SUPPORTING THE UK PUBLIC SECTOR IN PNT AWARENESS, RESEARCH AND KNOWLEDGE (SPARK)

EXISTING AND EMERGING PNT SERVICES

EXECUTIVE SUMMARY

This combined SPARK publication provides a structured reference for UK decision-makers, programme owners and engineers who require a clear map of Positioning, Navigation and Timing (PNT) capabilities and how they interconnect. Part 1 surveys the main families of PNT services and hardware, including space-based systems in Geostationary Orbit (GEO) and Low Earth Orbit (LEO), terrestrial Radio Frequency (RF), local sensing of all types including quantum, time transfer, and PNT Situational Awareness (PNT SA). Their contexts, performance, use-cases, advantages and limitations, and integration considerations are captured, providing a succinct capability and technology landscape. Part 2 focuses on Satellite-Based Augmentation Systems (SBAS), including what each SBAS system provides, its performance, the use-cases it enables, and how the global landscape is developing for existing and new systems.

READING SPARK

SPARK is a landscape text for orientation and lookup that also explains core PNT concepts, and signposts readers to detailed references where needed. It is aimed at policy leads shaping national approaches, programme owners planning investment, technical architects and engineers, and procurement and commercial teams. Readers can scan the headline priorities, review the capability snapshots, and then move directly to sections or technologies most relevant to their domain, for example, local sensing, network time distribution, or integrity services. It also relates domains and technologies to current and future use-cases, enabling a capability-led approach to understanding PNT using SPARK.

STRATEGIC PRIORITIES

The landscape review carried out in SPARK reveals several strategic priorities for achieving resilient, assured and performant PNT – capable of underpinning high value applications today and in the future.PNT should be treated as critical infrastructure, realised through a resilient system-of-systems architecture delivering accuracy, availability, integrity and continuity.

- Resilient system behaviour depends on diversity. Multi-constellation Global Navigation Satellite Systems (GNSS) provide the backbone, complemented by terrestrial RF, local sensors and clocks, assured network time, and continuous PNT SA.
- Receiver and network readiness must be raised, with priority on multi-frequency GNSS capability and terrestrial signals such as eLoran, signal authentication where available, robust holdover clocks, and readiness for advanced time-transfer methods such as Precise Time Protocol (PTP) and White Rabbit (WR). Corresponding standards must also be matured so industries are able to assure and adopt new solutions.
- A clear UK pathway to integrity services is needed. For regulated sectors, SBAS and credible alternatives should be assessed together, aligned with international standards but tailored to UK operational contexts.
- PNT Situational Awareness should be embedded as routine practice, with continuous monitoring, escalation routes, and mechanisms for data sharing.
- Architectures must be designed to degrade gracefully, maintaining essential functions through holdover, sensor fusion and independent cross-checks when disruption occurs.
- Evaluation of emerging solutions, including LEO-based services, terrestrial augmentation, and new forms of local sensing and holdover, should be undertaken through open, evidence-led trials with traceability to Coordinated Universal Time (UTC) where required, and transparent reporting.
- Timing infrastructure should be assured explicitly, with governance, monitoring and UTC traceability, where required, across public and private networks.
- All approaches should remain vendor-agnostic and standards-aligned, ensuring portability across providers and resilience against future standards evolution.

TECHNOLOGY DOMAINS

SPARK covers the following technology domains, for which the reader can directly jump to their domain of choice while reading SPARK.

- **Space-based PNT:** GNSS remains the primary PNT source for most users, strengthened by multi-constellation and multi-frequency capability. Integrity monitoring and authentication continue to improve, while new LEO and alternative-PNT concepts offer complementary diversity and faster convergence, but should be understood as overlays rather than replacements.

- **Terrestrial RF:** Ground-based transmitters, timing beacons and wide-area signals can reinforce availability where space signals are obstructed. Their practicality depends on realistic coverage, spectrum policy and operator models, with utility in urban, indoor and timing-first contexts. Long-range terrestrial signals such as eLoran present a performant, jamming resilient, complement to GNSS.
- **Local sensing:** All area of local sensing, including technologies such as Inertial navigation systems, vision-based navigation, LiDAR, radar, magnetometry and more, deliver significant signal-independent PNT capability. This is improving rapidly with innovations in sensor technologies, and new data fusion and Artificial Intelligence (AI) approaches delivering fused PNT solutions from complex sensor architectures. These systems can provide stand-alone PNT for some platforms and are integral for holdover to ensure PNT continuity when external signals are degraded. Local holdover clocks are a critical part of this, necessary for timing holdover, but also working as the backbone for sensor synchronisation necessary for data fusion.
- **Network time transfer:** Techniques such as Network Time Protocol (NTP), PTP and WR, support timing requirements from millisecond-level synchronisation to sub-microsecond precision. Performance in practice depends less on protocol choice than on careful engineering of asymmetry, routing and monitoring, all anchored in traceability to UTC.
- **PNT situational awareness:** Once seen as experimental, PNT SA is now an operational discipline. Continuous monitoring on platforms, at fixed sites and across networks, provides early warning of interference or anomalies and strengthens assurance in safety-critical domains.
- **Quantum PNT:** Quantum enabled PNT technologies are reaching maturity in key areas. Portable quantum clocks are becoming Commercial Off The Shelf (COTS) products, increasing the stability achievable in standard, ruggedised, form factors, and making meaningful timing holdover more accessible and less costly. Quantum inertial navigation, based on atom interferometry, is yielding fieldable prototype systems that show promise in extending strategic-grade PNT holdover. Map-matching sensors are providing passive and resilient means of position fixing, constraining navigation error growth in denied environment, and in the case of magnetometry are reaching commercial maturity. The UK has built a strong global position in quantum PNT, with a diverse, mostly sovereign, supply chain. This aligns with national strategy and represents a near-to-medium term enabler of resilience. Integration planning, testbeds and standards and assurance work is required to ensure that future quantum systems can be adopted smoothly into hybrid quantum-classical PNT architectures.

SBAS

SBAS is the established international mechanism for improving GNSS integrity, availability and accuracy. It enables safety-of-life operations, especially in commercial aviation, by bounding errors, providing rapid time-to-alert, and signalling when protection levels are exceeded. For regulated sectors, SBAS is not optional but foundational, with ICAO and regional aviation authorities embedding it in standards and certification pathways. Globally, SBAS provision is expanding, with systems in Europe, the US, Asia and new deployments in Africa and Australasia, and a clear trajectory towards dual-frequency, multi-constellation (DFMC) operation.

For the UK, SBAS must be viewed in this international context: as the baseline for regulated safety operations, interoperable with global standards, and co-existing with complementary approaches such as Precise Point Positioning (PPP) and local augmentation. Receiver readiness, certification pathways and alignment with ICAO SARPs will be decisive factors in its role.

RESILIENCE AND RISK

The SPARK review has highlighted that resilience is a system behaviour and a way of thinking. PNT is exposed both to benign risks such as multipath, occlusion and interference, and to adversarial threats including jamming and spoofing. A resilient posture assumes degradation will occur and mitigates through layered diversity of mitigation techniques, from redundant systems to switching to alternate PNT sources: multi-constellation GNSS, terrestrial RF, local sensing and clocks, assured network time and embedded monitoring.

Not applying this resilience thinking to PNT results in systems that are brittle, slow to recover, and poorly equipped to handle modern complexities and uncertainties. This leads to increased risks of disruption, safety hazards, and economic losses, while stifling innovation and equitable outcomes. Resilience thinking offers a proactive path to robust, adaptable systems, mitigating the cascading risks of current shortcomings. It is top-down and starts at the values of stakeholders as well as their critical functionality criteria, progressing through decision models to the generation of metrics and data - that ultimately can inform risk assessments and plans, which deal with known threats and vulnerabilities to systems.

NEXT STEPS AND STRATEGIC DIRECTION

The development of a UK **Radionavigation Plan (RNP)** is now the central requirement. Such a plan would provide the national framework for assured PNT, integrating global GNSS with complementary UK measures and setting out how resilience, diversity and integrity will be delivered across sectors. It should not only define technical pathways but also establish governance, certification and operational models that anchor PNT as critical infrastructure.

SPARK highlights the evidence base on which this plan should be built. The UK will need to establish its position on integrity services, including SBAS and its dual-frequency evolution, ensuring alignment with ICAO and allied standards. Receiver and network readiness must be baselined and improved, with migration towards multi-frequency GNSS, robust holdover clocks and advanced time-transfer protocols. PNT situational awareness should move beyond pilot activity to become an operational discipline with clear processes for incident response and data sharing. In parallel, a roadmap for assured timing infrastructure—with UTC traceability and continuous monitoring—must be set out as a foundation for all sectors.

Emerging solutions, including LEO-based services, terrestrial augmentation, local sensing and quantum PNT, should be evaluated through open, evidence-led trials conducted against common standards and shared transparently. By drawing these strands together, the Radionavigation Plan can provide a **unifying national architecture** that is both internationally harmonised and grounded in UK operational needs, giving government, industry and operators a common direction of travel.

TABLE OF CONTENTS

RECORD OF ISSUE

Issue	Date	Author	Reason for Change
1.0	22-Oct-25	Andy Proctor, Kieran Bjergstrom, Mia Wood	First Issue

1. INTRODUCTION

1.1. SCOPE & APPLICABILITY

This SPARK Part 1 document details existing and future positioning, navigation, and timing (PNT) systems for the UK geographic area. It is not intended to be a PNT tutorial, nor is it an industrial survey that will list out specific companies and products; therefore, the reader should review the references and relevant PNT training courses, such as those available from the Royal Institute of Navigation, Satellite Applications Learning Hub (SALHUB).

1.2. LIMITATIONS AND CADENCE OF UPDATE

The PNT landscape evolves rapidly: services mature, providers change, and performance shifts as deployments scale. SPARK focuses on durable architectures, integration points and assurance concepts, while pointing to authoritative sources for specifications. Users should verify figures and certification status against current documentation before committing to procurement or safety-critical use. Updates will be issued on a regular cadence to reflect material changes while maintaining a stable, vendor-agnostic frame of reference.

1.3. STRUCTURE OF DOCUMENT

This document will start by giving some general PNT information that is common across all technology groupings and types, including some measurement metrics and applications for PNT.

Figure 1 graphically displays the subsequent document structure, indicating that after the initial general information, the document will cover first space-based PNT, then terrestrial radio frequency (RF) systems, then local sensing forms of PNT derivation, finally followed by a section on PNT situational awareness.

This document is not intended to be an industrial survey of companies and procurement options, but it focuses on technologies and reference companies, where appropriate to do so.

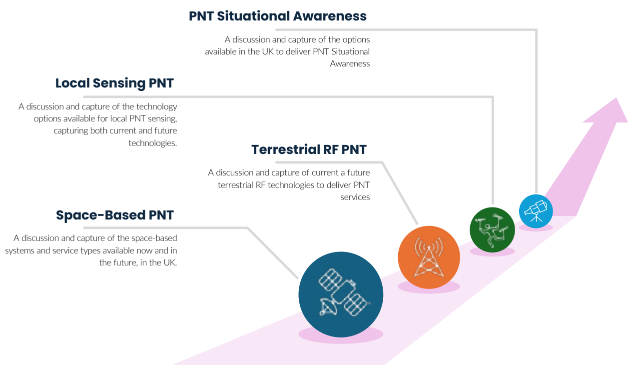


Figure 1: Document structure

1.4. GENERAL INFORMATION ABOUT PNT

PNT technologies constitute a fundamental enabler of contemporary infrastructure, underpinning advancements in defence, transportation, telecommunications, and scientific domains. This section provides an overview of the principles and technologies involved in the determination of position and/or time, and the relevant applications. As reliance on PNT proliferates across critical sectors (Government Office for Science, 2018), a deeper understanding of PNT is required at all levels of government and industry.

1.4.1. PNT PRINCIPLES

This section, a modified version of (Proctor, 2025), will briefly discuss some of the principles of PNT systems.

1.4.1.1. TRIANGULATION AND TRILATERATION

Triangulation is the determination of an object's location by measuring angles from two or more known reference points to the target. The position is calculated using geometric relationships, widely applied in surveying, optical tracking, and early radio navigation systems (Hoffman-Wellenhof, 2001).

Trilateration, often confused with triangulation, determines an object's position based on distance measurements rather than angles. By calculating the intersection of three or more spheres (in 3D space) or circles (in 2D space), the exact position of an object is determined. Global Navigation Satellite Systems (GNSS), such as the US Global Positioning System (GPS), rely on trilateration using time-of-flight by assessing the time-of-arrival (TOA) measurements from multiple satellites (Kaplan & Hegaty, 2017).

1.4.1.2. HYPERBOLIC NAVIGATION SYSTEMS

Hyperbolic navigation systems are systems designed to provide long distance positioning and uses a technique based on the measurement of differences in the time-of-arrival of signals from two or more transmitting stations (Misra & Enge, 2004).

These transmitters should be at known locations and synchronised so that a receiver can measure the time difference, without needing to be synchronised to the transmitters directly. This is called a Time-Difference-Of-Arrival (TDOA) system. The signals from a pair of transmitters received by the receiver are measured, and the time difference and distance to the known transmitters calculated to create a hyperbola along which the user position lies. A second pair of transmitters are also measured in the same way to determine the intersection of the hyperbolas—which represents the user's position.

Ambiguities are inherent in hyperbolic navigation systems but can be mitigated by additional measurements (Boşneagu & Lupu, 2014). An example of a hyperbolic navigation system is Loran/eLoran, which was originally developed during World War II. This provided maritime and aviation users with positioning information based on time-differentiated signals from ground-based transmitters. The later development of eLoran enhanced signal reliability and accuracy, offering an alternative to GNSS-based navigation (Lachapelle, 2018).

1.4.1.3. DOPPLER POSITIONING

Exploited for navigation from the Russian Sputnik I mission, doppler positioning uses the doppler effect (or the change in apparent frequency of a received signal by an observer, due to relative motion between the transmitter and observer) (Misra & Enge, 2004). This is easily exemplified by the sound of the siren from a fast-moving police car as it travels to and from a person. To calculate a receiver's position, in the case of the US Transit system, measurement of doppler shifts from multiple spacecraft signals is carried out. Transit allowed users to determine their location with increasing accuracy. Notwithstanding limitations in update frequency and user availability, it laid the foundation for modern GNSS systems, particularly GPS (Teunissen & Montenbruck, 2017) (He, 2025).

1.4.1.4. DEAD RECKONING

Dead reckoning is a method of navigation whereby, from a start or current position, the measured change in distance and integrated velocity are added to obtain the new position. Methods include counting paces, using a knotted rope, wheel tick sensors (into an odometer), and ships log. These changes can be integrated with a change in heading measurement to compute the new position, reset, and restart the process. Dead reckoning is subject to lots of uncertainty directly related to the quality and accuracy of the methods used to measure distance and velocity (Groves, 2018).

1.4.1.5. CDMA AND FDMA OPERATION

Code Division Multiple Access (CDMA) is a spread-spectrum technique used in satellite communications, radio communications and GNSS, where, in the case of GNSS, each satellite transmits signals encoded with a unique pseudo-random noise (PRN) code. This enables multiple satellites to share the same frequency spectrum while allowing receivers to distinguish between them through cross-correlation of the unique codes (Misra & Enge, 2004).

Frequency Division Multiple Access (FDMA) assigns different frequency bands to separate transmissions. This method is used in the Russian Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) system, whereby each satellite operates on a distinct frequency within a given range, ensuring minimal signal interference between satellites (Spilker, Axelrad, Parkinson, & Enge, 1996).

1.4.1.6. GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

GNSS relies on constellations of satellites that broadcast radio signals containing time-stamped data. Receivers calculate positions via trilateration, requiring signals from at least four satellites to resolve three-dimensional coordinates and time offsets (Teunissen & Montenbruck, 2017). GPS, operational since 1995, uses carrier frequencies of 1.57542 GHz (L1 band), 1.2276 GHz (L2 band), and 1.17645 GHz (L5 band), and it employs CDMA for signal differentiation (Kaplan & Hegaty, 2017). Galileo and BeiDou also use this multi-frequency approach to mitigate ionospheric errors, allowing receivers to achieve sub-meter precision in optimal conditions (European GNSS Service Centre, 2025).

Atomic clocks play a crucial role in GNSS by providing extremely precise and stable timekeeping. Each satellite carries multiple (normally, for redundancy) atomic clocks that are synchronised with ground-based master clocks. These clocks measure time based on the vibrations of atoms, typically caesium or rubidium atoms, maintaining time to within nanoseconds (NASA, 2019).

The accurate timing from these clocks allows GNSS satellites to broadcast precise time signals to Earth. GNSS receivers calculate their position by measuring the time delay between when the satellite signal was sent and when it was received. Since the speed of the signals is the speed of light, even the tiniest timing errors would translate to significant errors in positioning. For example, a timing error of just one microsecond would cause a location error of about 300 meters (Misra P. , 2023).

Additionally, atomic clocks in GNSS satellites are regularly synchronised from the ground and corrected for relativistic effects caused by their high speeds and the difference in gravitational fields between space and Earth's surface. This synchronisation ensures positioning accuracy better than 10 nanoseconds in time, which is essential for overall system precision.

1.4.1.7. GNSS AUGMENTATION SYSTEMS

As described in (NLA International, 2025), Satellite-Based Augmentation System (SBAS), such as the Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay Service (EGNOS), improve GNSS accuracy by correcting atmospheric and orbital errors. Ground-based systems like Differential GPS (DGPS) use fixed reference stations to broadcast correction signals, achieving centimetre-level precision (Misra & Enge, 2004). Real-Time Kinematic (RTK) positioning, leveraging carrier-phase measurements, further refines potential accuracy to millimetres, critical for surveying and autonomous systems (Hoffman-Wellenhof, 2001) (Teunissen & Montenbruck, 2017).

1.4.1.8. INERTIAL NAVIGATION SYSTEMS

Inertial Navigation Systems (INS) operate based on dead reckoning by integrating the acceleration and angular velocity data outputs from inertial sensors (accelerometers and gyroscopes) (Groves, 2018). These are generally mounted orthogonally with the gyroscopes measuring angular rate and the accelerometers measuring acceleration. By continuously measuring the motion of an object and integrating these measurements over time, an INS determines position, velocity, and orientation. However, due to the accumulation of small measurement errors (drift), an INS typically requires external updates from GNSS or other sources to maintain long-term accuracy (Groves, 2018). INS remains a critical component of modern navigation systems, particularly for GNSS-obstructed platforms such as submarines, spacecraft, and autonomous vehicles.

