to an external magnetic field, which causes atomic spin precession at the Larmor frequency.^{h,41}

^f The number of measurements that can be made per unit time.

^g A sensor's ability to obtain identical results on repeated measurements.

^h The frequency at which the magnetic moment of a particle precesses when placed in an external magnetic field.

Quantum Technology and Quantum Sensing

Rydberg Atom

Rydberg atom electric field receivers utilise lasers to excite atoms to high-energy Rydberg states, which are extremely sensitive to electric fields and hence can be used to measure them. While electric field sensors do present future implications for augmenting classical PNT systems, particularly in the domain of quantum imaging, they are currently nascent.

Atomic sensors can also be categorised based on the particular platform employed, which (in increasing order of complexity) can be warm vapour, atomic beams, or trapped atoms (neutral atoms or charged ions). Technological developments have also led to new paradigms such as sensor arrays, cold atom interferometry, and miniaturised atomic vapour cells, which can have profound future implications in terms of size, weight, and power (SWaP), and stability.^{i,42}

B. Superconducting Sensors

Superconducting circuits are based on the Josephson Effect, which determines quantum tunnelling^j between two superconductors.⁴³ Typically, superconducting sensors such as the Superconducting Quantum Interference Device (SQUID) employ the use of a superconducting ring split into two regions by thin non-superconducting regions. The voltage drop across the two regions determines the incoming magnetic flux and can be used to determine the magnetic field.⁴⁴ Superconducting sensors can also be employed to detect changes in gravitational fields by levitating a test mass, using magnetic suspension provided by the Meissner Effect.^{k,45}

i The degree of sensor drift over time.

j A purely quantum mechanical phenomenon in which a particle can pass through a potential energy barrier despite having a height larger than the total energy of the particle.

k A unique property of superconductors that allows them to behave as perfect conductors and diamagnets upon reaching a critical temperature, typically near absolute zero (0K).

Quantum Technology and Quantum Sensing

C. Solid-State Defect Sensors

These sensors employ point defects such as Nitrogen Vacancy (NV) centres in diamonds or wide-band semiconductors like Silicon Carbide (SiC).⁴⁶ In a diamond lattice, NV centres function by replacing a pair of carbon atoms with a single nitrogen atom, thereby creating a vacancy. The resultant long coherence times^l and fluorescence^m properties possessed by these NV centres can be used to detect changes in physical quantities like magnetic fields. The primary advantage with NV centres is that they can be operated at room temperature, as opposed to other quantum systems like superconductors that can only operate at extremely low temperatures (close to 0 Kelvin or -273° Celsius).

^l The period over which a quantum particle retains its quantum properties before they are lost due to interactions with the environment (or noise).

^m The property by which a substance emits light of a longer wavelength after absorbing radiation of a shorter wavelength. The emission typically occurs in the form of a bright glow.

Currently, there are four main applications of quantum sensing for PNT systems:

Timing

Quantum sensing-based timing systems can be divided into two categories:

Microwave Atomic Clocks

These were developed in the 1940s and are widely used for precision timing applications.⁴⁷ For instance, GPS satellites use microwave atomic clocks to provide timing information in their signals. The most commonly used microwave atomic clocks function by exposing alkali-metal atoms like Rubidium (Rb) gas to microwave radiation.⁴⁸ The frequency at which the gas's energy absorption is maximised determines the accuracy (or 'tick') of the clock. Examples include Hydrogen Masers and Cesium (Cs) Beam Clocks, which provide high precision and accuracy, respectively, though at the cost of size and mobility;⁴⁹ and vapour-cell microwave clocks, which, though less precise, offer enhanced mobility and are employed for applications requiring portability, such as GPS satellites and telecommunications.

Figure 4: Cesium Beam Clock



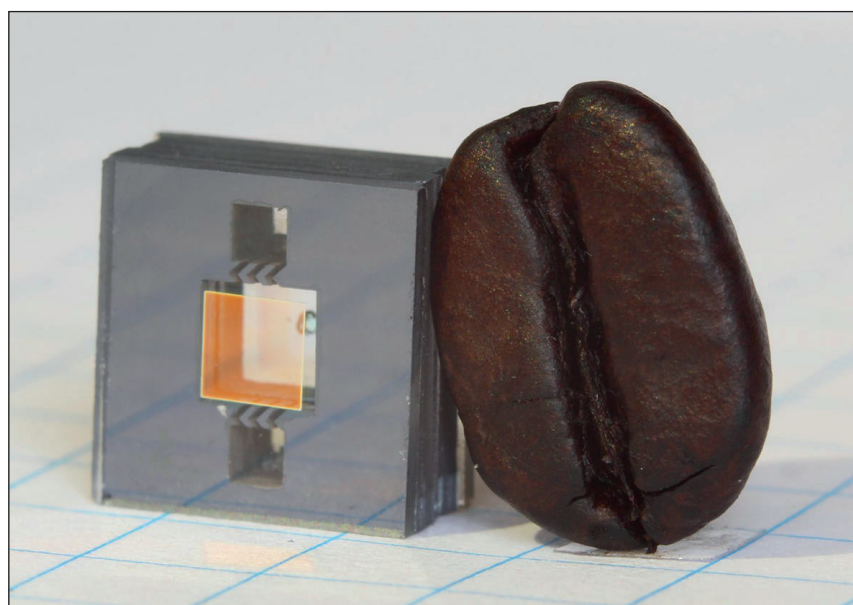
Source: Chronos Technology⁵⁰

The growing military need for portable atomic clocks in GPS-denied scenarios has led to the development of Chip-Scale Atomic Clocks (CSACs), which are essentially miniaturised microwave atomic clocks and can be as small as a coin.⁵¹ However, the portability offered by CSACs comes at the cost of clock stability, with efforts ongoing to improve this function. Vapour-cell, solid-state defect, and nuclear clocks are some of the areas currently being explored to develop enhanced CSACs.⁵²