Modern systems integrate Micro-Electro-Mechanical Systems (MEMS) for cost-effective, compact solutions, though drift errors accumulate over time. Coupling INS with GNSS via Kalman filtering mitigates this, providing robust PNT in GNSS-denied environments (Groves, 2018).

Accelerometers measure linear acceleration along one or more axes. These devices operate based on principles of Newtonian mechanics, detecting changes in velocity by measuring the force exerted on a proof mass suspended within a MEMS structure. High-precision accelerometers, such as those used in aviation and defence, utilise piezoelectric, capacitive, or optical sensing methods to minimize errors and improve accuracy (Woodman, 2007).

Gyroscopes measure angular velocity, enabling orientation determination by detecting rotational motion. Modern gyroscopes operate using mechanical, fibre-optic, or ring laser technologies, each with varying levels of precision and stability. For instance, Ring Laser Gyroscopes (RLGs) and Fibre-Optic Gyroscopes (FOGs) provide drift-free rotational measurements critical for navigation in GNSS-denied environments, such as submarines and interplanetary spacecraft (Lefevre, 2014).

1.4.1.9. OTHER PNT CAPABILITIES

Low Earth Orbit (LEO) Satellites: Companies like SpaceX (Starlink) and EutelSat OneWeb propose LEO constellations for PNT, offering stronger signals and reduced latency compared to GNSS (Frontier SI, 2024). Simultaneous Localisation and Mapping (SLAM) leverages cameras and LiDAR for PNT in robotics and autonomous vehicles (Durrant-Whyte & Bailey, 2006).

Quantum Technologies such as atomic clocks and quantum inertial sensors promise unprecedented timing precision, with applications in future PNT systems (Everitt, Bjergstrom, & Duffus, 2024).

1.4.2. KEY APPLICATIONS AND BENEFICIARIES

PNT systems are foundational technologies that underpin a wide range of societal functions, providing critical capabilities across diverse sectors. By leveraging GNSS alongside other PNT sources, such as eLoran, INS, and emerging quantum technologies, these systems enable precise location, navigation, and timing services across major societal sectors – transportation, defence, telecommunications, energy, agriculture, emergency services, and finance are just a few.

1.4.2.1. TRANSPORTATION: ENABLING SAFE AND EFFICIENT MOBILITY

In the transportation sector, PNT is the backbone of modern mobility, supporting aviation, maritime, rail, and road systems. In aviation, it ensures precise navigation for aircraft during take-off, en-route navigation, and landing, particularly through systems like WAAS or EGNOS (NLA International, 2025), thereby enhancing GPS accuracy for precision approaches. Maritime navigation relies on PNT for ship routing, collision avoidance, and port operations, with GNSS providing real-time positioning even in remote oceanic regions.

On roads, PNT technologies power autonomous vehicles, ride-sharing apps, and traffic management systems, enabling route optimisation, lane-keeping assistance, as well as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. For railways, PNT supports positive train control (PTC) systems, ensuring train separation and preventing derailments. PNT improves safety by reducing navigation errors, enhances efficiency through optimised routing, reduces fuel consumption, and supports the scalability of autonomous systems, transforming urban mobility and logistics.

1.4.2.2. DEFENCE: ENSURING OPERATIONAL EFFECTIVENESS

The defence sector relies heavily on PNT for mission-critical operations. Alternative methods to GNSS are essential for PNT capability/information delivery in contested environments where GNSS signals may be jammed or spoofed. Military applications include navigation for troops, aircraft, ships, and unmanned systems like drones, as well as precision-guided munitions that require accurate targeting. PNT (specifically timing systems) also synchronises communication networks, ensuring secure and reliable data exchange across units. In electronic warfare, PNT situational awareness systems can detect and mitigate threats like jamming, enabling forces to maintain operational continuity. Technologies like Controlled Reception Pattern Antennas (CRPAs) and INS integration provide resiliency technique options in GNSS-denied environments. PNT information, both of friendly and adversary forces, enhances situational awareness, improves mission success rates, ensures secure communication, and maintains operational effectiveness under adversarial conditions, safeguarding national security.

1.4.2.3. TELECOMMUNICATIONS: SYNCHRONISING GLOBAL NETWORKS

Telecommunications networks depend on PNT for precise timing to synchronise data transmission across cellular, satellite, and internet infrastructure. In 5G networks, PNT ensures low-latency communication by synchronising base stations, enabling efficient handoffs between cells and supporting high-density device connectivity. Precise time is also critical for satellite communications to synchronise uplink and downlink signals to prevent data loss. Additionally, timing systems support network security by timestamping data packets, aiding in the detection of cyber threats, ensuring network reliability, reducing latency, enhancing data throughput, and strengthening cybersecurity. PNT information (both position and time) enables the seamless operation of global communication systems.

1.4.2.4. ENERGY: POWERING GRID STABILITY AND EXPLORATION

In the energy sector, PNT plays a vital role in power grid synchronisation and resource exploration. For power grids, precise timing from GNSS synchronises phasor measurement units (PMUs), which monitor voltage and current phases to prevent blackouts and ensure grid stability. In oil and gas exploration, PNT enables precise seismic mapping and drilling operations, improving resource extraction efficiency. Renewable energy systems, such as solar and wind farms, use timing technologies to optimise energy distribution by aligning generation with demand cycles. PNT enhances grid reliability, prevents power outages, improves resource exploration accuracy, and optimises energy distribution, supporting sustainable energy systems.

1.4.2.5. AGRICULTURE: DRIVING PRECISION AND PRODUCTIVITY

Precision agriculture employs PNT to revolutionise farming practices, enabling farmers to optimise yields while minimising environmental impact. GNSS-guided tractors and drones perform automated tasks like planting, fertilising, and harvesting with centimetre-level accuracy, reducing overlap and waste. PNT also supports soil mapping, crop monitoring, and irrigation management by providing geospatial data for variable rate applications. In livestock management, animal movements can be tracked, improving grazing efficiency and health monitoring. Use of PNT systems increases crop yields, reduces resource waste (e.g., water and fertilisers), lowers operational costs, and promotes sustainable farming practices, addressing global food security challenges.

1.4.2.6. EMERGENCY SERVICES: SAVING LIVES THROUGH RAPID RESPONSE

Emergency services—including police, fire, medical response, and coastguard—rely on PNT for rapid and accurate operations. GNSS enables precise location tracking of emergency calls, allowing first responders to reach incident sites quickly, even in remote areas. In disaster scenarios, such as earthquakes or hurricanes, PNT systems support search-and-rescue operations by guiding teams to trapped individuals and mapping affected areas. Accurate position and location facilitate fleet management for police, ambulances and fire appliances by understanding location and situational awareness information, optimising response times. PNT systems can enhance coordination during crises, increase the accuracy of location-based services, ensure infrastructure stability through use of timing technologies, and ultimately saves lives by ensuring timely interventions.

1.4.2.7. FINANCE: SECURING TRANSACTIONS AND MARKET STABILITY

The finance sector depends on high-precision timing to synchronise transactions and maintain market integrity. Stock exchanges use GNSS-derived timing to timestamp trades, ensuring fairness and transparency in High-Frequency Trading (HFT). PNT systems also synchronise banking networks for secure data transfers, such as those in the SWIFT (Society for Worldwide Interbank Financial Telecommunications) system, preventing fraud and errors.

In payment systems, accurate timestamping for credit card transactions and ATM (automated teller machine) operations ensures transaction integrity, prevents financial fraud, maintains market fairness, and supports the reliability of global financial systems, fostering economic stability.

1.4.2.8. CONSTRUCTION AND SURVEYING: PRECISION IN BUILDING AND MAPPING

In the construction and surveying sector, PNT systems are indispensable for ensuring precision, efficiency, and safety in infrastructure development and land management. Surveyors rely on GNSS receivers to perform high-accuracy geospatial measurements, mapping land boundaries, topography, and site layouts with centimetre-level precision. This is critical for urban planning, road construction, and large-scale projects like bridges and skyscrapers. In construction, machine control systems, such as GNSS-guided bulldozers and excavators enable automated grading, excavation, and foundation laying, ensuring adherence to design specifications.

Real-Time Kinematic (RTK) positioning enhances accuracy for staking out building footprints and aligning structural components. PNT also supports building information modelling (BIM) by providing geospatial data for 3D project visualisation and monitoring. For infrastructure monitoring, GNSS-based systems track structural deformations in bridges, dams, and tunnels, ensuring safety over time. PNT reduces surveying errors, accelerates project timelines, minimizes material waste, and enhances safety through precise monitoring, revolutionizing how we build and maintain infrastructure.

1.4.2.9. SCIENTIFIC SECTOR: ADVANCING RESEARCH AND DISCOVERY

The scientific sector leverages PNT for a wide range of research applications, from studying Earth's systems to exploring the cosmos. In geophysics, PNT enables precise monitoring of tectonic plate movements and volcanic activity through GNSS monitoring networks, providing data for earthquake prediction and disaster preparedness. Atmospheric scientists use PNT to track weather patterns, with GNSS radio occultation, and reflectometry, measuring atmospheric properties like temperature and humidity for climate modelling. In astronomy, PNT synchronises telescopes and observatories for coordinated observations, such as those in the Event Horizon Telescope project, which captured the first image of a black hole, or the Square Kilometre Array (Jiménez-López, 2019). PNT also supports space missions by providing navigation for satellites.

In oceanography, seafloor mapping and tracking of ocean currents aids research on marine ecosystems and climate change. PNT systems enhance measurement accuracy, enable global collaboration, support autonomous exploration, and provides critical timing for experiments, driving scientific breakthroughs across disciplines.

1.4.3. KEY PNT METRICS

PNT systems are evaluated using performance metrics to ensure their effectiveness across applications, as described in section 1.4.2. These metrics provide a standardised method to assess system reliability, precision, and resilience, which are critical for operational success. Below, the key PNT performance metrics—accuracy, availability, integrity, and continuity—are briefly described focusing on definitions, measurement methods, and their significance in practical contexts. These have been chosen as key metrics; many others, including robustness and resilience, have been well defined. For detail on definitions refer to the bibliography (RethinkPNT, 2022).

1.4.3.1. KEY PNT PERFORMANCE METRICS

- Accuracy quantifies how closely a PNT system's output matches the true position, velocity, or time. For positioning, it is typically measured in metres, representing the error between the estimated and actual location. Modern GNSS achieve positional accuracy of 1-5 meters, while advanced techniques like Real-Time Kinematic (RTK) positioning can reduce this to centimetres or less. For timing, accuracy is measured in nanoseconds (some applications measure the nanosecond offset from an international standard such as Universal Coordinated Time (UTC)), critical for applications like telecommunications where synchronisation errors can disrupt data transmission. High accuracy ensures reliable navigation and timing, foundational for autonomous vehicles and network synchronisation.
- Availability measures the percentage of time a PNT system can provide usable positioning, navigation, or timing data. Expressed as a percentage over time (e.g., 99%), it reflects the system's operational uptime. Availability can be degraded by environmental factors, such as urban canyons or dense foliage, or by intentional interference, such as jamming. For example, GNSS availability may drop in dense urban areas due to signal obstructions. High availability is essential for continuous operation in critical applications like air traffic control, where downtime can lead to operational delays.
- Integrity assesses the trustworthiness of the PNT system's data, specifically the probability that it provides accurate information without undetected errors. It is often quantified as the risk of a system delivering hazardous misleading information (HMI), such as a positional error exceeding a threshold without an alert. For aviation, integrity requirements may demand a risk of less than 1 in 10^7 per approach. Integrity is crucial for safety-critical applications, ensuring users can rely on the system or receive timely warnings of anomalies, as in precision aircraft landings.
- Continuity is the probability that a PNT system remains operational without interruption during a specific task or time-period, typically expressed as a percentage (e.g., 99.9% over a one-hour operation). It is particularly important in dynamic scenarios where interruptions could lead to failure, such as during an aircraft's approach phase or an autonomous vehicle's navigation through an intersection. Continuity ensures uninterrupted service, minimizing the risk of mission failure in time-sensitive operations.

2. SPACE BASED PNT SYSTEMS & SERVICES

This section will give a brief overview of the characteristics of space-based PNT before providing information on available services for use in the UK. The reader is encouraged to review the references for more technical and detailed information, as required.

2.1. OVERVIEW

Space-based PNT systems provide critical services for determining location, navigating routes, and synchronising time across various applications, from civilian navigation to military operations. These systems, exemplified by the US Global Positioning System, rely on constellations of satellites and ground infrastructure to deliver and enable the calculation of precise geospatial and temporal data.

Space-based PNT systems are typically organised into three primary segments: the space segment, the control (or ground) segment, and the user segment (Kaplan & Hegaty, 2017). Below is an overview of these segments and their key components.

2.1.1. SPACE SEGMENT

The space segment consists of a constellation of satellites orbiting Earth, designed to transmit signals that enable PNT services. These satellites, often in Medium Earth Orbit (MEO) at approximately 20,000 km altitude, are equipped with atomic clocks and radio transmitters. The signals they broadcast include precise time data and orbital information, allowing receivers to calculate position and time. For example, GPS operates with a nominal constellation of 24 satellites arranged in six orbital planes to ensure global coverage (Navstar GPS Joint Program Office, 2020).

Key components include:

- Atomic Clocks: Provide highly accurate timekeeping, critical for signal timing (error margins are in nanoseconds)
- Signal Generators: Emit radio signals (e.g., L1 and L2 frequencies[1] in GPS) containing pseudorandom codes and navigation messages
- Antennas: Broadcast signals to Earth, ensuring wide coverage

The space segment's reliability depends on satellite redundancy and periodic replacements to maintain continuous service.

2.1.2. CONTROL/GROUND SEGMENT

The control (sometimes termed "ground") segment is the ground-based infrastructure responsible for monitoring, maintaining, and updating the satellite constellation. It ensures the accuracy of satellite signals and orbital parameters. The control segment includes a network of monitoring stations, one or more master control stations, and ground antennas. For GPS, the control segment is managed by the U.S. Space Force, with facilities worldwide (US Space Force, 2021).

Key components include:

- Monitoring Stations: Track satellite signals to assess clock accuracy and orbital positions
- Master Control Station(s): Processes data from monitoring stations to compute satellite ephemeris (orbital data) and clock corrections
- Ground Antennas: Uplink commands and updated data to satellites (for onward broadcasting to users)

This segment is critical for correcting satellite errors and mitigating signal degradation due to factors like atmospheric interference or clock drift.

2.1.3. USER SEGMENT

The user segment encompasses the devices and receivers that process [Space-based] PNT signals for end-user applications. These range from smartphones and vehicle navigation systems to precision-guided munitions and scientific instruments. Receivers calculate position, velocity, and time by trilateration, using signals from at least four satellites to solve for three-dimensional coordinates and clock offset (Kaplan & Hegaty, 2017).

Key components include:

- Receivers: Hardware that decodes satellite signals, often supporting multiple frequencies for enhanced accuracy (e.g., dual-frequency GPS for ionospheric correction)
- Antennas: Capture satellite signals, varying from simple designs in consumer devices to sophisticated arrays in high-precision applications
- Processing Software: Algorithms that compute position and time, often integrating augmentation systems like Differential GPS or SBAS (Satellite-Based Augmentation Systems) for improved accuracy

The user segment is diverse, serving industries such as transportation, agriculture, telecommunications, and defence.

A typical space-based PNT system is shown in Figure 2.

1 L1 Frequency is 1.57542 GHz. L2 Frequency is 1.2276 GHz.

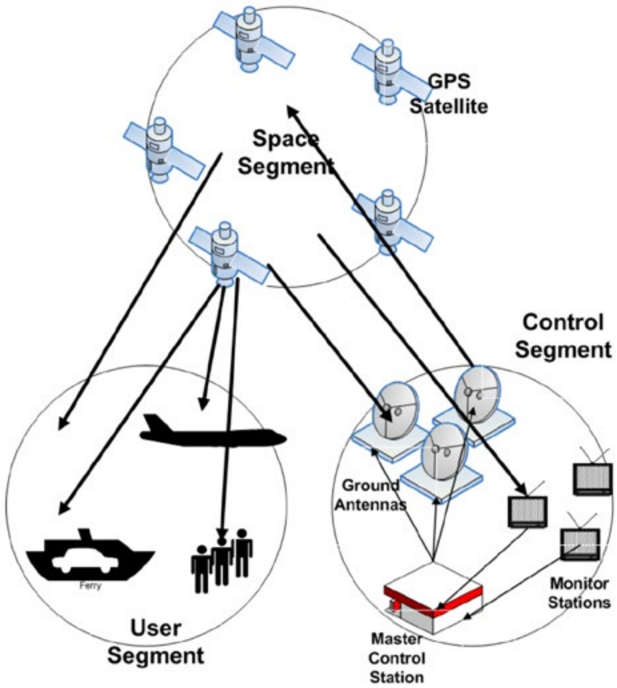


Figure 2: Typical space-based PNT system overview (Montillete, 2008)

2.1.4. BASIC DEFINITIONS

This section provides some of the basic definitions used throughout this report, but the reader is invited to review the referenced document (RethinkPNT, 2022) for a full description of PNT definitions.

- Positioning: Determining a user's location in three-dimensional space (latitude, longitude, altitude) using satellite signals, with reference to a coordinate system
- Navigation: Using position data to guide movement from one point to another, often in real-time
- Timing: Providing precise time determination and synchronisation, critical for applications like financial transactions and power grid management
- Trilateration: The process of calculating position by measuring distances to multiple satellites based on signal travel time

Space-based PNT systems integrate the space, control, and user segments to deliver seamless positioning, navigation, and timing services globally. The space segment provides the signal infrastructure, the control segment ensures operational accuracy, and the user segment enables diverse applications. These systems are foundational to modern technology and continue to evolve with advancements like multi-constellation integration (e.g., GPS, GLONASS, and Galileo) as well as enhanced resilience against jamming or spoofing.

2.2. ORBITAL REGIMES AND THEIR DISTINCT CHARACTERISTICS

2.2.1. LOW EARTH ORBIT (LEO)

Low Earth Orbit typically refers to orbits ranging from approximately 160 km to 2,000 km above the Earth's surface. Satellites in LEO complete an orbit in about 90 to 120 minutes due to the high orbital velocity required to counteract Earth's gravity at that altitude. This orbit is particularly advantageous for Earth observation, imaging, reconnaissance, and some communications due to the low latency and high resolution achievable from a short distance to Earth (Teunissen & Montenbruck, 2017).

However, the lower altitude means these satellites have a relatively small footprint on the Earth's surface. Therefore, large constellations—often consisting of hundreds or thousands of satellites—are needed to ensure continuous global coverage. Recent systems like Starlink (Starlink, 2025) and OneWeb (EutelSat OneWeb, 2025) are prime examples of large-scale LEO constellations offering broadband internet services.