Optical Atomic Clocks

Optical atomic clocks function by exposing an atomic gas to light instead of microwave radiation. Since light possesses a higher frequency band, the tick of the clock can be over 100 times lower (as frequency is inversely related to the time scale) and consequently, provides much more accuracy.⁵³ Optical atomic clocks are currently in the advanced research/early prototype stage. Vapour-cell-based optical atomic clocks, such as Rb Two-photon atomic clocks, are commercially available and provide performance similar to Hydrogen Masers but with a significant reduction in size.⁵⁴ There are also quantum logic clocks (based on trapped ions) and optical lattice clocks that utilise laser-cooling to trap atoms in a regular grid, thereby minimising errors caused by atomic motion and interactions.⁵⁵ Though they lie at the pinnacle of precision timing, the requirement for bulky optical components has confined them to the lab prototype stage of development.⁵⁶

Figure 5: Rubidium Two-Photon Optical Clock



Source: NIST⁵⁷

Inertial Navigation

Unlike classical IMUs that provide short-term stability, quantum IMUs can be most effective in providing long-term accuracy and stability (longer than a day) for naval vessels and submarines. This could be particularly useful during GPS outages or in GPS-denied environments.

The most viable prospect for quantum IMUs lies in cold atom interferometry, which combines atom interferometry with laser cooling techniques that significantly enhance atom interferometer performance. As opposed to classical sensors, a cold atom interferometer can, in principle, function simultaneously as an accelerometer and a gyroscope.⁵⁸

Another type of sensor that could be significant for inertial navigation is an NMR gyroscope, which uses warm vapour and is currently in the advanced prototype stage. Superconducting gyroscopes are also a viable avenue for quantum IMUs, though they are currently in the early stages of laboratory demonstrations.⁵⁹

Figure 6: NMR Gyroscope



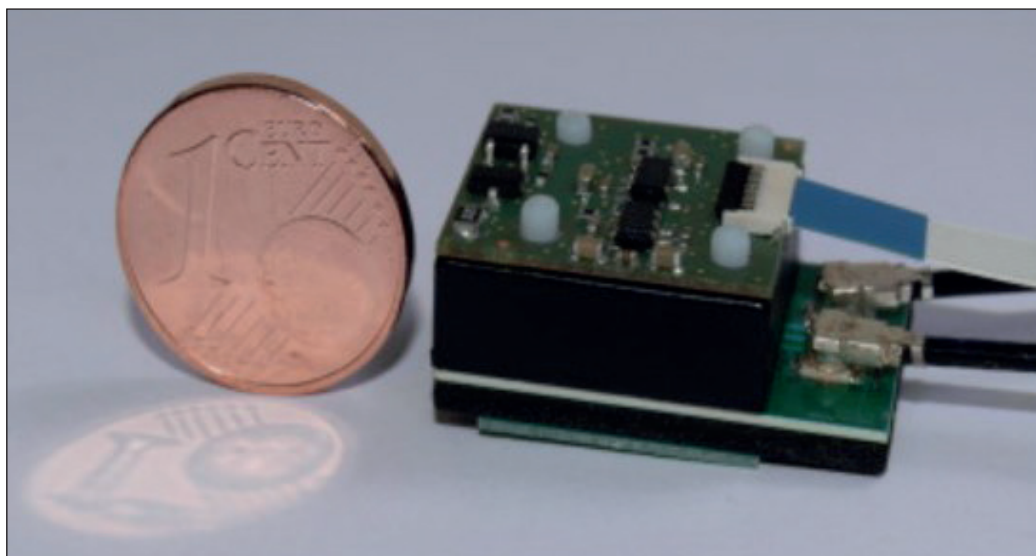
Source: Wen, "Toward Inertial-Navigation-on-Chip."⁶⁰

Magnetic Navigation (MAGNAV)

The magnetisation of different materials within the earth's crust, induced by its core, has created distinct magnetic features based on geographical location. These features remain relatively static over several human lifetimes. Since magnetic field strength diminishes rapidly with distance from the source, magnetic signatures within the earth's crust cannot be significantly altered by any adversarial attempts.⁶¹ Consequently, multiple nations are in the process of developing 'magnetic anomaly' maps to provide an additional navigational input. These are particularly useful for aerial (within a certain altitude range) and naval navigation.

Scalar magnetometers (measuring only magnetic field strength), such as Ce or Rb vapour-cell magnetometers, have been commercially available for decades.⁶² However, for precise positioning capabilities, vector magnetometers are required as they can also measure the direction of the magnetic field. The NV centre-based magnetometer has emerged as a leading candidate in this domain, though more sophisticated vapour-cell and cold-atom interferometry-based magnetometers are also being pursued.⁶³