LEO satellites face higher atmospheric drag, especially at altitudes below 600 km, which can reduce satellite lifespan unless compensated by propulsion systems. Nonetheless, their proximity to Earth makes them easier to launch and deorbit, simplifying space traffic management and reducing long-term space debris risks (Frontier SI, 2024).

2.2.2. MEDIUM EARTH ORBIT (MEO)

The Medium Earth Orbit ranges from 2,000 km to about 35,786 km above the Earth's surface. This is commonly used for navigation and timing applications. The most notable examples are the constellations of Global Navigation Satellite Systems, such as GPS (U.S.), Galileo (EU), GLONASS (Russia), and BeiDou (China), which all operate within the MEO band (Frontier SI, 2024).

Satellites in MEO typically have orbital periods between 2 to 12 hours, allowing broader Earth coverage per satellite compared to LEO. GNSS satellites in MEO offer the optimal balance between coverage area, latency, and energy requirements for spacecraft onboard systems. Their greater distance provides a wider signal footprint and contributes to the robustness of global positioning systems (Parkinson & Spilker, 1996).

However, MEO satellites are more exposed to the Earth's Van Allen radiation belts than those in LEO or GEO (Geostationary Orbit), necessitating hardened electronics and shielding. Despite these challenges, MEO remains ideal for consistent global coverage for PNT, with relatively few satellites (Kaplan & Hegaty, 2017).

2.2.3. GEOSTATIONARY ORBIT (GEO)

GEO is a unique orbital regime located precisely at 35,786 km above the equator, where a satellite's orbital period matches Earth's rotation (24 hours). This allows satellites in GEO to remain fixed over a single point on Earth's surface, making them extremely useful for applications like weather monitoring, satellite television, and telecommunications (Fortescue, Swinerd, & Stark, 2011).

The fixed position simplifies ground antenna designs because users do not need to track moving satellites. One GEO satellite can cover roughly a third of the Earth's surface, enabling global coverage with just three evenly spaced satellites. However, the high altitude leads to signal latency of about 240 milliseconds round-trip, which is a limitation for latency-sensitive applications like real-time voice or gaming (Roddy, 2006).

Launching to GEO requires significant energy and often complex transfer orbits, such as the Geostationary Transfer Orbit (GTO). Satellites in this orbit also experience limited spatial resolution due to their distance and suffer from orbital crowding and potential signal interference, given the fixed orbital slot capacity (Fortescue, Swinerd, & Stark, 2011).

Geostationary satellites are also used to provide GNSS augmentation services, the subject of Part 2 of this report.

2.2.4. HIGHLY ELLIPTICAL ORBIT (HEO)

Highly Elliptical Orbits, such as the Molniya and Tundra orbits, are characterised by high eccentricity, leading to one end of the orbit (apogee) being significantly farther from Earth than the other (perigee). These orbits allow satellites to dwell for extended periods over specific regions—often high-latitude areas—making them ideal for countries in the far north such as Russia or Canada (Pratt, 2002).

HEO satellites typically have orbital periods of 12 or 24 hours and can maintain a high position over target areas during apogee, delivering near-continuous service when deployed in pairs or small constellations. This is especially valuable for providing communications or surveillance coverage in polar regions, which GEO satellites cannot cover effectively due to their equatorial location.

However, designing for HEO requires accounting for extreme variations in radiation exposure, gravitational perturbations, and changes in satellite velocity throughout the orbit. These technical complexities increase costs and make HEO less common than circular orbits like GEO or MEO, despite its strategic advantages (Fortescue, Swinerd, & Stark, 2011).

2.3. CHALLENGES OF SPACE BASED PNT

Space-based PNT systems despite their critical role, face several technical, environmental, and strategic challenges.

2.3.1. SIGNAL VULNERABILITY

PNT signals transmitted from satellites are extremely weak by the time they reach the Earth's surface—often below the ambient noise floor. This makes them highly susceptible to jamming (denial) where intentional or unintentional interference blocks the signal, and spoofing (deception) where false signals deceive receivers into reporting incorrect time or location. Such vulnerabilities pose major risks to safety-critical sectors like aviation, maritime transport, and autonomous systems (Government Office for Science, 2018).

2.3.2. LIMITED COVERAGE AND AVAILABILITY

While systems like GPS and Galileo provide near-global coverage, certain environments—such as dense urban areas, deep canyons, forests, and indoor spaces—can obstruct satellite visibility, leading to reduced accuracy or service denial. Additionally, GNSS signals do not cover polar regions well, limiting access for users in high latitudes. Reliance upon line-of-sight visibility to multiple satellites is a fundamental constraint of current space-based architectures (Teunissen & Montenbruck, 2017).

2.3.3. TIMING ERRORS AND ATMOSPHERIC DELAYS

Accurate PNT performance depends on precise timing. Even nanosecond-level errors in satellite clocks or transmission delays caused by the Earth's ionosphere and troposphere can translate into several meters of positional error. Atmospheric models help mitigate this, but residual errors remain, particularly during geomagnetic storms or solar activity, which can significantly degrade system performance (Kaplan & Hegaty, 2017).

2.3.4. SPACE ENVIRONMENT AND SATELLITE RELIABILITY

Satellites operating in MEO (for GNSS) or other orbits are exposed to harsh radiation environments, especially the Van Allen belts. This can degrade electronics, reduce lifespan, or cause anomalies. Space debris also poses a collision risk, especially as orbits become increasingly congested with satellites from multiple constellations. Maintaining system integrity over decades is a complex and resource-intensive challenge (Fortescue, Swinerd, & Stark, 2011).

2.3.5. DEPENDENCY AND STRATEGIC VULNERABILITY

As critical infrastructure becomes increasingly dependent on space-based PNT, a single point of failure risk emerges. A systemic GNSS outage could disrupt transportation, finance, agriculture, and emergency response systems. This makes PNT a strategic asset and a potential target in geopolitical conflicts (HM Government, 2023). Nations are investing in redundancy measures, including regional augmentation systems, terrestrial backups (e.g., eLoran), and alternative PNT (A-PNT) solutions (The White House, 2020).

2.3.6. LATENCY AND INTEGRITY CONSTRAINTS

For applications like autonomous vehicles, drones, and high-frequency trading, latency and integrity of navigation and timing data are paramount. Traditional GNSS solutions often cannot meet real-time integrity monitoring or low-latency demands without additional infrastructure such as ground-based augmentation or space-based PPP (Precise Point Positioning) services. LEO solutions offer reduced latency with higher data rates (Frontier SI, 2024).

2.4. FREQUENCY BANDS

The allocation of frequency bands is a highly intricate process because multiple services and users often share the same frequency band. This means that the same frequencies may be assigned for different purposes across various countries and systems.

The International Telecommunication Union (ITU), a United Nations agency, is responsible for coordinating the global use of the radio spectrum. This coordination covers a wide array of services, including television, radio, cellular networks, radar, satellite communications, and satellite navigation systems.

The ITU Allocation Agreements for the satellite navigation bands (Radio Navigation Satellite Services or RNSS) were established during the World Radiocommunication Conferences held in 2000 and 2003, where ITU finalised agreements to ensure compatibility and frequency sharing between the various GNSS constellations.

Figure 3 shows the current GNSS frequency bands for the global systems (including IRNSS - Indian Regional Navigation Satellite System), demonstrating the complexity and overlap of frequencies and underscoring the need for careful management of both transmitters and receivers.

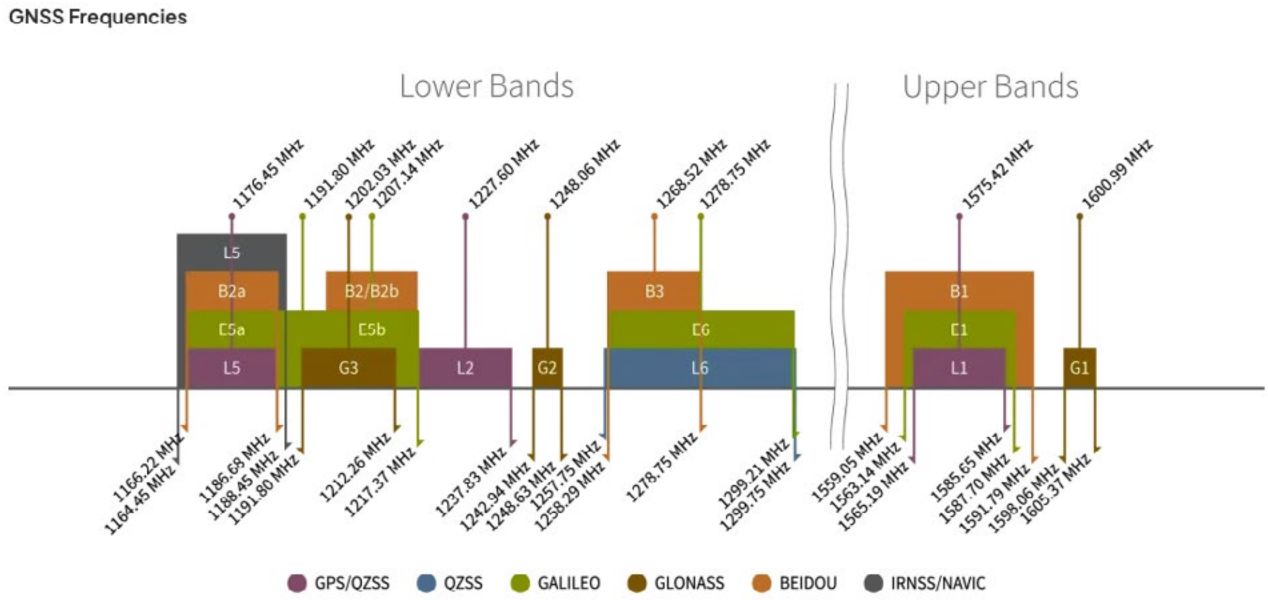


Figure 3: GNSS Frequency Bands (Calian, 2025)

Constellations	Bands	Frequency in MHz				Wavelength (cm)	Minimum Received Power (5° Elev) dBW*	Signals / Comments
		Centre	Bandwidth	Lower	Upper			
GPS	L1	1575.42	±2	1573.42	1577.42	19.0	-163.0(D) / -158.25(P)	L1C GPS III
			±1.023	1574.397	1576.443		-157	L1C/A
			±10.23	1565.19	1585.65		-161.5	L1P(Y)
			±15	1560	1590		-158.0	M Code
	L2	1227.60	±10.23	1217.37	1237.83	24.4	-160.0 (Block II F)	L2P(Y)
			±1.023	1226.577	1228.623		-161.5 (Block II F)	L2C
			±15	1212	1242		-164.0	M Code
	L5	1176.45	±10.23	1166.22	1186.68	25.5	-157.9 (Block II F)	L5I/Q
QZSS	L1	1575.42	±2	1573.42	1577.42	19.0	-163.0(D) / -158.25(P)	L1C D/P
			±1.023	1574.397	1576.443		-158.5	L1C/A
	L6	1278.75	±21.0	1257.75	1299.75	23.4	-156.82	Block II
	L2	1227.60	±1.023	1226.577	1228.623	24.4	-158.5	L2C
	L5	1176.45	±10.23	1166.22	1186.68	25.5	-157	I/Q
GALILEO	E1	1575.42	±12.276	1563.144	1587.696	19.0	-157.25	D/P
	E5a	1176.45	±10.23	1166.22	1186.68	25.5	-155.25	D/P
	E5(altBOC)	1191.795	±25.575	1166.22	1217.37	25.2	-155.25	AltBOC
	E5b	1207.14	±10.23	1196.91	1217.37	24.8	-155.25	D/P
	E6	1278.75	±20.46	1258.29	1299.21	23.4	-155.25	D/P
GLONASS	G1	N/A		1598.0625	1605.37	~18.7	-161.0	FDMA
			±0.5					CA
			±5.0					P
	G1a CDMA	1600.995	±5.0	1595.995	1605.995	18.7	-158.5	L1SC
			±1	1599.995	1601.995			L1OC-D
			±2	1598.995	1602.995			L1OC-P
	G2	N/A		1242.9375	1248.625	~24.0	-167	FDMA
			±0.5					CA
			±5.0					P
	G2a CDMA	1248.06	±7.0	1241.06	1255.06	24.0	-158.5	L2SC
			±1	1247.06	1249.06			L2OC-D
			±2	1246.06	1250.06			L2OC-P
	G3 CDMA	1202.025	±10.23	1191.795	1212.255	24.9	-158.5	L3OC-D / L3OC-P
BEIDOU	B1I	1561.098	±2.046	1559.052	1563.144	19.2	-163	BeiDou(II) OS
	B1	1575.42	±16.368	1559.052	1591.788	19.0	-159(MEO) / -161(IGSO)	BeiDou (III) / B1A-D / B1A-P
	B2a	1176.45	±10.23	1166.22	1186.68	25.5	-163	BeiDou (III) I/Q
	B2/B2b	1207.14	±10.0	1197	1217	24.8	-163	BeiDou (III) Not Published
	B3I	1268.52	±10.23	1258.29	1278.75	23.6	-163	B3C-D / B3C-P
IRNSS/NAVIC	L5	1176.45	±12.0	1164.45	1188.45	25.5	-159.0	SPS
	S	2492.028	±16.0	2476.03	2508.3	12.0	-162.3	SPS
WAAS/EGNOS	L1	1575.42	±1.023	1574.397	1576.443	19.0	-158.5 / -152.5 (Future)	C/A
	L5	1176.45	±10.23	1166.22	1186.68	25.5		L5 I/Q
L-BAND CORRECTIONS	L			1539	1559			
IRIDIUM				1616	1626.5			RHCP
				1621.35	1626.5			Up Load
GLOBALSTAR	L-Band			1610	1618.75			LHCP
	C-Band			6875	7055			
INMARSAT	L-Band			1525	1559			Downlink
				1626.5	1660.5			Uplink
	Extended			1518	1559			Alphasat
				1668	1675			
LIGHTSQUARED/LIGADO				1526	1536			Limits power to 10 W
LTE JAPAN	Band 11			1475.9	1500.9			Down Link
	Band 21			1495.9	1510.9			Down Link
LTE EUROPE	Band 32			1452	1496			Down Link

** Power is received with a 0dB gain antenr*

Table 1: GNSS Constellations and Frequencies - Detailed (Calian, 2025)

As shown in **Figure 3** and Table 1, GNSS signals, apart from NaVIC (Navigation with Indian Constellation), which has an S band component, are exclusively in the L-band. Frequencies above 2 GHz necessitate the use of directional beam antennas for signal reception, which are a more complex design, although mitigated with modern phased array systems, increasing overall system complexity.

Code Division Multiple Access (CDMA) based GNSS (Teunissen & Montenbruck, 2017) uses Pseudorandom Noise (PRN) codes, which are unique sequences of binary signals used to identify and synchronise with specific satellites. The selected frequency should be in a range that is minimally impacted by weather conditions such as rain, snow, or clouds, as well as the ionospheric delays, which are significant at frequencies below 1 GHz.

This makes L-Band a very good frequency band for satellite navigation systems.

3. EXISTING SPACE BASED PNT SERVICES

3.1. GLOBAL POSITIONING SYSTEM (GPS)

The Global Positioning System is a U.S. government-owned satellite constellation that provides precise positioning, navigation, and timing (PNT) services globally. It operates in Medium Earth Orbit (MEO) and consists of over 30 satellites transmitting synchronised signals that allow GPS receivers to calculate their position by trilateration of distances from multiple satellites (US. Government, 2025).

GPS plays a critical role in everyday applications, such as navigation in smartphones and vehicles, as well as in military[2] operations and scientific research. The signals carry precise timestamps generated by onboard atomic clocks, allowing users to compute time within nanosecond accuracy. This synchronisation is crucial for telecommunications, power grids, and financial networks (Parkinson & Spilker, 1996).

In addition to the Standard Positioning Service (US Department of Defense, 2020), GPS supports a military Precise Positioning Service (US Department of Defence, 2017). High-precision applications are supported through augmentation systems like WAAS and commercial RTK (real-time kinematic) corrections. Its long-standing reliability and global availability make GPS a backbone of the world's PNT infrastructure.

3.1.1. SYSTEM OVERVIEW

- Operator: U.S. Space Force
- Orbit Type: MEO (Medium Earth Orbit)
- Constellation: 31+ satellites in MEO (~20,200 km altitude), Figure 4.
- Signals & Frequencies: L1, L2, L5 (civil & military signals) (Frontier SI, 2024)
- Current Generations: GPS Block IIR, IIR-M, IIF, and III

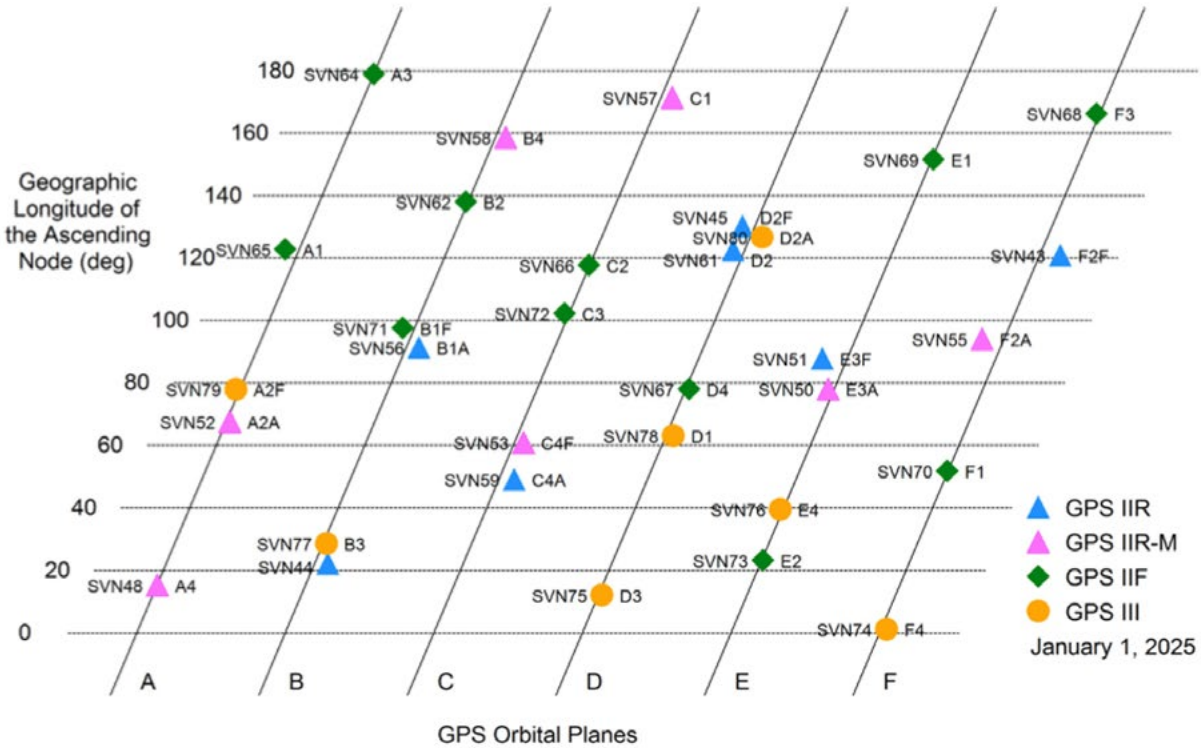


Figure 4: Current GPS Orbital Configuration, April 2025 (US Government Navigation Center, 2025; Government Office for Science, 2018; Government Office for Science, 2018)

2 Discussion of the military aspects of GPS is outside of the scope of this report.

3.1.2. PERFORMANCE METRICS

The metrics noted here are detailed in GPS information documents kept up-to-date by the US Government (US Department of Defense, 2020) (US Department of Defence, 2017).