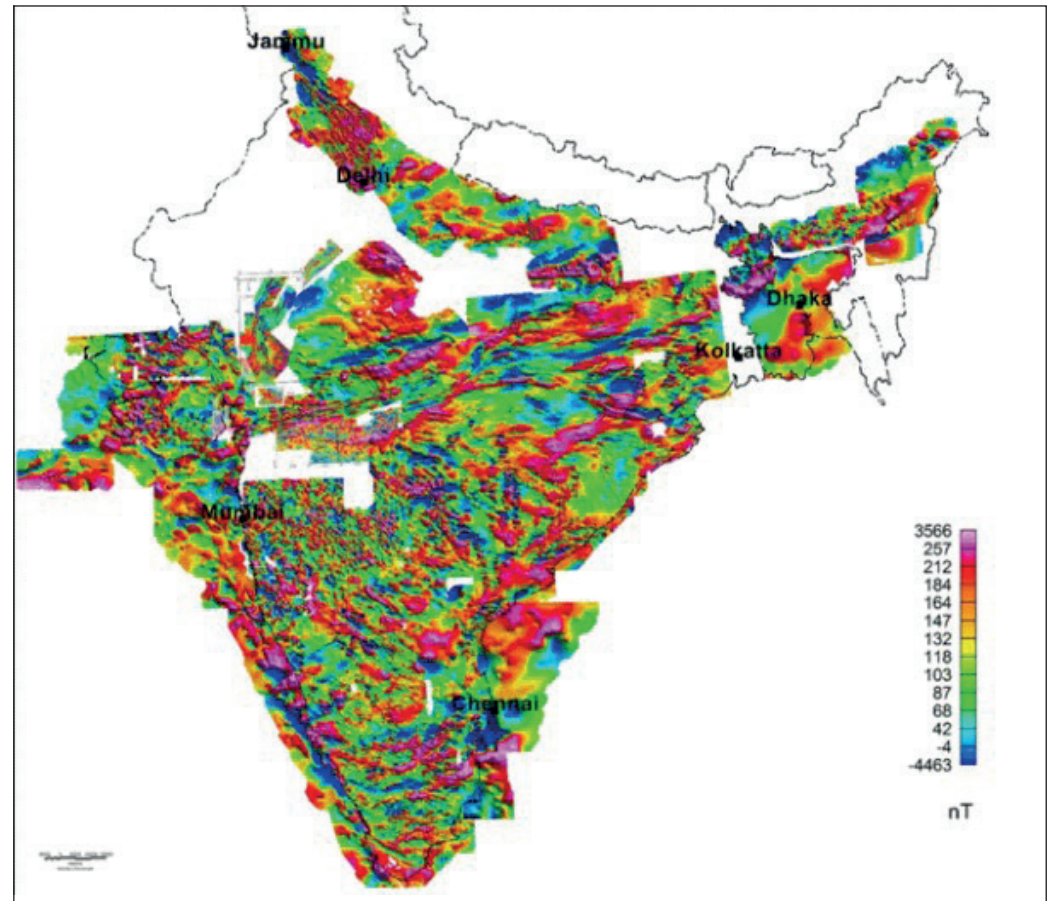
Figure 7: NV Centre Magnetometer



Source: Sturmer et al.⁶⁴

While superconducting magnetometers such as SQUIDs are amongst the most accurate and widely available magnetic-sensing platforms, their requirement for cryogenics severely limits SWaP and ruggedisation, making them less viable candidates for military applications.⁶⁵

Figure 8: A Magnetic Anomaly Map



Source: Indian Institute of Geomagnetism⁶⁶

Gravitational Navigation (GRAVNAV)

GRAVNAV is a map-matching technique which utilises ‘gravitational anomaly’ maps to track the variation of the earth’s gravitational field instead of its magnetic field. However, as compared to MAGNAV, gravitational field variations are weaker and occur over longer distances, requiring greater measurement time and distance to be covered in order to give a precise location reading. The best application for GRAVNAV is in the underwater domain, for vehicles such as submarines that cannot rely on external signals such as GPS, which could potentially give away the vehicle’s position to the adversary.⁶⁷

Atom interferometer gravimeters are the most promising quantum sensors for GRAVNAV and are being pursued around the world.⁶⁸ Superconducting gravimeters, though commercially available, are handicapped by SWaP limitations. However, they are more viable for large underwater vessels like submarines that have relatively less stringent SWaP requirements.

Figure 9: Vector Atomic Gravimeter



Source: Vector Atomic⁶⁹

Classical versus Quantum PNT Systems

Quantum sensors provide a range of benefits over classical PNT systems. They rely on atoms or elementary particles whose properties are identical across all sensors and that have a well-defined relationship to fundamental constants. In most cases, atomic interactions are well-characterised and can be understood from first principles. As such, quantum sensors offer long-term stability and predictability while being essentially exempt from the need for regular recalibration or auxiliary signal augmentation. Some quantum sensors, such as cold atom interferometers, can potentially be utilised for simultaneous measurement of multiple inputs while eliminating systematic shifts, which is not possible in case of classical sensors.⁷⁰ However, quantum sensors also have some inadequacies.

Comparing the performance of classical and quantum PNT systems requires a demarcation of PNT sensor grades. For military PNT systems, the last three columns are the most relevant.

Table 4: PNT Sensor Grades

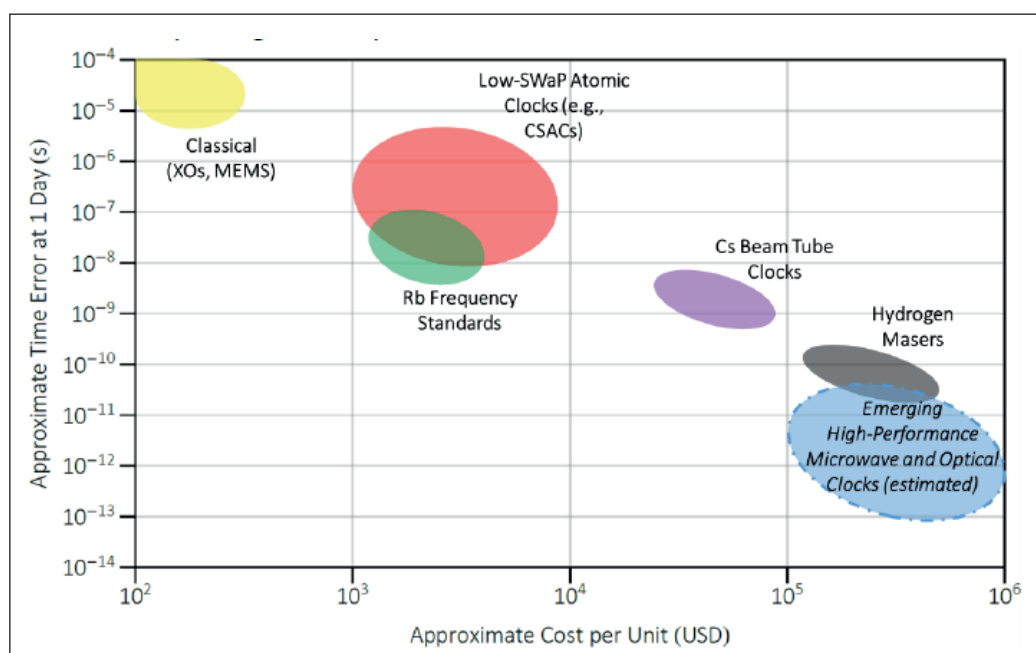
Consumer Grade	Industrial Grade	Tactical Grade	Navigation/Aviation Grade	Strategic/Marine Grade
Used for automobiles and consumer electronics.	Used for industrial applications like small unmanned aerial vehicles (UAVs) and robotics.	Used for larger UAVs and guided weapons. Can be used without PNT-aiding sources for up to 10 minutes. Cost less than US\$ 50,000.	Used for commercial and military aircraft. Can function without PNT aiding sources for less than 2 hours. Costs over US\$100,000.	Used on submarines, ships, long-range missiles, and spacecraft. Can function without PNT-aiding sources for up to a few days. Costs over US\$1,000,000.