Accuracy:

- Civilian: ~3–5 meters (standard positioning)
- Military[3]: Sub-meter accuracy
- Augmented[4]: Centimetre-level accuracy
- Availability & Reliability:
  - 24/7 global coverage
  - Satellite redundancy for fault tolerance
- Signal Strength & Integrity:
  - Power levels across different bands
  - Resistance to interference and signal disruptions

3.1.3. OPERATIONAL ARCHITECTURE

The GPS operated by the U.S. Space Force provides global, all-weather, 24/7 positioning, velocity, and timing services. Its operational architecture is organised into three primary segments: the Space Segment, the Control Segment, and the User Segment.

These segments work in tandem to ensure accurate and reliable PNT services for civilian, commercial, and military applications.

3.1.3.1. SPACE SEGMENT

The Space Segment comprises a constellation of satellites that transmit signals used for PNT calculations. As of 2023, GPS operates with a baseline of 24 satellites, typically expanded to 31 operational satellites to enhance coverage and redundancy (US Space Force, 2023). These satellites are positioned in Medium Earth Orbit at approximately 20,200 km, arranged in six orbital planes inclined at 55 degrees, with each satellite completing an orbit every 11 hours and 58 minutes (Kaplan & Hegaty, 2017).

The satellites transmit pseudorandom noise (PRN) codes, including the Coarse/Acquisition (C/A) code for civilian use and the Precise (P) code for military applications, along with a navigation message containing satellite ephemeris, clock corrections, and almanac data. Directional antennas ensure signal transmission to Earth, covering wide geographic areas. The Space Segment's design ensures that at least four satellites are visible from any point on Earth at any time, enabling trilateration for position determination (Teunissen & Montenbruck, 2017).

3.1.4. CONTROL SEGMENT

The primary operations Master Control Station (MCS) is located at centre at Schriever Space Force Base, Colorado (US Space Force, 2021). This processes data from monitoring stations to compute satellite clock corrections, ephemeris updates, and system health status. It generates navigation messages uploaded to satellites. An Alternate Master Control Station (AMCS) located at Vandenberg Space Force Base, California, serves as a backup to ensure continuity of operations.

A global network of 16 monitoring stations (six operated by the Space Force and ten by the National Geospatial-Intelligence Agency), Figure 5, tracks satellite signals to assess orbit accuracy, clock performance, and signal integrity. Four dedicated uplink antennas at Cape Canaveral, Ascension Island, Diego Garcia, and Kwajalein transmit commands and updated navigation data to satellites.

The Control Segment ensures that satellite signals remain accurate, correcting for clock drift, orbital perturbations, and environmental factors like ionospheric delays. The Next Generation Operational Control System (OCX), currently in development, aims to enhance cybersecurity and support modernised signals (U.S. Government Accountability Office, 2022).

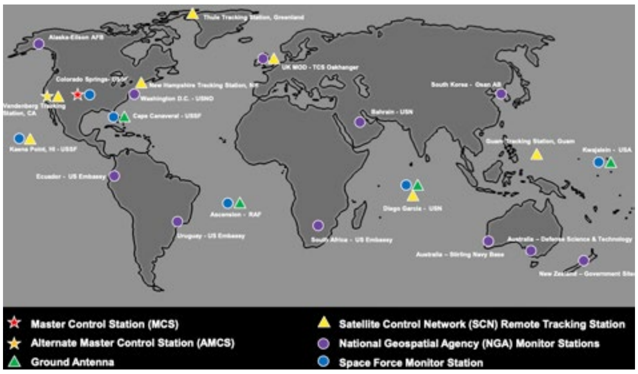


Figure 5: GPS Ground Architecture Locations (Wray, 2023)

3.1.4.1. USER SEGMENT

Estimating the exact number of GPS receivers worldwide is challenging due to their integration into diverse devices (e.g., smartphones, vehicles, IoT devices) and the lack of comprehensive global tracking. However, recent market analyses and historical estimates provide insight into their proliferation.

As of 2021, the European Union Agency for the Space Programme (EUSPA) estimated that over 8 billion Global Navigation Satellite System (GNSS) devices, which include GPS receivers, were in use globally, with projections to exceed 10 billion by 2030. This figure encompasses GPS-enabled smartphones, automotive navigation systems, wearables, and specialized receivers for industries like agriculture, aviation,

3 Precise Positioning Service or PPS

4 For example, SBAS (NLA International, 2025) (US Department of Transportation, 2008) and RTK.

and surveying. The consumer devices segment, particularly smartphones, dominates, accounting for approximately 46% of the GPS market share in 2023 (European Agency for Space Programmes, 2024).

Thus, a reasonable estimate as of 2025 is that approximately 8–10 billion GPS receivers exist worldwide, with the majority being embedded in smartphones and vehicles. This aligns with the rapid growth of the GPS market, valued at USD 109.42 billion in 2024 and projected to reach USD 472.16 billion by 2034 (Straits Research., 2025).

3.1.4.2. INTERSEGMENT INTERACTIONS

The GPS operational architecture relies on seamless interactions among the segments. The Space Segment broadcasts signals containing precise time and orbital data. The Control Segment monitors these signals, updates satellite parameters, and uplinks corrections to maintain accuracy. The User Segment receives and processes signals to deliver PNT services, often leveraging Control Segment data for enhanced precision.

3.1.5. KEY DOCUMENTS

- GPS Standard Positioning Service Performance Standard (5th Edition) (US Department of Defense, 2020)
- GPS Wide Area Augmentation System (WAAS) Performance Standard (1st edition) (US Department of Transportation, 2008)
- GPS Precise Positioning Service Performance Standard (US Department of Defence, 2017)
- GPS Civil Monitoring Performance Specification (3rd edition) (US Space Force, 2021)

3.2. GLOBALNAYA NAVIGATSIONNAYA SPUTNIKOVAYA SISTEMA (GLONASS)

GLONASS is Russia's counterpart to GPS, operated by the Russian Space Forces. Like GPS, it offers global PNT services and consists of satellites in MEO. The system provides an alternative and often complementary source of positioning and timing data which enhances resilience and redundancy for users worldwide (Kaplan & Hegaty, 2017).

GLONASS primarily uses slightly different signal structures and frequency allocations compared to GPS, which can help improve accuracy when used together with other GNSS systems. It is particularly important for ensuring operational independence and security in Russia and neighbouring regions (Teunissen & Montenbruck, 2017).

Timing from GLONASS is derived from Russian time standards, and while its clock precision is comparable to GPS, minor differences in signal timing can influence multi-GNSS integration. It plays a vital role in ensuring robust time synchronisation in Eastern Europe and Central Asia.

3.2.1. SYSTEM OVERVIEW

- Operator: Russian Federation
- Orbit Type: MEO (Medium Earth Orbit) (European Space Agency, 2011)
- Constellation: 24 satellites in MEO (~19,100 km) (Figure 6)
- Signals & Frequencies: L1 (1602 Mhz), L2 (1246 MHz), and L3 bands (1201 MHz)
- Current Generations: 2nd generation (GLONASS-M), 3rd generation (GLONASS-K), advanced generation (GLONASS-K2) (Karutin, n.d.)

GLONASS constellation status at 16.04.2025

Total satellites in constellation	27
In operation	24
In commissioning phase	0
In maintenance	0
Under check by the Satellite Prime Contractor	0
Spares	3
In flight tests phase	0

Figure 6: GLONASS Constellation status, April 2025 (Space Agency of Russia, 2025)

The following availability map, Figure 7, for GLONASS indicates that the system is capable and provides good availability. This shows integral availability of the GLONASS navigation (Position Dilution of Precision (PDOP)=6) during the 24 hours period (masking angle =5 degrees) on 23 January 2012.

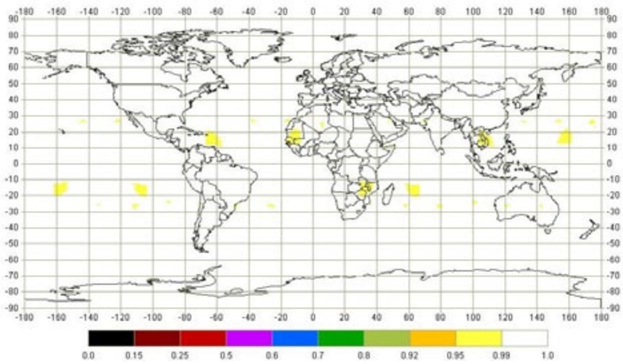


Figure 7: GLONASS Availability Map, (European Space Agency, 2011)

3.2.2. PERFORMANCE METRICS

- Accuracy: (European Space Agency, 2011)
  - Horizontal accuracy of 5-10 m
  - Vertical accuracy of 15 m
- Availability & Reliability: (European Space Agency, 2011)
  - The ground segment is limited to Russian territory
- Signal Strength & Integrity: Signal strength varies based on location, satellite geometry, and environmental factors like urban canyons or dense foliage, but typically offers comparable performance to GPS, with signal power levels around -160 dBW at the receiver.
- GLONASS operates using Frequency Division Multiple Access (FDMA) for civilian signals and Code Division Multiple Access (CDMA) for newer, high-precision signals. Signal integrity is maintained through robust anti-jamming measures and error correction protocols, though it can be affected by ionospheric disturbances or multipath errors. The system's accuracy is enhanced by ground-based control stations and continuous modernisation, achieving 5-10 metre accuracy for civilian users, with integrity monitoring ensuring reliability for critical applications like aviation and maritime navigation (Parkinson & Spilker, 1996).

3.2.3. OPERATIONAL ARCHITECTURE

3.2.3.1. SPACE SEGMENT

The GLONASS space segment constellation is comprised of 24 satellites distributed over 3 orbital planes to provide continuous and worldwide PNT (European Space Agency, 2011).

3.2.3.2. CONTROL SEGMENT:

- The GLONASS control/ground segment, responsible for satellite control, monitoring, and data processing, is primarily located in Russia.
- The System Control Centre located in Krasnoznamensk, Moscow Oblast, oversees satellite operations and constellation management (Global Security.Org, n.d.) (European Space Agency, 2011).
- Ground Control Stations: Spread across Russia, with major stations in Shchelkovo (Moscow Oblast), Komsomolsk-on-Amur (Far East), Yeniseisk (Krasnoyarsk Krai), and Ussuriysk (Primorsky Krai). These stations handle telemetry, tracking, and command functions (Space Agency of Russia, 2025).
- Monitoring and Correction Stations are deployed nationwide, including sites in Moscow, St. Petersburg, Novosibirsk, and Khabarovsk, to collect data and improve signal accuracy.
- Laser Ranging and Time Synchronisation Stations: Facilities like those in Altay and Kaluga ensure precise orbit determination and timekeeping (Space Agency of Russia, 2025) (European Space Agency, 2011).
- Some additional monitoring stations exist outside Russia, such as in Belarus and Kazakhstan, through international agreements, but the core infrastructure is domestically based. Exact locations of all facilities are not always publicly disclosed due to strategic sensitivity.
- In summary:
  - 5 telemetry tracking and command centres (TT&C)
  - Central clock
  - 3 upload stations
- 2 satellite laser ranging stations (SLR)
- 4 monitoring and measuring stations (MS)

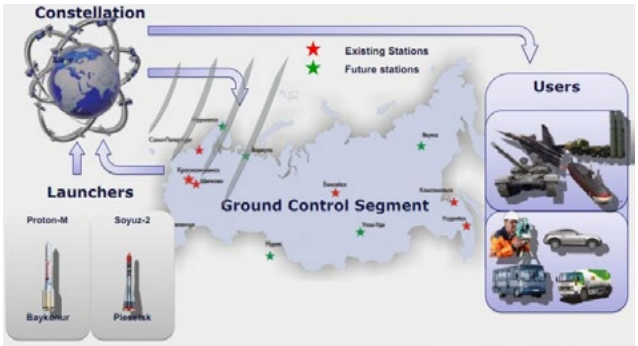


Figure 8: GLONASS Control Segment (European Space Agency, 2011)

3.2.3.3. USER SEGMENT

L-band radio receivers and processers take GLONASS signals, determine pseudoranges, and solve navigation equations for accurate coordinates and time (Korolov, 2020).

- Standard Positioning Service (SPS) – an open service that is free worldwide (Korolov, 2020)
- Precise Positioning Service (PPS) – a restricted signal to military and authorised users only.

3.2.3.4. DEPENDENCE ON RUSSIAN INFRASTRUCTURE:

As a system controlled by the Russian government, GLONASS is subject to potential political or funding-related disruptions. Historical underfunding in the

1990s led to a degraded constellation (down to 7 satellites by 2002), and users remain cautious about reliance on a single nation's infrastructure, especially in geopolitically sensitive contexts. The GLONASS ground control segment is primarily located in Russia, with limited international stations (e.g., in Belarus and Kazakhstan). This restricts real-time orbit and clock corrections compared to GPS or Galileo, which have more globally distributed ground networks. A more global ground segment is needed to enhance reliability and accuracy for users worldwide.

3.2.4. KEY DOCUMENTS

Key documents are not publicly available apart from the performance standard below.

- Global Navigation Satellite System GLONASS - Open Service Performance Standard (Edition 2.2) (Korolov, 2020)

3.3. GALILEO

Galileo is the European Union's global satellite navigation system. Managed by the European Space Agency (ESA), it is designed for civilian use and provides high-accuracy PNT data, independent from U.S. or Russian systems. Galileo also operates in MEO and supports interoperability with GPS and GLONASS (Teunissen & Montenbruck, 2017).

Galileo differentiates itself with its ability to deliver encrypted services for government, through the Public Regulated Service (PRS) and commercial applications through its High Accuracy Service (HAS), Commercial Authentication Service and Open Service Navigation Message Authentication (OSNMA). It also provides enhanced distress localisation and call features for the provision of a Search and Rescue (SAR) service, interoperable with the Cospas-Sarsat system (European Union Agency for Space Programmes (EUSPA), 2023). Galileo also provides Integrity Support Messages (ISMs), which are broadcast through the Galileo E1-B signal component.

The timing capabilities of Galileo are supported by high-stability atomic clocks onboard each satellite and a timing system on the ground. It also provides time dissemination services synchronised to European time standards, aiding in the diversification of time sources globally.

3.3.1. SYSTEM OVERVIEW

- Operator: European Union Agency for the Space Programme (EUSPA) (Teunissen & Montenbruck, 2017)
- Orbit Type: MEO (Medium Earth Orbit)
- Constellation: 28 satellites in MEO (~23,200 km) (Parkinson & Spilker, 1996) (European GNSS Service Centre, 2025)
- Signals & Frequencies: E1 (1575.42 MHz), E5a and E5b (1176.45 and 1207.14 MHz), E6 (1278.75Mhz) (European GNSS Service Centre, 2025) (Kaplan & Hegaty, 2017) (Teunissen & Montenbruck, 2017)
- Current Generations: 1st generation with 28 satellites in orbit, 2nd generation in developmental stage due for first launches in 2026

3.3.2. PERFORMANCE METRICS

- Accuracy: (EUSPA, 2024)
  - Signal in space accuracy: <2 m
  - Positioning Accuracy <5 m (global average horizontal single & dual frequency), <8 m vertical
- Availability & Reliability: (EUSPA, 2024)
  - Signal Availability: >92%
  - Good coverage up to 75° North
  - Service availability: 99.5%

3.3.3. OPERATIONAL ARCHITECTURE

3.3.3.1. SPACE SEGMENT

The Galileo space segment is defined as a 24/3/1 Walker constellation: 24 nominal (active) Medium Earth Orbit (MEO) satellites are arranged in 3 orbital planes, with their ascending nodes uniformly distributed at intervals of 120 degrees, inclined at 56 degrees with respect to the equator (Teunissen & Montenbruck, 2017) (European GNSS Service Centre, 2025). The constellation is complemented by Galileo 6 auxiliary satellites—which occupy orbital slots that are not part of the baseline constellation and are not defined a priori. These constitute a constellation of 30 satellites to provide global coverage. The frequency plan is different from other GNSS systems in that it transmits on three frequencies and the E5 band is split into two components which can be combined for a large bandwidth signal (Figure 9) (European Union Agency for Space Programmes (EUSPA), 2023).

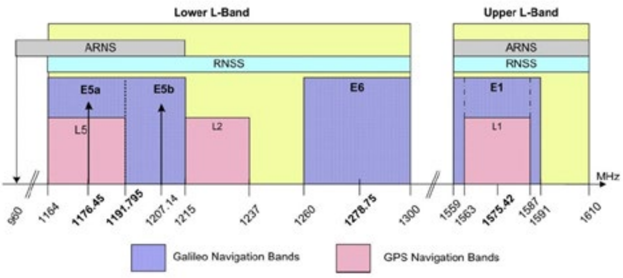


Figure 9: Galileo Frequency Plan (European Union Agency for Space Programmes (EUSPA), 2023)

3.3.3.2. CONTROL/GROUND SEGMENT (EUROPEAN GNSS SERVICE CENTRE, 2025) (KAPLAN & HEGATY, 2017) (PARKINSON & SPILKER, 1996)

The Galileo ground segment consists of two Galileo Control Centres (GCC) situated in Oberpfaffenhofen (Germany) and Fucino (Italy). Each GCC manages 'control' functions supported by a Ground Control Segment (GCS) and 'mission' functions, supported by a dedicated Ground Mission Segment (GMS).

The GCS handles spacecraft housekeeping and constellation maintenance by means of the network of TT&Cs stations globally distributed. The scope includes "control and monitoring of the satellites and payload, planning and automation functions that allow safe and correct operations to take place, and the support of payload related operations" (European GNSS Service Centre, 2025).

The GMS determines the "navigation and timing data part of the navigation messages by means of the network of Galileo Sensor Stations (GSS)" (European GNSS Service Centre, 2025). The GMS communicates with the Galileo satellites through a network of Uplink Stations (ULSs). The GMS and GCS interface the satellites with a worldwide network of ground stations, implementing monitoring and control functions (European GNSS Service Centre, 2025):

- Galileo Sensor Stations (GSS) collects and forwards Galileo SIS measurements and data to the GCCs in real time.
- Galileo Uplink Stations (ULS) distributes and uplinks the mission data to the Galileo constellation.
- Telemetry, Tracking & Control stations (TT&C) collects and forwards telemetry data generated by the Galileo satellites and distributes and uplinks the control commands required to maintain the Galileo satellites and constellation.

Figure 10: Galileo Ground Segment (European GNSS Service Centre, 2025)

3.3.3.3. USER SEGMENT

Like GPS, estimating the exact number of Galileo receivers worldwide is challenging due to their integration into diverse devices (e.g., smartphones, vehicles, IoT devices) and the lack of comprehensive global tracking. However, recent market analyses and historical estimates provide insight into their proliferation.

As of 2021, the European Union Agency for the Space Programme (EUSPA) estimated that over 8 billion GNSS devices, which include GPS receivers, were in use globally, with projections to exceed 10 billion by 2030. This figure encompasses GPS-enabled smartphones, automotive navigation systems, wearables, and specialized receivers for industries like agriculture, aviation, and surveying. The consumer devices segment—particularly smartphones—dominates, accounting for approximately 46% of the GPS market share in 2023 (European Agency for Space Programmes, 2024).

Since Galileo receivers are generally integrated with GPS receivers (Teunissen & Montenbruck, 2017), it can be assumed, likewise, that there are approximately 8–10 billion Galileo receivers worldwide, with the majority being embedded in smartphones and vehicles.

From a security standpoint, PRS receivers are just starting to become available (Leonardo, 2021) (Fraunhofer Institute for Integrated Circuits IIS, n.d.) (GMV, n.d.).

3.3.4. KEY DOCUMENTS

- Galileo Open Service Service Definition Document (SDD) (EUSPA)
- Galileo Open Service Interface Control Document (European Union Agency for Space Programmes (EUSPA), 2023)
- Galileo High Accuracy Service (HAS) Interface Control Document (EUSPA, 2022)
- Galileo Open Service Navigation Message Authentication Interface Control Document (EUSPA, 2024)
- European GNSS (Galileo) Initial Services - Open Service: Quarterly Performance Report (EUSPA, 2024)

3.4. BEIDOU

BeiDou is China's global navigation satellite system. Initially a regional system, it delivers worldwide PNT services with a mix of MEO, geostationary, and inclined geosynchronous orbit satellites. BeiDou is notable for providing two-way communication capabilities in addition to conventional navigation services (China Satellite Navigation Office, 2020) (China Satellite Navigation Office, 2019).

The system supports various applications such as transportation, agriculture, disaster relief, and public security. BeiDou provides high-accuracy positioning through its PPP (Precise Point Positioning) service and offers strong regional performance in Asia-Pacific. The navigation system is operated by the China National Space Administration (CNSA) (China National Space Administration, n.d.), which is a governmental agency of the People's Republic of China. CNSA is headquartered in Haidian, Beijing, and is entrusted with the responsibility of overseeing civil space administration and international space cooperation.

BeiDou also supports timing synchronisation, providing nanosecond-level accuracy in some implementations. It contributes to the growing diversity and robustness of global PNT infrastructure, reducing dependency on legacy systems (China Satellite Navigation Office, 2019).

3.4.1. SYSTEM OVERVIEW

- Operator: China National Space Administration (CNSA)
- Orbit Type: MEO, GEO, and Inclined Geosynchronous Orbit (IGSO) (China Satellite Navigation Office, 2020)
- Constellation: 35 satellites (China Satellite Navigation Office, 2019)
- Signals & Frequencies: B1I (1561.09 MHz), B1C (1575.42 MHz), B2a (1176.45 MHz), B3 (1268.520 MHz) (China Satellite Navigation Office, 2020)
- BeiDou services are shown in Figure 11.

Service Types		Signal(s)/Band(s)	Broadcast Satellites
Worldwide	Positioning, Navigation and Timing (RNSS)	B1I, B3I	3GEO+3IGSO+24MEO
		B1C, B2a, B2b	3IGSO+24MEO
	Global Short Message Communication (GSMC)	Uplink: L Downlink: GSMC-B2b	Uplink: 14MEO Downlink: 3IGSO+24MEO
	International Search And Rescure (SAR)	Uplink: UHF Downlink: SAR-B2b	Uplink: 6MEO Downlink: 3IGSO+24MEO
China and Surrounding Areas	Satellite-based Augmentation System (SBAS)	BDSBAS-B1C, BDSBAS-B2a	3GEO
	Ground Augmentation System (GAS)	2G, 3G, 4G, 5G	Mobile communication networks, Internet
	Precise Point Positioning (PPP)	PPP-B2b	3GEO
	Regional Short Message Communication (RSMC)	Uplink: L Downlink: S	3GEO
Note: China and surrounding areas means 75°E to 135 °E, 10°N to 55°N			

Figure 11: BeiDou Services (China Satellite Navigation Office, 2019)

3.4.2. PERFORMANCE METRICS

(China Satellite Navigation Office, 2019) sets out the performance of BeiDou well. This is shown in Figure 12 for the same parameters as the other systems in this report, but (China Satellite Navigation Office, 2019) sets out in detail the performance for all of BeiDou services. Additional information can also be found at (Wang., 2021).

Performance Characteristics		Performance Indicators
Service Accuracy (95%)	Positioning Accuracy	Horizontal≤10m, Vertical≤10m
	Timing Accuracy	≤20ns
	Velocity Measurement Accuracy	≤0.2m/s
Service Availability		≥99%

Figure 12: BeiDou performance (China Satellite Navigation Office, 2019)

For GEO positioning and augmentation performance, refer to (NLA International, 2025).

3.4.3. OPERATIONAL ARCHITECTURE

Figure 13 gives a graphical overview of the BeiDou operational system architecture.

Figure 13: BeiDou overview (China Satellite Navigation Office, 2021)

3.4.3.1. SPACE SEGMENT

The nominal space constellation of BDS-3 consists of 3 Geostationary Earth Orbit (GEO) satellites, 3 IGSO satellites, and 24 MEO satellites. Spare satellites may be deployed in orbit. The GEO satellites operate in orbit at an altitude of 35,786 km and are located at 80°E, 110.5°E, and 140°E, respectively. The IGSO satellites operate in orbit at an altitude of 35,786 km and an inclination of the orbital planes of 55 degrees with reference to the equatorial plane. The MEO satellites operate in orbit at an altitude of 21,528 km and an inclination of the orbital planes of 55 degrees with reference to the equatorial plane (China Satellite Navigation Office, 2020).

3.4.3.2. CONTROL/GROUND SEGMENT

The BeiDou ground segment consists of:

- Master Control Station (MCS) responsible for satellite constellation control and processing the measurements received by the Monitor Stations to generate the navigation message.
- Upload Stations responsible for uploading the orbital corrections and the navigation message to BeiDou satellites
- Monitor Stations, which collect BeiDou data for all the satellites in view from their locations.

Currently, the Ground Segment includes one Master Control Station, two Upload Stations and 30 Monitor Stations.

3.4.3.3. USER SEGMENT

Estimating the number of BeiDou receivers in use worldwide is challenging due to limited comprehensive and up-to-date data, as most sources provide only partial or dated figures. The latest available data indicate that the number of BeiDou receivers in use globally is likely in the range of several hundred million to possibly over a billion, driven by widespread adoption in China and growing use in other regions. This is derived from:

- Reported user base: A 2020 source from China's state media claimed BeiDou had 500 million subscribers for its high-precision positioning services, suggesting a significant number of receivers, particularly in China (InsideGNSS, 2020).
- Integration in Devices: By 2019, BeiDou receivers were reported to be integrated into over 400 million users' devices worldwide, including millions of taxis, buses, and trucks.
- Market Growth: A 2019 estimate from the European Global Navigation Satellite Systems Agency projected that the global GNSS receiver market (including BeiDou, GPS, Galileo, etc.) will reach 8 billion receivers by 2020. Given BeiDou's dominance in China and increasing adoption in 165 countries (as reported in 2020), it likely accounts for a substantial portion of this market, potentially hundreds of millions of receivers. (European Agency for Space Programmes, 2024)
- Smartphone Penetration: Modern smartphones, especially those from Chinese manufacturers like Huawei, increasingly incorporate BeiDou chips. For example, Huawei's Mate 50, launched in 2022, uses BeiDou for enhanced positioning. With millions of such devices sold globally, this furthermore boosts receiver numbers (International Defence Security and Technology, 2023).

Key Points Supporting the Estimate:

- China's Dominance: China, with its population of over 1.4 billion and mandatory BeiDou integration in many sectors (e.g., transportation, fisheries), accounts for most receivers. For instance, millions of vehicles and fishing vessels use BeiDou for navigation and messaging services (International Defence Security and Technology, 2023).
- Global Reach: BeiDou products have been exported to over 120 countries, with significant adoption in Africa, Southeast Asia, and along China's Belt and Road Initiative countries, where Chinese-subsidized equipment promotes BeiDou use (InsideGNSS, 2020).
- Two-Way Communication: Unlike GPS, BeiDou's two-way messaging capability requires specialised receivers for certain applications (e.g., military, maritime), but most mass-market devices (e.g., smartphones) use receive-only chips, which are widely distributed (GPS World, 2020).

For more precise estimates, further research into manufacturer data would be needed, but such data is not publicly available in the provided sources.

3.4.4. KEY DOCUMENTS

- BeiDou Navigation Satellite System Signal in Space – Interface Control Document (China Satellite Navigation Office, 2020)
- BeiDou Navigation Satellite System Open Service Performance Standard (China Satellite Navigation Office, 2018)

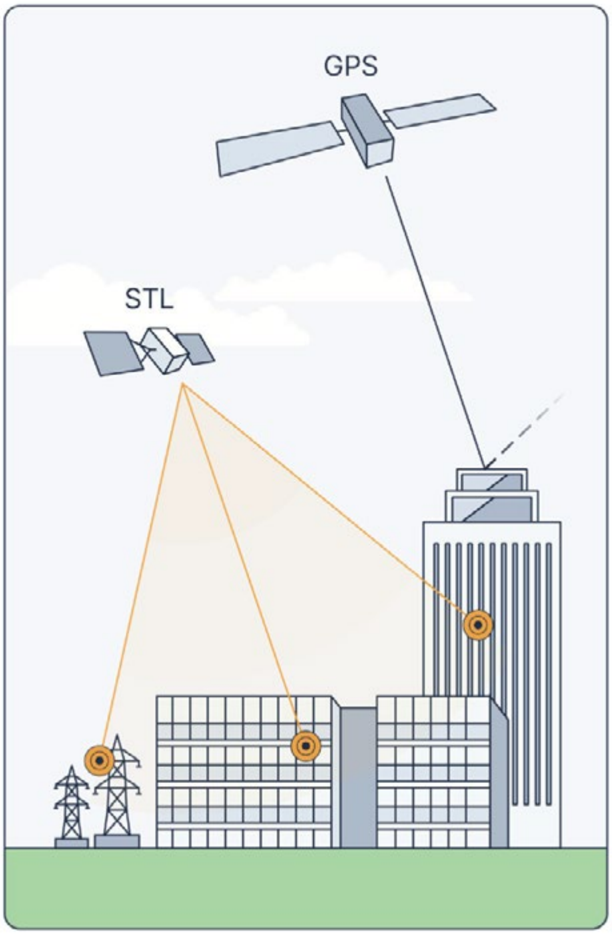
3.5. IRIDIUM SATELLITE TIMING AND LOCATION (STL)

Iridium STL is a commercial alternative PNT system that operates on the Iridium communications satellite network in LEO. Unlike GNSS, STL is designed specifically to resist interference and jamming, offering encrypted, high-integrity positioning and timing (Iridium, 2024) (InsideGNSS, 2019).

The STL signal is much stronger (30 dB stronger or about 1000 times GNSS (Iridium, 2024)) and more resilient than traditional GNSS, making it suitable for indoor or underground use where GPS might be inaccessible (Figure 14). It supports timing to sub-microsecond accuracy and can operate as a backup or augmentation layer for mission-critical timing infrastructure (Iridium, 2024). An STL receiver can detect if a GNSS receiver is affected by interference (or degraded due to environmental conditions) and can continue to deliver PNT data by transitioning to STL (Iridium, 2024).

STL is used by financial institutions and telecom operators to maintain timing continuity in case of GNSS disruption. It demonstrates the growing trend toward complementary PNT systems, which ensure resilience in a contested or congested space environment.

Since it is a stronger signal, compared to GPS/GNSS, STL is less susceptible to denial attack and can be more reliable when facing threats from manipulation. STL makes use of the complex and overlapping beam patterns of Iridium satellite signals and incorporates cryptographic techniques in ways that make it very difficult to manipulate, providing further layers of protection (O'Connor, 2025).



NOTE: Image depicts indoor reception of Iridium STL compared to GPS. Orbital altitudes not to scale.

Figure 14: Iridium STL Overview (Iridium, 2024)

3.5.1. SYSTEM OVERVIEW

- Operator: Iridium Communications Inc. (Iridium, 2024)
- Orbit Type: LEO (Satelles, 2025)
- Constellation: 66 Iridium Next spacecraft (Figure 15) (Satelles, 2025)
- Signals & Frequencies: L-band (1621-1626 MHz) [33,67]

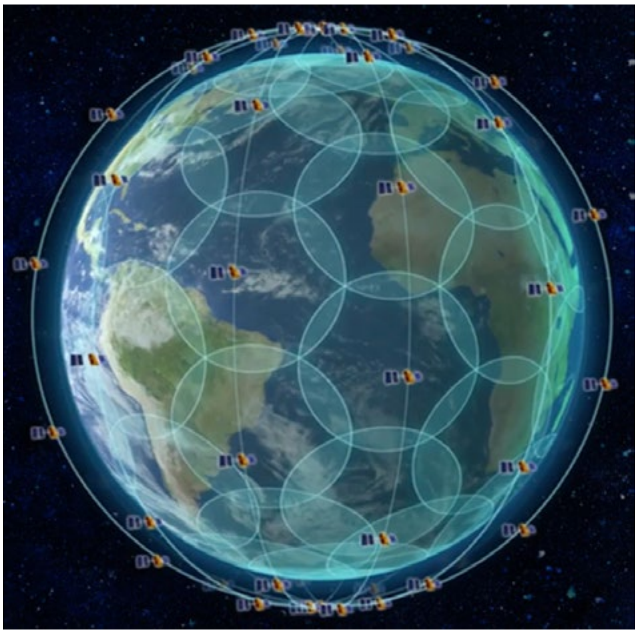


Figure 15: Iridium Constellation (Satelles, 2025)

3.5.2. PERFORMANCE METRICS (IRIDIUM, 2024) (O'CONNOR, 2025)

- Accuracy:
- Horizontal accuracy: 10 m 1 sigma static
- Vertical accuracy: 10 m 1 sigma static
- Sub-microsecond and sub-hundred-nanosecond precise timing
- Timing accuracy and stability: <9 ns of UTC after 69 days
- Availability & Reliability: global availability 24x7
- Signal Strength & Integrity: 30 dB and uses internal commercial encryption

Note that (Frontier SI, 2024) presents accuracy numbers that are not as idealised as (Iridium, 2024), which may indicate that the system still has some way to go.

3.6. PARSONS/GLOBALSTAR

The Globalstar satellite communication system, a Low Earth Orbit (LEO) constellation, is primarily designed for voice, data, and tracking services but has emerging applications in Position, Navigation, and Timing (PNT) services, leveraging its signal characteristics and global coverage and via a partnership with Echo Ridge, now Parsons (Parsons Corporation, 2025).

Globalstar operates a constellation of 32 second-generation LEO satellites at an altitude of approximately 1,414 km, distributed across eight orbital planes with four satellites per plane, utilising Wideband Code Division Multiple Access (WCDMA) technology with Quadrature Phase Shift Keying (QPSK) modulation for its communication signals.

For PNT purposes, Globalstar's forward link (downlink) in the S-band (2,483.5–2,500 MHz) is particularly relevant, as it carries a pilot signal that can be exploited for Doppler-based positioning (Globalstar Inc, 2025) (He, 2025).

Echo Ridge, now Parsons have a patent for satellite Signal of Opportunity (SoOP) to determine the location of a receiver based on each received SoOP using time-of-arrival based techniques (Joseph P Kennedy, 2022) (Justia, 2019). This "Assured Positioning System" (APS) provides positioning, navigation and timing information in environments where GPS or other GNSS is unavailable or unreliable. APS derives location information from ordinary communications signals transmitted from Globalstar satellites (Parsons, 2025).

The APS system is aimed at Internet of Things (IOT) and for mobile (dismounted) applications and combined the SoOP technology with IMU and barometric sensor inputs. In addition, APS is provided as a plug-in to the Android Team Awareness Kit (ATAK) residing on a user smartphone and claims to be Unaffected by GPS/GNSS jamming and spoofing (Parsons, 2025).

PNT in Globalstar relies on the use of Doppler shift measurements from its pilot signals. Studies have shown that Globalstar's pilot signal, when processed with techniques like square cross-harmonic decoding and parallel code phase frequency searches, can extract Doppler observations even under low signal-to-noise ratio (SNR) conditions. This enables positioning accuracy within tens of meters (Zhang Y. S., 2025) (He, 2025).

Globalstar/Parsons services are also used for asset tracking and Supervisory Control and Data Acquisition (SCADA) and can integrate GPS receivers in user terminals to transmit location data via satellite, enhancing PNT capabilities in remote areas.

3.7. PRECISE POINT POSITIONING OVER SATELLITE

Precise Point Positioning (PPP) (Precise Point Positioning and Its Challenges, Aided-GNSS and Signal Tracking, 2007) over satellite is a technique that involves broadcasting correction data from satellites to improve the accuracy of GNSS positioning in real time. Unlike differential GNSS, which requires ground-based infrastructure, PPP delivers wide-area corrections from space, making it more scalable and suitable for global applications (Novatel, 2025).

This approach allows GNSS users to achieve centimetre-level accuracy without the need for local base stations. It is particularly valuable for precision agriculture, construction, surveying, and autonomous systems where lane-level accuracy is essential (European Agency for Space Programmes, 2024) (EUSPA, 2025).