Source: Lawrence Livermore National Laboratory⁷¹

Classical versus Quantum PNT Systems

Figure 10 represents error versus cost for a one-day free-running operation of different atomic clocks.

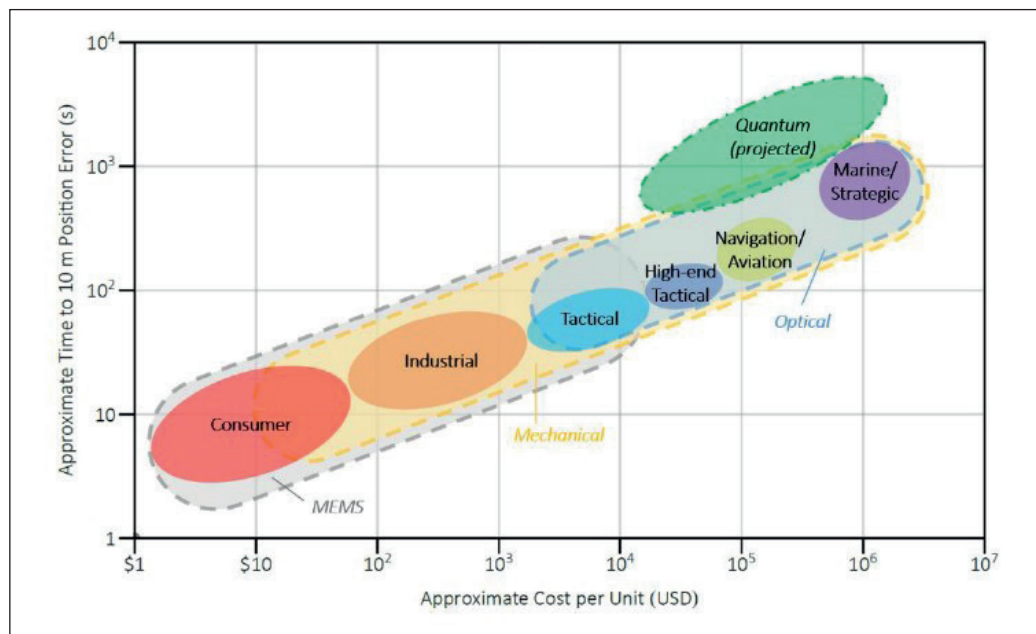
Figure 10: Error vs Cost for Different Varieties of Atomic Clocks



Source: "Quantum vs. Classical Complementarity PNT"⁷²

As is evident, enhanced sensitivity comes at a greater cost as well as increased SWaP. While classical oscillators offer lower accuracy compared to quantum sensors, they cost less. With the further development of MEMS, this situation is poised to change. However, the advancements in CSACs could potentially pose stiff competition for MEMS advancements. On the other hand, though emerging microwave and optical atomic clocks are costlier, they offer enhanced sensitivity and may become more practically feasible over time.

Figure 11: Error vs Cost for Different Varieties of Inertial Sensors



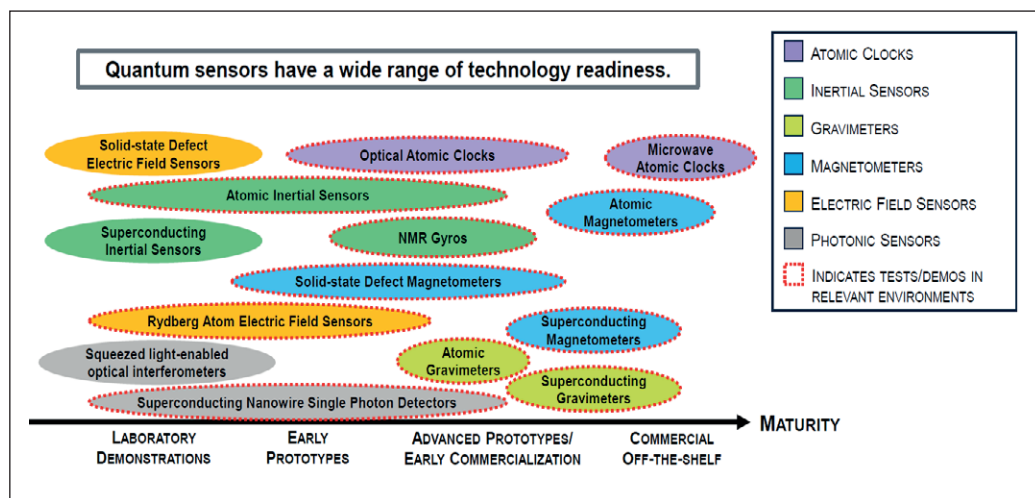
Source: “Quantum vs. Classical Complementarity PNT”⁷³

For inertial sensing, the figure above represents position error as a function of cost. Again, though quantum IMUs offer better long-term stability, they come at a greater cost and SWaP. Currently, GNSS is the most accurate, followed closely by RF and optical techniques like radars and lidars. MAGNAV and GRAVNAV provide the most viable avenues for quantum inertial sensing in the near future, particularly for navigation and strategic-grade systems, since they provide certain advantages, as discussed in an earlier section. Additionally, they provide all-weather operation even in visually sparse terrain as opposed to map-matching techniques, which require an unobstructed view of the ground.