In terms of timing, PPP also improves the quality of time estimation by refining clock and ephemeris data, enabling more accurate synchronisation (Feiyu Mao, 2024) (Han, 2024). This is key for sectors like power distribution and financial services, where small timing errors can lead to significant disruptions (Government Office for Science, 2018).

3.7.1. SYSTEM OVERVIEW

There are many commercial providers of PPP correction services, some using GEO communication satellites (Figure 16) or LEO communication satellites, such as Starlink. This overview will provide generic information without detailing specific service provider architecture.

In general, GNSS corrections are generated from a global reference station network and delivered to the end user by satellite (or by internet or radio in some cases) to improve position accuracy (European Space Agency, 2011).

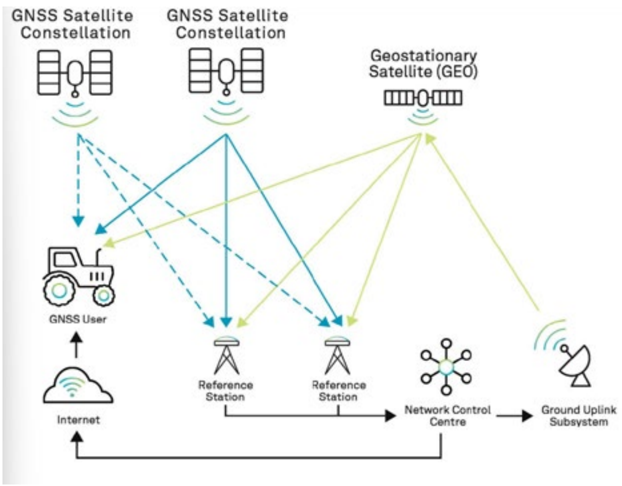


Figure 16: Generic PPP over satellite (Novatel, 2025)

A user receives signals from both the GNSS systems enabled in their equipment and the GEO (or LEO) satellites under the management of their PPP service provider. The user applies the corrections within the receiver to improve the position delivered. The service provider is responsible for the ground reference network, as well as the generation of the corrections and their delivery to the GEO spacecraft.

3.7.2. PERFORMANCE METRICS

This section will not detail the comparisons of commercial providers, since these constantly change and improve. The following should be noted:

- Accuracy: centimetre- to sub-centimetre-level precision (European Space Agency, 2011)
- Availability & Reliability: regional and global (European Space Agency, 2011)

3.7.3. FUTURE ENHANCEMENTS AND MODERNISATION (EUROPEAN SPACE AGENCY, 2011)

- Include more low-cost, multi-sensor integration with PPP augmentation
- Optimising navigation algorithms and user processing systems for mass-market applications
- Momentum in providing enhanced correction products (e.g., a public GNSS constellation-owner can provide PPP-like corrections/services)
- PPP to be used for safety-of-life applications (e.g., vehicle automation) (European Space Agency, 2011)

4. EMERGING SPACE BASED PNT SYSTEMS AND SERVICES

Several GEO and LEO services are proposed by various companies and agencies globally. These are briefly discussed in this section. For the LEO services, there is heavy reliance on the recent FrontierSI report, State of the Market Report - Low Earth Orbit PNT (Frontier SI, 2024), because it is a comprehensive round-up and market analysis. Therefore, it was not necessary to repeat this for Project SPARK.

4.1. STARLINK

Starlink, operated by SpaceX, is a global broadband internet satellite constellation in LEO. While its primary function is connectivity, research and trials have demonstrated that Starlink's signals can be repurposed to support PNT capabilities, especially in GPS-denied environments (Sharbel Kozhaya J. S., 2024) (Mohammad Neinavaie, 2021) (Sharbel Kozhaya J. S., 2025).

Unlike traditional GNSS systems that transmit specialised navigation signals, Starlink satellites broadcast high-rate communication signals. These signals, when tracked using advanced receivers, can be exploited to derive precise positioning through multilateration and time-of-arrival measurements (Mohammad Neinavaie, 2021) (Sharbel Kozhaya J. S., 2025).

Starlink's ultra-dense constellation (Figure 17) and low latency could make it valuable for resilient timing and navigation applications, particularly in military or urban settings where GNSS signals are weak or jammed. This could be transformative for navigation redundancy and next-generation positioning systems (Sharbel Kozhaya J. S., 2025).

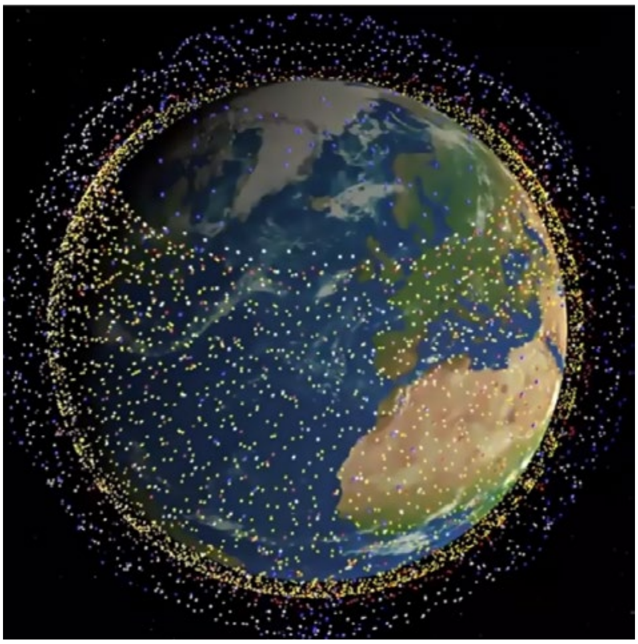


Figure 17: Starlink Constellation, from (Maloney, 2020)

4.1.1. SYSTEM OVERVIEW (STARLINK, N.D.)

- Operator: SpaceX
- Orbit Type: LEO
- Constellation: thousands of satellites (800-42,000), 'mega constellation'
- Signals & Frequencies: Ka, Ku, V
- The system parameters are shown in Figure 18.

Parameter	Value
Altitude [km]	540–570
Current number of satellites	6,219
Planned number of satellites	30,000
Downlink frequency [GHz]	10.7–12.7
Number of channels	8
Useful channel bandwidth [MHz]	240
Number of steerable spotbeams	48
Spotbeam radius [km]	[illegible] 10
Modulation	OFDM
Frame duration [ms]	4/3

Figure 18: Starlink system parameters (Sharbel Kozhaya J. S., 2025)

4.1.2. PERFORMANCE METRICS

The recent testing of the use of Starlink for positioning (Sharbel Kozhaya J. S., 2025) shows that metre positioning is possible using the communications signals (Figure 19). Moreover, a positioning solution with meter-level 3D position root-mean-squared error can be achieved in 10 seconds from just three satellites.

Framework	Data Set D1		Data Set D2	
	2D error [m]	3D error [m]	2D error [m]	3D error [m]
Pilot tones	1.32	10.40	–	–
OFDM (uncorrected)	47.62	52.01	43.80	86.74
OFDM (corrected on-the-fly)	7.50	12.27	5.31	16.54
OFDM (corrected from assumed base-station)	1.79	6.97	2.09	13.8

Figure 19: Starlink Performance (Sharbel Kozhaya J. S., 2025)

4.1.3. CHALLENGES AND LIMITATIONS

Using Starlink for PNT presents significant potential but also several challenges. These challenges stem from the fact that Starlink's primary function is broadband communication, not navigation, and its signal structure and operational design are not optimized for PNT. These constraints can also apply to other LEO PNT systems; therefore, a full discussion is provided.

- Signal Structure and Stability Issues
  - Starlink's frame timing is loosely disciplined to GPS time, with adjustments occurring every 15 seconds that maintain timing within a few milliseconds but allow drift exceeding 20 ppm. This drift, combined with episodic high frame jitter and discontinuities in frame timing, is incompatible with the precise timing required for accurate PNT, particularly pseudorange-based positioning (E. Grayver, 2024).
- Step-Like Corrections in Observables:
  - Before 2024, Starlink's Orthogonal Frequency Division Multiplexing (OFDM) signals exhibited step-like corrections in carrier phase, Doppler shift, and code phase, which contaminated navigation observables and made raw integration challenging for precise positioning. While these corrections diminished post-2024, the proprietary nature of Starlink's signals means such changes could recur, affecting reliability (Sharbel Kozhaya J. S., 2025).
- Complex Signal Processing:
  - Starlink's Ku-band signals (10.7–12.7 GHz) use OFDM, which requires sophisticated receiver architectures to extract navigation observables. The full OFDM beacon, only recently characterized, spans a wide time-frequency grid, but extracting it requires blind beacon estimation and high computational complexity, unlike the simpler signal structures of GNSS systems like GPS or BeiDou (Sharbel Kozhaya J. S., 2024) (Sharbel Kozhaya J. S., 2025).
- Receiver Design and Hardware Limitations:
  - High Bandwidth and Frequency Challenges: Starlink's downlink signals have bandwidths up to 240 MHz and operate in the Ku/Ka-bands, which exceed the capabilities of most commercial software-defined radios (SDRs). Receivers require additional downconverters and high-sampling-rate SDRs, increasing cost and complexity (Christina Pinell, 2023).
- Antenna Constraints:
  - Traditional parabolic antennas for Ku-band signals are impractical for mobile or small-vehicle navigation due to their size, weight, and directional gain, which limits simultaneous tracking of multiple satellites. Low-gain antennas improve feasibility but reduce signal-to-noise ratio (SNR), necessitating advanced signal processing to achieve reliable acquisition and tracking. Phased array antennas, while more suitable, are expensive and computationally intensive, limiting their use in consumer applications (Sharbel Kozhaya J. S., 2025).
- Lack of Standardised Receivers:
  - Unlike GNSS, which has well-established receiver standards, Starlink PNT requires custom receiver architectures, such as those using Extended Kalman Filters (EKF) or Maximum Likelihood Estimation (MLE) for Doppler-based positioning. Developing these for widespread use is a significant engineering challenge (Christina Pinell, 2023).
- Dependence on External Systems:
  - Starlink satellites calculate their own positions using GPS; therefore, Starlink-based PNT is indirectly dependent on GPS. If GPS signals are jammed or unavailable, Starlink's ability to provide accurate positioning could be compromised unless it uses alternative ephemeris sources (e.g., NORAD TLEs or commercial tracking), which are less precise and less frequently updated (Y Combinator: Technology Review, n.d.) (Harris, 2022).
- Lack of Onboard Atomic Clocks:
  - Unlike GNSS satellites, Starlink satellites do not carry precision atomic clocks, which are critical for accurate timing in navigation systems. This necessitates external clock corrections or on-orbit precision orbit determination (POD), adding complexity and potential points of failure (Wang B. , 2020).
- Environmental and Operational Constraints:
  - Low Orbit Altitude and High Doppler Effects: Starlink satellites operate in LEO at ~550 km, resulting in high satellite velocities and significant Doppler shifts (especially at 11.325 GHz). These high Doppler shifts and rates complicate signal acquisition and tracking, particularly for ground-based receivers. Additionally, the low altitude reduces satellite visibility duration, requiring frequent handoffs between satellites (Nabil Jardak, 2023).
- Interference and Jamming Vulnerability:
  - While Starlink's high signal power and Ku-band operation offer some anti-jam advantages over GNSS's L-band signals, the open-source nature of reverse-engineered Starlink signals makes them susceptible to spoofing. Adversaries could

generate fake signals if the synchronisation sequences become widely known (Harris, 2022).

- Tropospheric and Multipath Errors:
  - Starlink signals are subject to tropospheric-induced frequency errors and multipath effects in urban environments, which degrade positioning accuracy. These require compensation models or additional sensors, increasing system complexity (Nabil Jardak, 2023).
- Proprietary Nature and Lack of Cooperation:
  - Limited Access to Signal Information: SpaceX does not publicly disclose Starlink's signal structure, forcing researchers to reverse-engineer signals through eavesdropping and blind estimation. This lack of transparency hinders the development of standardized PNT solutions and increases the risk of obsolescence if SpaceX alters signal properties. It is entirely possible that SpaceX will investigate the provision of specific PNT functions (Harris, 2022).
- Scalability Limitations:
  - Scalability for Real-Time Use: Early experiments required 13 minutes to track six satellites sequentially, as simultaneous visibility of multiple satellites was limited. While Starlink's growing constellation (over 3,000 satellites) improves visibility, real-time positioning with sufficient accuracy remains a challenge without significant advancements in receiver technology and algorithms (Sharbel Kozhaya J. S., 2025).
- Cost and Resource Allocation:
  - System Resource Demands: Providing PNT services using Starlink requires allocating a portion of downlink capacity (estimated at ~1.6% for global coverage) and energy resources. While this is modest, it could impact broadband performance, and SpaceX may be reluctant to dedicate resources to a secondary function without financial incentives (E. Grayver, 2024).
  - High Development Costs: Developing PNT-capable receivers, antennas, and algorithms for Starlink signals involves significant research and engineering costs. These may be prohibitive for consumer applications, limiting adoption to specialized sectors like military or high-altitude platforms (Nabil Jardak, 2023).

The primary challenges of using Starlink for PNT include unstable signal timing, complex receiver requirements, dependence on GPS, environmental factors, proprietary barriers, limited accuracy, and resource costs. While experimental results demonstrate feasibility (e.g., 2-meter accuracy with Doppler-based methods), Starlink is not yet a viable replacement for GNSS, but continued research and third-party innovations could mitigate some issues.

4.2. ONEWEB

OneWeb is another LEO satellite internet provider with growing interest in PNT applications. It states that OneWeb's Gen2 satellites will offer full PNT capability as of 2026 (EutelSat OneWeb, 2021) (DatacenterDynamics, 2023). Similar to Starlink, its satellites were not originally designed for navigation but could be leveraged to provide positioning and timing support via opportunistic signal processing techniques (Zaher M. Kassas).

OneWeb's potential PNT utility lies in its global coverage and predictable satellite orbits. By tracking satellite signal phases and times of flight, researchers have demonstrated the feasibility of passive navigation using OneWeb's downlink signals, especially as part of hybrid positioning systems (Zaher M. Kassas).

In timing, OneWeb could provide alternative synchronisation paths for critical infrastructure. Its low-latency links could enable precision timing recovery in situations where GNSS is unavailable or degraded, enhancing the robustness of distributed systems like 5G networks or power grids (EutelSat OneWeb, 2021).

4.2.1. SYSTEM OVERVIEW

- Operator: Eutelsat OneWeb
- Orbit Type: LEO (~1,200km)
- Constellation: 630 satellites along 12 synchronised orbital planes, 'mega constellation' (Yoke T. Yoon, 2024)
- Signals & Frequencies: Ku (10.7-18.1 GHz) (Yoke T. Yoon, 2024)

Figure 20 shows the functional overview of how OneWeb Gen 1 services function for communications.

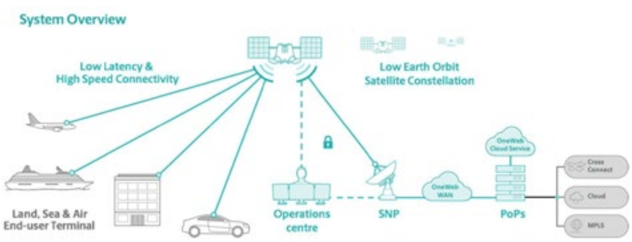


Figure 20: OneWeb Gen 1 system overview (Starcomm Solutions, n.d.)

4.2.2. CHALLENGES AND LIMITATIONS

Similar to the challenges outlined in 4.1.3, many of these challenges need to be overcome for OneWeb-based architecture. In addition:

Satellite Gen 1 design currently does not allow for miltary level encryption (Farragher, 2020)

Not optimised for positioning services (Zaher M. Kassas)

Components of the OneWeb platform and related ground infrastructure will need to be upgraded to produce high-quality positioning signals and military grade encryption (Farragher, 2020)

LEO satellites need to be replaced more often than MEO satellites.

4.3. GEELY

Geely, a prominent Chinese automotive company, is developing its own LEO satellite constellation to support high-precision PNT services. Though still in early deployment, the initiative aligns with the automotive industry's increasing need for precise positioning in connected and autonomous vehicles (Khalil, 2024).

Unlike traditional GNSS, Geely's system aims to provide a vertically integrated solution: from satellite infrastructure to in-vehicle receivers. By controlling the full stack, Geely seeks to reduce PNT dependency on external providers and enhance the reliability and latency of navigation data used in its vehicles.

Geely's constellation is expected to offer augmentation services, improving positioning accuracy via real-time kinematic (RTK) techniques or PPP (Precise Point Positioning). Timing synchronisation for vehicle-to-everything (V2X) communication is also a core application, ensuring consistent and safe coordination among intelligent transportation systems (Sony Semiconductor Solutions, 2023).

4.3.1. SYSTEM OVERVIEW

There is limited information available about the architecture of the Geely constellation, whether for communications or PNT. FrontierSI has compiled the known information (Frontier SI, 2024). See Figure 21.

General Information	
Country of Origin	China
System Ownership	Private
Services Provided	
Target Sectors	
Performance Targets	
System GNSS Independence	
Timescale Reference	
Service Area	Global
Operational/ Demonstration	Operational system
Constellation Details	
Orbital altitude	620km
Inclination	
Satellite class	Mini (100 kg)
Payload Type	
Constellation Type	Fused Communications and PNT Constellation
No of sats in orbit Dec 2024	
Initial Operational Capability	
Full Operational Capability	240
Signal Security Architecture	
Signal structure	
Signal Encryption	
Signal Authentication	
RF Characteristics	
Frequency Band	L-Band
Signal Names	
Signal Frequency	
ITU Approval Status	
Modulation Type	
Data Rate (bps)	
Chip Rate (Mcps)	
User Received power (dBW)	

Figure 21: Known information about Geely (Frontier SI, 2024)

4.4. XONA

Xona Space Systems is a startup that is developing Pulsar, a commercial PNT constellation in LEO. Unlike legacy GNSS, which operates in MEO, Xona's LEO-based model aims to deliver higher signal strength, lower latency, and centimetre-level positioning using encrypted signals (Xona Space, 2025).

Xona's approach is particularly suited for autonomous systems, robotics, and critical infrastructure that demand more secure and resilient PNT. By broadcasting stronger signals from closer orbits, Pulsar satellites can help overcome GNSS signal jamming or spoofing, which is a growing concern for safety-critical applications (Xona Space, 2025).

In addition to navigation, Xona's system promises precise timing support via highly synchronised LEO clocks. These capabilities could supplement or back up traditional GNSS timing sources, benefiting sectors such as telecom, energy, and finance that depend on continuous, high-precision timing.