The primary utility of quantum IMUs currently lies in providing long-term stability for strategic-grade systems. They are ideal for functioning in conjunction with classical sensors, with the latter providing short-term stability. As the technology continues to evolve, decreasing SWaP and cost requirements may make them more feasible for lower-grade systems.

One of the primary factors in determining applicability of quantum sensors is TRL or technological maturity. Quantum sensors are in varying stages of development, as given in Figure 12.

Figure 12: TRL for Different Quantum Sensors



Source: MITRE⁷⁴

Though MAGNAV and GRAVNAV have the most potential for military employment, they come with caveats. One of the primary hurdles is the lack of availability of high-quality gravity and magnetic anomaly maps.⁷⁵ It will require significant time and effort, and perhaps international collaboration, to develop these maps. Gravimeter and magnetometer performance is also severely degraded in so-called ‘dead zones,’ or areas where field gradients are small.⁷⁶ Another issue arises from platform effects, which can distort sensitivity.⁷⁷

In conclusion, though quantum sensors hold significant potential for navigation and strategic-grade PNT systems, they require improvements in terms of ruggedisation, SWaP, and cost requirements for large-scale military applicability. Consequently, complementary employment with classical sensors holds the maximum potential at present.

Global Initiatives in Quantum PNT Systems

Quantum PNT systems are being widely pursued by multiple nations. Some of the main initiatives are discussed below.

The United States

The US National Quantum Initiative (NQI) Act is the national strategy being pursued by the US and serves as the guiding principle for quantum technology development within the country.⁷⁸ It directed the US Department of Energy (DoE) to set up research initiatives and institutions in various quantum technology fields, including quantum sensing. Under the oversight of the National Quantum Coordination Office, it also oversaw the creation of a Subcommittee on Quantum Information Science (QIS) and the Subcommittee on the Economic and Security Implications of Quantum Science (ESIX) through the US National Science and Technology Council (NSTC), as well as the establishment of a National Quantum Initiative Advisory Committee (NQIAC).⁷⁹ While the QIS and the ESIX subcommittees are intended to gather government agencies, the NQIAC is meant to bring together representatives from industry and academia. The QIS subcommittee has been the main driver of US governance on quantum technology (QT) and comprises representatives from national security and intelligence agencies, as well as research heads from civil coordination bodies and government departments.⁸⁰ In 2022, the subcommittee published a report titled, “Bringing Quantum Sensors to Fruition,” which addressed challenges associated with commercialisation of quantum sensors.⁸¹

The US Department of Defence (DoD) has been actively involved in developing quantum PNT systems. After authorisation by the FY2020 National Defense Authorization Act, the US Air Force, Army, and Navy each house a Quantum Information Science (QIS) Research Centre, in addition to in-house research laboratories. Notable achievements in quantum PNT systems have been made by the Air Force Research Laboratory (AFRL) Quantum Sensing and Timing group, the Naval Research Laboratory’s QIS Research Centre, and the Army Research Laboratory’s QIS-PNT research programme.⁸²

Additionally, the US DoD has also been pursuing ‘multi-PNT receivers’ through a Modular Open Systems Approach (MOSA) that will offer flexibility by integrating inputs and data from both classical and quantum PNT sensors without requiring a complete system overhaul.⁸³ In order to do so, it is leveraging open-source data standards and sensor-fusion software frameworks.⁸⁴

Global Initiatives in Quantum PNT Systems

The Defense Advanced Projects Agency (DARPA) is pursuing over 24 initiatives pertaining to QT.⁸⁵ It has successfully developed second-generation CSACs via its recently concluded Atomic Clocks with Enhanced Stability (ACES) programme.⁸⁶ It also announced a new H6 initiative in 2022, which aims to create third-generation CSACs.⁸⁷

Recently, the Defense Innovation Unit (DIU) has started building quantum-sensing and alternate PNT systems with its Transition of Quantum Sensing (TQS) programme launched in May 2024 with “a focus on the strategic missions where quantum sensing is ideally suited.”⁸⁸ It has intentionally chosen a mixture of start-ups, non-traditional DoD solution providers, and traditional defence contractors to pursue quantum PNT platforms. For instance, in March 2025, Lockheed Martin, AOSense, and Australian start-up Q-CTRL procured a DIU contract to jointly develop quantum inertial navigation systems. The DIU also partnered with start-up Vector Atomic and Honeywell aerospace to test a quantum IMU aboard the US Space Force’s X-37B Orbital Test Vehicle-8 (OTV-8) launched in August 2025.⁸⁹

Start-ups such as Vector Atomic, AOSense, and SandboxAQ are playing a pivotal role in developing quantum PNT systems in the US.⁹⁰ For instance, Boeing has independently collaborated with AOSense in 2024 to successfully test a six-axis atom interferometry-based quantum IMU, enabling an in-flight aeroplane to navigate without GPS for four hours.⁹¹ The test also included AQNav, a full-stack quantum magnetometer-based navigation system developed by SandboxAQ. Vector Atomic tested a quantum gravimeter aboard a ship undergoing a multi-week voyage during the Rim of the Pacific Exercise (RIMPAC) 2022, with the device’s accuracy matching that of available maps.⁹²

Civilian research and development (R&D) institutions such as the National Aeronautics and Space Administration (NASA) and MITRE are also contributing through initiatives such as NASA’s S&T Partnership Forum and MITRE’s research on Rydberg Atom RF Sensors.^{93,94}