Xona Space is targeting a global PNT service provision with very high signal power, 10-20 satellites in view, centimetre-level positioning with less than a minute convergence, GNSS augmentations, as well as encryption and authentication services on the signals.

As of December 2024, Xona Space has achieved the greatest traction among GNSS receiver and chipset manufacturers as well as simulator manufacturers (GPS World, 2023) (Spirent Federal, n.d.) (Miller, et al., 2023).

Xona's service and signal is called Pulsar. Whilst initially it targeted both L- and C-bands, the company has decided to move away from C-band and concentrate only on dual L-band, to ensure direct compatibility with existing GNSS equipment. The two Pulsar signals are called X1 and X5 (Tyler G. R. Reid, 2025). As of December 2024, the exact X1 and X5 frequencies have not been made public. Figure 22 lists details on Xona, which launched its first satellite, PULSAR-0 in June 2025 (Xona Space Systems, 2025).

General Information	
Country of Origin	United States of America
System Ownership	Private
Services Provided	Positioning, timing, GNSS connections, integrity
Target Sectors	Heavy industry, critical infrastructure, transportation, mass market
Performance Targets	2.5cm with one minute PP convergence
System GNSS Independence	Xona PULSAR uses GNSS in nominal operations, but can operate indefinitely as a GNSS-independant system
Timescale Reference	GNSS and ground-based atomic timescales
Service Area	Global
Operational/ Demonstrations	Operational system
Constellation Details	
Orbital altitude	High LEO (exact altitude to be confirmed)
Inclination	
Satellite class	
Payload Type	Dedicated satellite
Constellation Type	Dedicated PNT Constellation
No of sats in orbit Dec 2024	0 (1 tech demo in 2022)
Initial Operational Capability	2026 / 16 satellites
Full Operational Capability	2030 / 258 satellites
Signal Security Architecture	
Signal structure	Proprietary
Signal Encryption	Signals have encryption
Signal Authentication	Signals have authentication
RF Characteristics	
Frequency Band	Dual L-band (wideband, continuous broadcast)
Signal Names	X1, XS
Signal Frequency	
ITU Approval Status	Pending
Modulation Type	
Data Rate (bps)	
Chip Rate (Mcps)	
User Received power (dBw)	-136.2 dBW

Figure 22: Xona System Constellation information (Frontier SI, 2024)

4.5. VIASAT

Viasat is a global communications company with a portfolio of geostationary and LEO/MEO satellites. While primarily known for satellite broadband services (Viasat, n.d.) and for providing hosting for SBAS transponders (Viasat, n.d.), Viasat has been exploring PNT-related use cases, especially for robust, alternative timing sources and situational awareness in defence contexts (Viasat, n.d.).

Viasat's satellites can offer Satellite Signals of Opportunity (SATSOO) for navigation in GPS-contested environments. These signals, though not originally intended for PNT, can be processed to extract positioning and timing data, providing complementary resilience to traditional GNSS.

In terms of timing, Viasat's wideband communication infrastructure can serve as an alternative distribution channel for time synchronisation, particularly in remote or infrastructure-limited areas. This capability is increasingly valuable for military and disaster-response applications where GNSS reliability is not guaranteed (Viasat, 2024).

4.5.1. OPERATIONAL ARCHITECTURE

A concept for precise time transfer via Viasat's Global Xpress (GX) satellites in GEO, independent of any GNSS, has been developed (Figure 23). It is referred to as Global Xpress Time Transfer. The concept uses enhanced orbit determination data and will make use of Code Division Multiple Access (CDMA) signals in the global beam of the satellite adjacent to the global signalling channel. In the first instance, the Global Xpress Time Transfer concept would use these signals as a mechanism for precise time transfer to user terminals at known locations (European Space Agency, 2024).

Since the Viasat space and ground segments are TRL9 (enhancing existing capabilities), the user terminal development is a key element of this proof-of-concept phase. The work will also include an evaluation of customer demand and market segmentation to inform and guide the future technical, operational and commercial developments (European Space Agency, 2024).

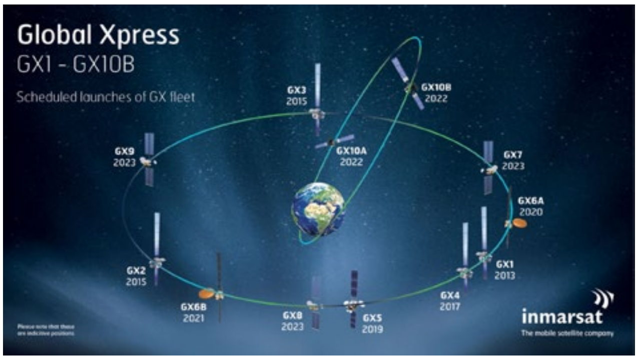


Figure 23: Viasat Global Express concept (UK Space, 2019)

4.6. SATNET LEO

The China Satellite Network Group Co. Ltd. (China SatNet), which oversees the Guowang megaconstellation, has commenced working on a LEO PNT system called SatNet LEO. No information on the SatNet LEO constellation is available. Some SatNet LEO information was presented at the second ICG LEO PNT workshop in 2024; however, the presentation has not been made public. Only a summary slide from the workshop is publicly available, which refers to a target constellation size of 508 satellites by 2030. Figure 24 has been included for completeness but mostly left blank due to lack of information available (Frontier SI, 2024).

General Information	
Country of Origin	China
System Ownership	
Services Provided	
Target Sectors	
Performance Targets	
System GNSS Independence	
Timescale Reference	
Service Area	Global
Operational/ Demonstration	Operational
Constellation Details	
Orbital altitude	
Inclination	
Satellite class	
Payload Type	
Constellation Type	
No of sats in orbit Dec 2024	
Initial Operational Capability	2025 / 168
Full Operational Capability	2023 / 508

Figure 24: SATNet LEO (Frontier SI, 2024)

4.7. JAPAN AEROSPACE EXPLORATION AGENCY (JAXA)

Japan Aerospace Exploration Agency (JAXA) is developing a LEO PNT constellation with the primary

purpose of augmenting the current GNSS to improve convergence time. The constellation is planned for rollout in two phases. The first phase will involve the launch of 240 satellites by 2030, which will allow decimetre-level positioning after a convergence time of 3 minutes. The second phase will involve the deployment of 480 satellites by 2035, which will reduce the convergence time even further.

No information on the satellite, constellation design and signal characteristics is available at this stage (See Figure 25).

General Information	
Country of Origin	Japan
System Ownership	Not decided
Services Provided	GNSS Augmentation, ultra-rapid PPP service, alternative PNT service
Target Sectors	
Performance Targets	Phase I: 10cm horizontal positioning after 3 minutes Phase II: 10cm horizontal positioning after 1 minute
System GNSS Independence	System is designed to augment GNSS
Timescale Reference	GNSS and ground stations
Service Area	Global
Operational/ Demonstrations	Operational system
Constellation Details	
Orbital altitude	975 km
Inclination	55°
Satellite class	
Payload Type	Dedicated satellite
Constellation Type	Dedicated PNT Constellation
No of sats in orbit Dec 2024	0
Initial Operational Capability	2030 / 240 satellites
Full Operational Capability	2035 / 480 satellites
Signal Security Architecture	
Signal structure	
Signal Encryption	
Signal Authentication	
RF Characteristics	
Frequency Band	C-Band
Signal Names	C1-C4 Bands
Signal Frequency	5030-5250 MHz
ITU Approval Status	
Modulation Type	
Data Rate (bps)	
Chip Rate (Mcps)	
User Received power (dBw)	

Figure 25: JAXA LEO Augmentation constellation details (Frontier SI, 2024)

4.8. ARKEDGE SPACE

ArkEdge has been selected by JAXA to perform a feasibility study into developing a LEO-PNT constellation. In parallel, they are also developing an alternative space-based PNT service utilising

communication-based VHF (Very High Frequency) Data Exchange System (VDES). A significant challenge for LEO PNT is the allocation of signal spectrum by the ITU. This is especially true for services in L-band. VDES offers the opportunity to provide a supplementary, dedicated pseudocode on an already ITU-supported frequency allocation, with a ready market (Critchley-Marrows, 2024).

VDES is a new communications solution for maritime which will act as an extension to the current Automatic Identification System (AIS) used for vessel identification and tracking, adding two-way data channels over VHF. VDES will also have a dedicated ranging mode (VDES-R) which will provide positioning and navigation capability to ships in the absence of GNSS information.

The exact size of the VDES constellation is not yet confirmed at this stage; however, it is known that a future VDES constellation is expected to be somewhere between 50-100 satellites at an altitude of 500-600 km. The primary purpose of VDES is communications, which means that the dedicated pseudocode ranging message will be sent only once every few seconds, between the communication messages. Figure 26 lists details on the ArkEdge VDES-R mode constellation.

General Information	
Country of Origin	Japan
System Ownership	Private
Services Provided	VDES R-Mode
Target Sectors	Maritime
Performance Targets	
System GNSS Independence	
Timescale Reference	
Service Area	60°N to 60°S, over ocean surface only
Operational/ Demonstrations	Operational system
Constellation Details	
Orbital altitude	500-600 km
Inclination	Sun-Synchronous or Mid-Inclination
Satellite class	Micro
Payload Type	Dedicated satellite
Constellation Type	Fused Communications and PNT Constellation

No of sats in orbit Dec 2024	0
Initial Operational Capability	
Full Operational Capability	
Signal Security Architecture	
Signal structure	
Signal Encryption	
Signal Authentication	
RF Characteristics	
Frequency Band	VHF
Signal Names	
Signal Frequency	157-162 MHz
ITU Approval Status	
Modulation Type	
Data Rate (bps)	
Chip Rate (Mcps)	
User Received power (dBw)	

Figure 26: Arkedge VDES Constellation information (Frontier SI, 2024)

Currently, VDES is optimised to work over water—not land—because it is a maritime system, and frequency permission is provided only over the world's oceans and seas. Alternative services to VDES already operate over land, and frequency is not presently available over terrestrial areas.

4.9. TRUSTPOINT

TrustPoint, founded in 2020, is a US-based startup headquartered in Washington, DC. TrustPoint is developing a purpose-built commercial (cubesat style) LEO PNT constellation based on a service in C-band. C-band provides some advantages for radionavigation, including reduced ionospheric path delay and increased resistance to jamming (Frontier SI, 2024).

TrustPoint is initially targeting a decimetre-level core service, which will be upgraded to a centimetre-level high accuracy service.

TrustPoint plans to use a 6U CubeSat platform weighing just 10 kg, which includes a <2 kg PNT payload. The projected cost per satellite is approximately $250k, which represents a dramatic cost reduction in the thousands, compared to the cost of a GPS Block III satellite, which is valued hundreds of millions of dollars. TrustPoint is targeting a 3-phase rollout with Phase 1 having roughly 100 satellites providing GPS augmentation and secure synchronisation. Phase 2 will consist of nearly 200 satellites and a timing service. Phase 3 will see full operational capability (FOC) with around 300 satellites and the provision of a global positioning service from LEO.

Figure 27 lists details on the TrustPoint constellation.

General Information	
Country of Origin	United States of America
System Ownership	Private
Services Provided	Positioning, Timing, Augmentation and Integrity
Target Sectors	Defence, Aviation, Automotive, Agriculture, Construction/Industrial, IoT, Infrastructure
Performance Targets	Decimetre-Level Core Service Centimetre-Level High Precision Service
System GNSS Independence	Independent of Heritage GPS and other GNSS
Timescale Reference	Time transfer from company operated ground segment
Service Area	Global
Operational/ Demonstrations	Operational system
Constellation Details	
Orbital altitude	< 700 km
Inclination	
Satellite class	Nano (6U, 10kg cubesat)
Payload Type	Dedicated satellite
Constellation Type	Dedicated PNT Constellation
No of sats in orbit Dec 2024	2 tech demos
Initial Operational Capability	2027 / 100+ satellites
Full Operational Capability	2029 / 300+ satellites
Signal Security Architecture	
Signal structure	Proprietary
Signal Encryption	Signals have encryption. Details available under NDA.
Signal Authentication	Signals have authentication. Details available under NDA.
RF Characteristics	
Frequency Band	C-band
Signal Names	C1
Signal Frequency	5020 MHz Center Frequency

ITU Approval Status	Filed, In Coordination
Modulation Type	BPSK
Data Rate (bps)	Variable
Chip Rate (Mcps)	Multiple
User Received power (dBw)	Variable, -158 to -148 dBW

Figure 27: TrustPoint Constellation and service details (Frontier SI, 2024)

4.10. CENTISPACE

Centispace is a commercial LEO PNT constellation which is being built by Beijing Future Navigation Technology Company in collaboration with the 29th Research Institute of China Electronic Technology Group Corporation (CETC-29). FrontierSI in their recent LEO PNT report (Frontier SI, 2024) summarise the Centispace approach well. It is repeated here for clarity, but the reader is encouraged to review the reference document (Frontier SI, 2024).

The Centispace constellation will be broadcasting navigation signals in the L-band, making it fully compatible with existing GNSS receiver hardware.

The goal of the Centispace constellation is to support BeiDou by reducing PPP convergence time from several tens of minutes to less than a minute. The Centispace constellation will consist of 190 satellites in three sub-constellations across three different orbital planes. The first segment contains 120 satellites at an orbital altitude of 975 km at inclination angle of 55°. This segment includes most of the satellites and provides coverage in mid-latitude regions. The second segment contains 30 satellites at an orbital altitude of 1,100 km at a polar orbit of 87.4°, which expands coverage over the polar regions. Finally, the third segment consists of 40 satellites at an altitude of 1,100 km and an inclination of 30° orbit to expand the coverage in low-latitude regions.

Centispace already has a number of demonstration satellites in orbit that allow some users to conduct performance evaluation trials. Centispace has presented at the 2023 and 2024 International

Committee on GNSS (ICG) workshops. The 2023 presentation is publicly available (Xucheng, 2023), but the 2024 presentation is not. The constellation's details are provided in Figure 28

General Information	
Country of Origin	China
System Ownership	Private
Services Provided	High Accuracy Service, Integrity Augmentation Service, GNSS Monitoring Service
Target Sectors	
Performance Targets	High Accuracy Service: < 10cm Integrity Service: Availability 99.99%, Alarm time: < 3s
System GNSS Independence	System is designed to augment GNSS
Timescale Reference	GNSS and ground stations
Service Area	Global
Operational/ Demonstrations	Operational
Constellation Details	
Orbital altitude	Segment 1 – 975 km; Segment 2 & 3 – 1100 km
Inclination	Segment 1 - 55°; Segment 2 – 87.4°; Segment 3 - 30°
Satellite class	Mini (100kg)
Payload Type	Dedicated satellite
Constellation Type	Dedicated PNT Constellation
No of sats in orbit Dec 2024	5 tech demos
Initial Operational Capability	
Full Operational Capability	2026 / 190
Signal Security Architecture	
Signal structure	
Signal Encryption	
Signal Authentication	
RF Characteristics	
Frequency Band	L-band
Signal Names	CL1, CL5
Signal Frequency	CL1 – 1569-1581 MHz; CL5 – 1170-1182 MHz
ITU Approval Status	Filed, pending
Modulation Type	BPSK
Data Rate (bps)	1000
Chip Rate (Mcps)	2.046
User Received power (dBw)	-157.0

Figure 28: Centispace Details (Frontier SI, 2024)

4.11. SATELLITE SIGNALS OF OPPORTUNITY (SATSOO)

Satellite Signals of Opportunity (SoOp or SATSOO) offer a promising non-GPS PNT solution by leveraging existing satellite signals not originally designed for PNT, such as those from communication or broadcasting satellites. These signals—abundant in LEO, MEO, and GEO constellations—may provide a resilient, robust and cost-effective approach to PNT determination.

SATSOO reuses existing satellite transmissions—such as television, radio, or internet satellite signals—for positioning and timing, without modifying the original broadcast purpose. These can be exploited using specialised receivers to extract useful PNT data (Zaher M. Kassas) (Stock, Schwarz, Hofmann, & Knopp, 2024).

In the navigation domain, techniques enable positioning in environments where GNSS is unreliable, such as indoors, underground, or urban canyons. By triangulating the signal arrival times from known satellite sources, users can estimate their location with surprising accuracy.

Beamforming antennas enhance signal acquisition and interference rejection, enabling reliable PNT in contested environments. LEO satellites provide high-density, precise signals; MEO offers stable coverage; and GEO ensures persistent timing. An integrated approach, supported by advanced receivers and algorithms, promises a resilient PNT ecosystem, critical for applications where GPS is unavailable or unreliable. Continued research and collaboration among satellite operators, receiver manufacturers, and regulators will drive the adoption of SATSOO-based PNT.

For timing, SATSOO can offer alternative synchronisation mechanisms when GNSS is unavailable. It is particularly attractive because it leverages existing infrastructure, making it cost-effective and rapidly deployable for resilience-focused applications like military operations or disaster response.

SATSOO exploits signals with known (or derived) characteristics, such as carrier frequency, modulation, or timing, to derive position and timing information. Key advantages include:

- Ubiquity and Redundancy: SATSOO leverages signals from diverse satellite constellations, reducing reliance on a single system like GPS. LEO constellations (e.g., Starlink, OneWeb, Globalstar) provide dense coverage, while GEO satellites offer stable, wide-area signals.
- Robustness: SATSOO systems are less susceptible to targeted jamming, as adversaries must disrupt multiple, heterogeneous signal sources.
- Cost-effectiveness: Utilising existing infrastructure avoids the need for dedicated PNT satellites.

Challenges include lower signal accuracy compared to GPS (as SATSOO signals lack precise ranging codes) and the need for sophisticated receivers to process diverse signal types. Techniques like carrier-phase measurements, time-difference-of-arrival (TDOA), and frequency-difference-of-arrival (FDOA) are used to extract PNT data, often requiring known satellite ephemeris and signal characteristics.

4.11.1. ROLE OF BEAMFORMING ANTENNAS

Beamforming antennas play a pivotal role in enhancing SATSOO-based PNT by improving signal acquisition, processing, and interference rejection. These electronically steerable antennas, such as those from Kymeta or ALLSPACE, dynamically adjust their radiation patterns to focus on specific signal sources, offering several benefits:

- Signal Enhancement: Beamforming increases the signal-to-noise ratio (SNR) by directing antenna gain toward the desired satellite, critical for weak or low-power SoOp signals (e.g., from LEO satellites).
- Interference Mitigation: By nulling interference sources (e.g., jammers or multipath signals), beamforming ensures robust signal reception in contested environments.
- Multi-Signal Processing: Beamforming enables simultaneous tracking of multiple satellites across LEO, MEO, and GEO orbits, supporting the heterogeneous nature of SATSOO.
- Adaptability: Digital beamforming allows real-time adjustment to changing satellite positions, essential for fast-moving LEO satellites.