China

Quantum sensing has received relatively less priority within the Chinese QT R&D ecosystem as compared to the other two primary branches. Currently, China does not have a publicly available national plan for it. Instead, its QT strategy comes in the form of “important instructions” by President Xi Jinping in October 2020, which provided “strategic guidance” for QT development. Other policy avenues such as the S&T Major Projects vehicle have served as valuable supplements, emphasising industry/R&D linkages over standard funding programmes.⁹⁵ The funding for the majority of QT research

Global Initiatives in Quantum PNT Systems

is provided by the National Natural Science Foundation of China (NSFC), with the Ministry of Science and Technology (MOST) and the Ministry of Industry coordinating civilian R&D strategy and the Ministry of Information Technology (MIIT) integrating QT into industrial policy.⁹⁶

The University of Science and Technology of China (USTC) has taken the lead in developing QT, largely thanks to individual scientists like Pan Jianwei, rather than an overarching national plan. USTC enjoys a close relationship with the Chinese Academy of Sciences (CAS), largely due to Pan's influence, which also led to the establishment of the Center for Excellence in Quantum Information and Quantum Physics under his leadership in 2014.⁹⁷ An independent company, Quantum CTeK, was also established by Pan and other individual researchers to support the development of military QT.

A speech by President Xi in 2018 prompted the China Academy of Information and Communication Technology (CAICT) to publish a series of reports on QT, shedding some light on China's plans. Its first publication noted that "technology companies entered late and had limited participation," further stating that the country possessed only one quantum sensing start-up at the time, while urging China to follow America's multiparty collaboration development model. Subsequently, China's State Department metrology development plan for 2021–35 prioritised quantum sensing as one of Beijing's core ambitions in achieving PNT dominance.⁹⁸

China's National Institute of Metrology (NIM) and the China Aerospace Science and Technology Corporation (CASC) also have pivotal roles in developing quantum-sensing platforms.⁹⁹ China's primary avenue for development of quantum PNT systems is reportedly in the realm of quantum radars. Moreover, in 2025, the NSFC launched the High-Precision Quantum Control and Detection programme, which is funding up to 35 projects in quantum metrology from 2026 to 2028.¹⁰⁰

Other Nations

Nations such as the United Kingdom (UK), France, and Australia are also actively pursuing quantum-sensing technologies. In 2023, the UK Quantum Technology Hub in Sensors and Timing at the University of Birmingham successfully tested a cold atom interferometry-based gravimeter aboard the RV Princess Royal.¹⁰¹ The project was developed by the university under contract from the UK Ministry of Defence's Gravity Pioneer project. In December 2025, Imperial College announced that it had completed a successful trial of a cold atom interferometer-based inertial sensor in the Arctic, in collaboration with the Royal Navy.¹⁰² It has previously tested the sensor aboard the XV Patrick

Global Initiatives in Quantum PNT Systems

Blackett in 2023 as well as on the London Underground in 2024. The project is backed by the UK Research and Innovation's Technology Missions Fund and the UK National Quantum Technologies Programme.¹⁰³

In France, companies like iXblue and Exail are actively developing quantum sensing and PNT systems.¹⁰⁴ In Australia, Q-CTRL has emerged as a global leader in quantum PNT systems. It developed the magnetometer-based Ironstone Opal quantum navigation system, which was successfully tested in April 2025.¹⁰⁵ The system was flown 500 km without GPS while maintaining a position accuracy within 150 m, a 50-fold improvement over traditional strategic-grade inertial navigation systems. The company claims that the system can now offer over a 100-fold improvement over classical sensors.¹⁰⁶

QTs such as quantum PNT systems constitute one of the tenets of the AUKUS Pillar 2.^{n,107} For instance, in 2025, four quantum clocks provided by Australia's QuantX Labs and the University of Adelaide completed successful trials in the US.¹⁰⁸

ⁿ AUKUS is a trilateral security partnership signed between the US, the UK, and Australia in 2021. The agreement consists of two pillars; Pillar One deals with the delivery of nuclear-powered attack submarines to Australia while Pillar Two entails cooperation on advanced technologies such as AI, QT, hypersonic, and EW capabilities.

India has established itself as a dominant player in developing domestic PNT capabilities. It is one of five nations to deploy a sovereign GNSS constellation: the Navigation with Indian Constellation (NavIC), earlier known as the Indian Regional Navigation Satellite System (IRNSS).¹⁰⁹ The need for developing a domestic GNSS constellation came about in the wake of the Kargil War in 1999 when India's request for access to GPS data for enemy locations was denied.¹¹⁰

Approved in 2006 and developed by the Indian Space Research Organisation (ISRO), the NavIC consists of a constellation of 11 satellites in addition to a network of ground stations. It utilises a combination of geostationary and geosynchronous satellites to provide precise PNT capabilities: Standard Position Service (SPS) for civilian use and Restrictive Service (RS) for strategic and military use. Its satellite coverage includes India as well up to 1,500 km beyond the country's borders. NavIC provides a position accuracy of 20 m and a timing accuracy of 50 nanoseconds, with SPS signals being interoperable with other GNSS signals. Additionally, ISRO and the Airport Authority of India have also developed the GPS Aided Geo Augmentation Navigation (GAGAN) satellite-based augmentation system (SBAS), though this is meant for civil aviation rather than military use.¹¹¹

Recently, the private sector has also entered the domain with Chennai-based start-up VyomIC announcing its plan to build India's first private LEO navigation constellation, consisting of a fleet of 125 to 150 LEO satellites employing the use of CSACs to provide commercial PNT capabilities.¹¹²

In terms of radionavigation, India currently operates six eLoran (LORAN-C) stations, three covering the west coast, and three for the east coast.¹¹³ Though India had announced its intention to expand its Loran network by building an additional 11 stations, there are no updates on this at the time of writing.¹¹⁴

While the Indian military currently operates 11 satellites such as the Cartosat, RISAT, and GSAT-7 series, these are mostly employed for surveillance and communication purposes rather than providing PNT capabilities.¹¹⁵ Indian defence establishments have developed domestic inertial navigation systems, primarily based on ring laser gyro (RLG), hemispherical resonator gyro (HSRG), fiber-optic gyro (FOG), and MEMS technologies, with the Defence Research and Development Organisation (DRDO) and Bharat Electronics Limited (BEL) spearheading most of the initiatives in this domain.¹¹⁶ Research Centre Imarat (RCI), a premier laboratory under the DRDO based in Hyderabad, has also developed indigenous inertial-sensing technologies.¹¹⁷ BEL has developed RLG-based systems such as the Advanced Land Navigation System (ALNS) and the Inertial Navigation System—Ship Applications (INS-SA).^{118,119}

India has made significant efforts towards building domestic PNT resilience, but this comes with several caveats and pitfalls. Despite taking a big step towards indigenising GNSS, the NavIC has suffered setbacks, with only four of its 11 satellites currently in operation: IRNSS-1B, IRNSS-1F, IRNSS-1I, and the new generation NVS-01. Even within this short list of fully functional satellites, the IRNSS-1B has already exceeded its planned 10-year mission life and is at risk of imminent failure, while the IRNSS-1F is also reaching the end of its lifecycle.¹²⁰ The NVS-02 (the successor to NVS-01) launched in January 2025, failed to reach its intended orbit due to a propulsion system malfunction. Though the Government of India has committed to launching three NVS satellites (NVS-03, NVS-04, and NVS-05) by the end of 2026, the less-than-stellar track record of the NavIC system has cast doubt on the initiative.¹²¹

In terms of alternative PNT systems, India is far behind its global peers. For instance, its eLoran system is limited and critically underdeveloped. Furthermore, while it has developed inertial navigation systems in some domains, it lags behind global leaders in terms of advanced systems like CSACs. India also lacks a comprehensive military PNT strategy/roadmap. Though the government had released an Indian Satellite Navigation Policy in 2021 (SATNAV Policy-2021), it was developed by the Department of Space and had no military involvement.¹²²

It is important for the military to pursue both traditional and alternative PNT systems, and this is borne out by multiple recent examples. India's recent conflict with Pakistan highlighted its necessity, with both sides employing EW to jam communication and navigation abilities.¹²³ India's deployment of the SCALP-EG and Brahmos cruise missiles, as well as AASM HAMMER guided bombs, were highly dependent on precise PNT capabilities provided by GPS and NavIC.¹²⁴ A major factor in Pakistan's favour was the assistance provided by China's Beidou satellite constellation, which reportedly led to the downing of at least one Indian aircraft.¹²⁵

The rising instances of GPS-jamming and spoofing along India's border is another incentive for developing alternative PNT systems. There have been multiple instances of jamming and spoofing along the India-Pakistan, India-Bangladesh, and India-Myanmar borders, as well as in the Jammu and Kashmir region.¹²⁶ The increasing commercial availability of jamming and spoofing devices has made them much more accessible to non-state actors and this has already become a source of consternation for the Indian military. Consequently, quantum PNT systems would serve as one of the most viable alternatives for India.

India's Initiatives in Quantum Sensing and PNT Systems

India is actively building a foundation for QT through its ambitious National Quantum Mission (NQM), established in 2023 with an initial corpus of INR 6,003 crore.¹²⁷ The NQM lays out four basic pillars for QT development: quantum computing, quantum communication, quantum sensing and metrology, and quantum materials and devices. Four Thematic Hubs (T-Hubs) were also created at premier academic institutions across the country to serve as focal points for each pillar.

Table 5 : T-Hubs under NQM

T-Hub	Quantum Technology Domain
Foundation For QC Innovation, IISc Bengaluru	Quantum Computing
IITM CDOT Samgnya Technologies Foundation, IIT Madras	Quantum Communication
Qmet Tech Foundation, IIT Bombay	Quantum Sensing and Metrology
QMD Foundation, IIT Delhi	Quantum Materials and Devices

Source: Ministry of Science and Technology, Government of India¹²⁸

In the realm of quantum sensing, the NQM has prioritised the development of high-sensitivity quantum magnetometers, gravimeters, and atomic clocks for precision timing, communication, and navigation.

India's progress in quantum sensing can be divided across three major sectors: academia, industry (largely start-ups), and the military.

Academia

As the designated T-Hub for quantum sensing and metrology, IIT Bombay plays a leading role in developing quantum-sensing systems within India. In 2025, its Photonics and Quantum Enabled Sensing Technology (PQuest) Lab announced the development of an indigenous Quantum Diamond Microscope based on NV centres in a diamond lattice, as well as QMagPI, India's first portable quantum magnetometer.¹²⁹ The Raman Research Institute (RRI) is developing novel magnetometers through methods such as Raman-Driven

India's Initiatives in Quantum Sensing and PNT Systems

Spin Noise Spectroscopy and Rydberg Atoms.¹³⁰ The Indian Institute of Science Education and Research (IISER), Bhopal, is working on NV centre-based magnetometers. The I-Hub Quantum Technology Foundation at IISER Pune is pursuing multiple avenues in quantum sensing, including NV diamond centres as well as atom interferometry-based gravimeters.¹³¹ The Inter-University Centre for Astronomy & Astrophysics (IUCAA), Pune, is focusing on trapped ion optical atomic clocks.¹³²

Start-ups

Start-ups also have a big role in developing quantum-sensing platforms in India. QuBeats, based in Hyderabad, is developing quantum magnetometers and optical atomic clocks, as well as Rydberg atom-based RF receivers.¹³³ PrenishQ, a start-up incubated at IIT Delhi, announced the development of India's first high-precision and compact diode laser in November 2025, an essential component of multiple quantum sensing and PNT platforms.¹³⁴ QuPrayog, a Pune-based start-up, is working on various aspects of quantum sensing such as Titanium Sapphire lasers, optical frequency combs, and optical atomic clocks.¹³⁵ Qanastra and Quan2D Technologies are working on quantum imaging through SNSPDs.^{136, 137}

Military

The DRDO's RCI has been developing quantum gravimeter as well as atom interferometer-based IMUs.¹³⁸ The DRDO also established the Quantum Technology Research Centre in New Delhi in May 2025, with atomic clocks and magnetometers serving as key thrust areas.¹³⁹ The Indian Army has set up a Quantum Lab at the Military College of Telecommunication Engineering, Mhow, in 2021.¹⁴⁰ In January 2026, the chief of defence staff (CDS) released the Military Quantum Mission Policy Framework, citing quantum sensing and metrology as one of the key focal areas for the Indian Armed Forces.¹⁴¹

Additionally, the Innovation for Defence Excellence (iDEX) scheme, under the Defence Innovation Organisation (DIO), has emerged as one of the top supplements to the NQM in terms of start-up funding and incubation, though it does not specifically cater to QT.¹⁴²

Comprehensive PNT Assessment and Strategy

The Ministry of Defence (MOD) must commission a comprehensive resilience assessment of the Indian military's current PNT capabilities, encompassing all platforms. This would identify shortcomings as well as provide recommendations for future work. Based on this assessment, the MOD should commission a long-term (five to 10 years) PNT strategy tailored for the Indian military, involving multiple stakeholders from all three armed forces, R&D organisations such as the DRDO, as well as representatives from academia, industry, and think-tanks. It should include a development plan that assesses the maximum utility based on a cost-benefit and SWaP analysis and the ideal pathway for utilising classical and quantum sensors complementarily. It is important to note that QTs such as quantum sensing are not monolithic, they rely on a host of other technologies and resources such as semiconductors, lasers, and critical minerals. Therefore, the strategy should also determine optimal pathways for integration with other technology missions such as the India Semiconductor Mission (ISM) and the National Critical Mineral Mission (NCMM). It should have both publicly available and classified versions since the former would help build public and industry sentiment while creating long-term predictability.

Designating a Nodal Agency

Quantum PNT systems are currently most relevant for military applications. Therefore, they should be steered primarily by the MOD. In order to do so, the MOD should designate a nodal agency/institution to coordinate PNT development, both in terms of classical and quantum sensors. This would enable the agency to pick an ideal combination of military, private, and academic personnel to build PNT systems and platforms. The agency should also guide and handhold emerging start-ups by streamlining funding procurement, thereby ensuring that they do not succumb to the infamous 'Valley of Death.'

Navigating Export Controls and Supply-Chain Constraints

A strong impediment for India's QT development is the slew of export controls implemented globally, including by players like the US and China.¹⁴³ This is compounded by supply-chain constraints for critical minerals and technology, which are essential requirements for quantum-sensing platforms. Addressing these vulnerabilities will require a comprehensive effort on the domestic and international fronts. Building domestic hardware and critical mineral capabilities through initiatives such as the NQM, ISM, and NCMM will

be of pivotal importance. On the other hand, pursuing bilateral and multilateral engagements with the US, China, the UK, Australia, and France will be equally beneficial. Developing gravitational and magnetic anomaly maps inherently requires global collaboration. Given its focus on maritime domain awareness, the Quad can serve as an ideal platform for cooperation in this domain.

Addressing R&D Bottlenecks

Delayed funding disbursements is an issue currently plaguing India's QT R&D ecosystem. While funding has begun for multiple projects, full financial approvals are pending in many cases. New procurement rules have made it difficult to utilise even approved funds. This has been particularly challenging for R&D institutions where researchers have been assigned spending limits, with each transaction requiring multi-level government approval. Similar delays are persistent in terms of equipment procurement. Quantum-sensing platforms require the import of expensive equipment such as diode lasers. Under India's Atmanirbhar Bharat policy, it is the researcher's onus to prove that no domestically made alternative exists when procuring scientific equipment exceeding a cost of INR 5 lakh.¹⁴⁴ Given that most quantum-sensing components are currently not built in India, and that they often cost much more than this ceiling, this is particularly frustrating for R&D institutions. Though new initiatives such as the Government e-Marketplace were developed to enhance transparency and save time, they often lack listings for specialised lab equipment.

In order to develop novel quantum sensing and PNT systems, funding disbursement and procurement must be streamlined, scaling down government approval mechanisms and significantly raising the ceiling for equipment requiring case-by-case approval. Digital platforms such as the Government e-Marketplace must be updated expeditiously, particularly in the domain of QT and related lab equipment.


Exploring Novel Testbeds

A key requirement for developing novel quantum PNT systems is the availability of testbeds, both traditional and novel. While India must scale up traditional terrestrial testbeds, it also needs to explore novel testbeds that are relevant for quantum PNT systems.

As mentioned earlier, both NASA and US Space Force are actively involved in testing quantum PNT systems in orbit. In India, the Defence Space Agency and ISRO can be engaged by the MOD to perform a similar role. Moreover, funding scientific expeditions for testing quantum sensors in novel environments like the Arctic could also be beneficial.

Utilising AI for PNT Enhancement

Artificial Intelligence (AI)-based navigation systems can help refine GNSS data while computer vision can serve as a valuable tool for map-matching techniques. The emerging field of Geospatial AI can have significant implications for map-making. In the field of quantum sensors, AI is being increasingly utilised for software, which is enhancing sensor operability and error correction. Consequently, identifying areas for AI application must be done strategically.

The world is in the midst of a technology transition. The ‘second quantum revolution’ is poised to disrupt the global technological landscape, with quantum sensors leading the charge. The imminent arrival of quantum sensors will offer a significant advantage to any nation in the near future. The Indian military must capitalise on this momentum, keeping in mind its delicate diplomatic situation on the borders. Augmenting PNT resilience nationally must take centre-stage. With the growing feasibility of quantum PNT systems and an already existing foundation established by the NQM, the Indian armed forces are in an ideal position to take advantage of a novel technology that could give them an edge. The demand created by the proliferation of quantum-sensing platforms within the military will trigger the commercialisation of the technology and lead to its gradual spilling over to civilian applications, thereby dictating the future of the QT ecosystem in India. 

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