For PNT, these beamforming antennas—called Controlled Reception Pattern Antennas (CRPA)—are often implemented as phased-array antennas, which use phase shifts to steer beams towards GNSS satellites (or steer nulls towards jammers), without mechanical movement. In SATSOO, the multiple beams are controlled to track communications satellites. Advanced techniques, such as adaptive beamforming (using algorithms like Minimum Variance Distortionless Response (Kiong, Salem, Paw, Sankar, & Darzi, 2014)), optimise performance in dynamic environments. However, beamforming requires complex signal processing and higher power consumption, posing challenges for resource-constrained devices.

4.11.1.1. ROLE OF LEO, MEO, AND GEO SATELLITES FOR PNT DETERMINATION IN SATSOO

The choice of satellite orbit—LEO, MEO, or GEO—impacts SATSOO-based PNT performance due to differences in signal characteristics, coverage, and geometry. Each orbit contributes uniquely to a hybrid PNT solution:

- Low Earth Orbit (LEO) Satellites:
  - Characteristics: LEO satellites (e.g., Starlink, Iridium) operate at 300–2,000 km altitudes, offering high signal strength due to proximity and rapid orbital motion (7–8 km/s).
- Advantages:
  - High Density: Mega-constellations like Starlink (>4,000 satellites) provide abundant signals and frequent satellite passes, enabling continuous PNT updates.
  - Geometric Diversity: LEO satellites' rapid movement can improve dilution of precision (DOP), enhancing positioning accuracy.
  - Low Latency: Proximity reduces signal propagation delays, beneficial for timing applications
- Challenges:
  - Ephemeris Requirements: Accurate satellite position data is needed, as LEO satellites lack the stable orbits of GPS.
  - Doppler Effects: High relative velocities cause significant Doppler shifts, requiring advanced receiver algorithms.
  - Intermittent Visibility: LEO satellites are visible for short periods, necessitating multi-satellite tracking.

LEO-based SATSOO is ideal for urban or contested environments, where GPS signals may be obstructed, but it requires beamforming to track fast-moving satellites and mitigate Doppler effects.

- Medium Earth Orbit (MEO) Satellites:
  - Characteristics: MEO satellites (e.g., SES O3b) operate at 8,000–20,000 km, balancing coverage and signal strength.
- Advantages:
  - Moderate Coverage: MEO satellites cover larger areas than LEO, with longer visibility periods.
  - Stable Signals: Lower Doppler shifts compared to LEO simplify signal processing.
  - Complementary Role: MEO signals (e.g., from navigation augmentation systems) can enhance SATSOO accuracy when combined with LEO/GEO signals.
- Challenges:
  - Lower Signal Density: Fewer MEO satellites limit redundancy compared to LEO mega-constellations.
  - Weaker Signals: Greater distance reduces SNR, requiring sensitive receivers or beamforming.

MEO satellites serve as a bridge between LEO and GEO, providing stable signals for regional PNT applications.

- Geostationary Earth Orbit (GEO) Satellites:
  - Characteristics: GEO satellites (e.g., Inmarsat, Intelsat) at ~36,000 km remain fixed relative to Earth, transmitting continuous signals.
- Advantages:
  - Persistent Coverage: GEO satellites provide constant visibility over large regions, ideal for timing and coarse positioning.
  - High-Power Signals: GEO communication satellites often transmit strong signals, simplifying acquisition.
  - Simplified Tracking: Fixed positions reduce the need for dynamic beam steering.
- Challenges:
  - Poor Geometry: Fixed positions result in high DOP, limiting positioning accuracy.
  - Weaker Ranging Precision: GEO signals lack the precise timing of GPS, requiring augmentation with LEO/MEO signals.
  - Longer Delays: Greater distance introduces propagation delays, affecting real-time applications.

GEO satellites are best suited for timing synchronisation and as a fallback PNT source in GPS-denied environments.

A hybrid SATSOO-based PNT system combining LEO, MEO, and GEO signals maximises robustness, redundancy and accuracy. LEO provides high-density, dynamic signals for precise positioning; MEO offers stable, regional coverage; and GEO ensures persistent timing references. Beamforming antennas are critical for integrating these signals, enabling receivers to track multiple satellites across orbits while mitigating interference (SES SA, 2023) (Karlsson, 2023).

4.11.1.2. CURRENT DEVELOPMENTS AND FUTURE OUTLOOK

Recent advancements in SoOp-based PNT include Software-Defined Radios (SDRs) that enable flexible processing of diverse SATSOO signals, reducing hardware costs. AI/ML-Driven signal processing enhances signal characterisation and ephemeris estimation, improving accuracy.

Future challenges include standardising SATSOO protocols, ensuring satellite operators share ephemeris data, and developing compact, low-power beamforming antennas for widespread adoption. Regulatory frameworks must also address spectrum allocation and interference risks.

4.11.2. UK AVAILABILITY

Below is a list of commercial companies actively providing or developing SATSOO services for PNT, focusing on those leveraging non-GNSS satellite signals (e.g., from communication satellites in LEO, MEO, or GEO).

This list emphasises companies with operational or near-operational SATSOO-based PNT services, rather than just potential signal sources (e.g., Starlink, OneWeb) and provides specifics on their technologies, applications, and status.

- NAVSYS Corporation, United States (Colorado Springs, CO)
  - Service: Position, Navigation, and Timing as a Service (PNTaaS) (Brown, Nguyen, & Huerta, 2024)
  - Technology: NAVSYS's PNTaaS leverages existing SATCOM signals from LEO, MEO, and GEO constellations (e.g., Starlink, OneWeb, Inmarsat) as SATSOO. It integrates Software-Defined Radios (SDRs) with inertial measurement units (IMUs) and clocks to provide assured PNT in GPS-denied environments. It monitors SDRs at ground stations and publishes timing and signal data, enabling precise positioning and timing through the use of snapshots.
  - Applications: Military (e.g., UAV (unmanned aerial vehicle) navigation, tactical communications), commercial (e.g., power grids, financial services, telecom), and critical infrastructure. Successfully tested with OneWeb terminals in active jammer scenarios, demonstrating resilience against GPS disruptions.
- Parsons Corporation, United States (Centreville, VA)
  - Service: Assured Positioning System (APS) (Parsons, 2025)
  - Technology: APS uses SATSOO from LEO communication satellites (e.g., Iridium, Orbcomm) to derive PNT data, independent of GPS/GNSS. It employs the Peanut SDR platform, a low-Size, Weight, and Power (SWaP) solution, to process SoOp signals. For dismount applications, APS integrates SoOp with IMUs and barometric sensors.
  - Applications: Military (e.g., dismounted soldiers, tactical edge), commercial (e.g., logistics, autonomous systems), and homeland security. APS is provided as a plug-in to the Android Team Awareness Kit (ATAK) for smartphone-based navigation.
- CACI International, United States (Reston, VA)
  - Service: Resilient PNT and Tactical ISR Payload (CACI international, 2025)
  - Technology: CACI's SATSOO-based PNT solution uses two-way time transfer (TWTT) and oscillator modelling to deliver sub-nanosecond time synchronisation via SATCOM signals from LEO satellites. It has been demonstrated via a 2023 DemoSat with York Space Systems, which included a multi-mission PNT and Tactical ISR (TacISR) payload.
  - Applications: National security (e.g., remote sensing, special operations), commercial (e.g., communications, ISR), and critical infrastructure. It provides augmented PNT for airborne and ground assets in GPS-denied environments.
- Leonardo DRS, United States (Arlington, VA)
  - Service: Assured Positioning, Navigation, and Timing (A-PNT) via AC2ES (LeonardoDRS, 2025)

- Technology: The Assured Command and Control Enablement System (AC^2ES) integrates SATSOO from LEO SATCOM signals with a fusion engine combining GPS, inertial, and vision navigation. Embedded in the Data Distribution Unit – Expandable (DDUx) II, it processes SATSOO for PNT in GPS-denied environments. It uses Controlled Reception Pattern Antennas (CRPAs) to mitigate jamming.
- Applications: Military (e.g., over 150,000 vehicles, combat management systems) with potential commercial crossover (e.g., autonomous vehicles). It supports real-time jamming or spoofing detection.

Currently, there are limited commercial offerings for SATSOO, but antenna manufacturers like ALLSPACE and Kymeta are entering the non-GNSS PNT domain. It is expected that this situation will change dynamically as more companies move into SATSOO as an Alt-PNT capability.

5. EXISTING TERRESTRIAL RF SYSTEMS

Terrestrial PNT systems are technologies that utilise RF signals to provide accurate PNT information for a wide range of applications. These systems, including technologies, play an essential role in ensuring reliable PNT services in environments where satellite signals may be degraded, jammed, or unavailable, such as urban canyons, indoors, or during intentional interference. By leveraging ground-based transmitters, terrestrial PNT systems support diverse sectors, including transportation, telecommunications, defence, and emergency services, thereby enhancing safety, efficiency, and resilience in modern navigation and timing-dependent operations.

Figure 29 shows the number of different technologies available. A more exhaustive description is provided in the sections that follow.

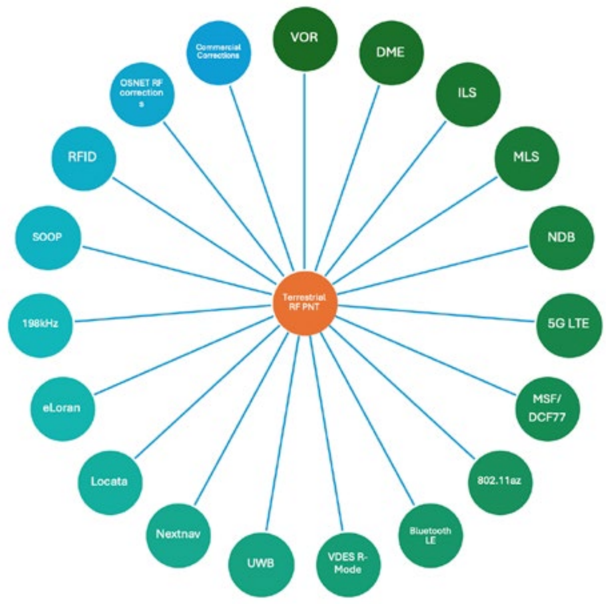


Figure 29: Terrestrial RF PNT Systems

5.1. VOR

5.1.1. SYSTEM OVERVIEW

Very High Frequency (VHF) Omnidirectional Range (VOR) is a ground-based radio navigation system that provides accurate directional information to the aviation industry (GlobeAir, 2025).

Operating in the VHF band (108–117.95 MHz), VOR stations transmit two signals: a constant omnidirectional reference signal and a rotating directional signal. By comparing the phase difference between these signals, an aircraft's receiver determines its bearing (azimuth) relative to the VOR station, expressed as a radial (0–360°). Pilots can use this information to navigate toward or away from the station or follow specific flight paths.

VOR is reliable, resistant to most weather interferences, and widely used for en-route navigation and instrument approaches, often in conjunction with Distance Measuring Equipment (DME) for precise positioning (Nolan, 2014).

5.1.1.1. TYPES OF VOR (GLOBEAIR, 2025; STUDY AIRCRAFTS, 2025)

- BVOR: Broadcast VOR - gives weather and airfield information between beacon identification.
- CVOR: Conventional VOR – provides azimuth information so pilots can determine bearing from the station and use it for defining airways and for en-route navigation
- DVOR: Doppler VOR – an enhancement of conventional VOR by utilising the Doppler effect to improve accuracy and reliability at high altitudes
- Distance Measuring Equipment (DME)/VOR – provides directional and distance information to pilots for a precise location
- TVOR: Terminal VOR - has only low power and is used at major airfields
- VOT: VOR test facility - This is found at certain airfields and broadcasts a fixed omni-directional signal for a 360° test radial. This is not for navigation use but is used to test an aircraft's equipment accuracy before IFR flight. More than ±4° indicates that equipment needs servicing.
- VORTAC: Co-located VOR and TACAN (DME) beacons (Study Aircrafts, 2025)

The two most commonly types used are VOR (CVOR) and the Doppler VOR (DVOR). They both use the same design of VHF antenna to generate the carrier, which is known as the Alford Loop (Study Aircrafts, 2025).

5.1.2. PERFORMANCE METRICS

VOR systems have a short to medium range of 200 nm or 370 km which is often considered as line-of-sight with an accuracy of ±1° bearing (~200-1000 m) (ICAO, 2023) (Navigraph, 2024). The size, weight, and power associated with VOR can be variable depending on the type used and its application. Despite this, the cost range is considered medium for these systems.

5.1.3. INFRASTRUCTURE REQUIREMENTS

For VOR systems to function, ICAO calibrated fixed ground stations are required. These have a transmission power between 50 and 200 W (Study Aircrafts, 2025) (ICAO, 2023).

5.1.4. APPLICATIONS AND BENEFITS

The wide coverage and highly reliable nature of VOR systems render them useful for aeronautical navigation and flight operations. When travelling across countries, VOR allows for continuous navigational and directional guidance and structured approach and departure routes around busy airspaces, making it an important back-up navigation system for redundancy and safety. VOR is also interoperable, making it compatible with a range of different aircraft types (GlobeAir, 2025) (Navigraph, 2024).

5.1.5. CHALLENGES AND LIMITATIONS

The main challenges a VOR system faces include its limited accuracy as well as intensive and costly system maintenance. As VOR is limited to line-of-sight operations, signals can be blocked by terrain and structures. As a result, the range of a VOR system will decrease with altitude (Clear Flight, n.d.) (Navigraph, 2024).

5.2. DISTANCE MEASURING EQUIPMENT (DME)

5.2.1. SYSTEM OVERVIEW

DME is a pulsed, 2-way, ultra-high frequency ranging system developed in the 1950s. A receiver in an aircraft measures the time delay between the pulses to calculate the slant range distance. Slant range distance is the straight-line distance between two points at different altitudes, such as between an aircraft and a transmitting station, typically measured along the line of sight and accounting for both horizontal and vertical separation (NAVAC, 2024) (Institute for Communications and Navigation, 2018) (Federal Aviation Administration, 2024).

5.2.2. PERFORMANCE METRICS

DME operates in the 960-1215 MHz frequency range and has a range of 200 NM (line-of-sight) (AV Web, 2019). The system is made up of a small airborne receiver and a medium ground station which facilitate an accuracy of ±0.5 NM or ±3% slant range (ICAO, 2018). The cost range for this system is considered medium (NAVAC, 2024) (Federal Aviation Administration, 2024).

5.2.3. INFRASTRUCTURE REQUIREMENTS

A DME system has a transmission power of up to 1 kW on the ground and 250 W airborne (Federal Aviation Administration, 2024). The infrastructure required for a DME system includes a transponder ground station and an interrogator in an aircraft (Study Aircrafts, 2025).

5.2.4. APPLICATIONS AND BENEFITS

Like VOR, DME systems are primarily used for aeronautical navigation purposes due to its extensive coverage (Institute for Communications and Navigation, 2018). Also, DME is commonly used in conjunction with other systems like VOR and ILS for highly accurate navigation fixes (Study Aircrafts, 2025).

5.2.5. CHALLENGES AND LIMITATIONS

DME systems measure the slant range and not the horizontal (ground) distance, which means that at higher altitudes or closer to the stations the slant ranges may be longer than the actual ground distance; this is known as slant range error (FAA, 2025). Like VOR, a DME system requires a line-of-sight between the aircraft and ground station, as obstructions like topographic features or man-made obstructions can block the signal, causing complete signal loss or degradation (FAA, 2025). Furthermore, due to the frequency range within which DME operates, there can be congestion which is increased in a busy airspace (ICAO, 2023). To achieve the accuracy and precision an aircraft needs for a safe final approach, DME must be combined with other systems like ILS and GPS (FAA, 2022).

5.2.6. FUTURE ENHANCEMENTS

Since DME is a two-way system, high traffic zones could cause transponders to become overwhelmed (Institute for Communications and Navigation, 2018). Two enhancements have been developed to mitigate this:

- One-way ranging is broadcast from the ground as a pseudorandom pulse pair sequence with no capacity limits. However, one-way ranging requires time synchronisation (Institute for Communications and Navigation, 2018).
- Hybrid ranging has also been developed to overcome the congestion issues. This incorporates both two-way and one-way ranging which lowers the risk of a transponder being overloaded, and it is more compatible with legacy interrogators (Institute for Communications and Navigation, 2018).

5.3. INSTRUMENT LANDING SYSTEM (ILS)

5.3.1. SYSTEM OVERVIEW

An ILS provides an ICAO standard precision runway approach and landing in aviation (ICAO, 2023). Two radio beams provide pilots with both vertical and horizontal guidance during the approach and landing when there is a lack of visual cues due to fog, rain or snow. A localiser (LOC) provides azimuth, whilst a glideslope (GS) defines a vertical descent profile to assist the pilot. Furthermore, marker beacons and runway lights aid the use of an ILS (Skybrary, 2025).

5.3.2. PERFORMANCE METRICS

For an ILS, a large ground installation and small onboard receiver are required for operation, which makes the cost range high (ICAO, 2023). A localiser has a range of 18 NM using a frequency band of 108.1 to 111.95 MHz, whereas a glideslope provides a shorter range of 10 NM between the frequencies of

328.6 and 335.4 MHz (Simple Flying, 2022) (Federal Adviation Administration, 2025). An ILS can provide a CAT III accuracy of ±1 ft vertically, ±10 ft laterally (EUROCAE, 2019).

5.3.3. INFRASTRUCTURE REQUIREMENTS

Fixed ground stations, critical area protection, marker beacons, and intense runway lights are all required for the operation of an ILS. The transmission power needed for a localiser is around 100 W, whereas for a glideslope, less power (around 5 W) is required (Skybrary, 2025).

5.3.4. CHALLENGES AND LIMITATIONS

An ILS signal requires a clear line-of-sight between the aircraft and antenna, which consequently makes it sensitive to terrain. Terrain can prevent the proper installation of the system or restrict its coverage (ICAO, 2018). Furthermore, signals from both the glideslope and localiser are vulnerable to multipath reflections caused by large metallic objects like other aircrafts or vehicles (ICAO, 2023). Also, the signal propagation and its associated infrastructure are vulnerable to weather variables such as heavy rain, fog, and snow (FAA, 2025). Alternative navigation aids through additional installation are needed for the reverse approach, because ILS guidance is only provided in one direction along the runway (ICAO, 2023).

5.4. MICROWAVE LANDING SYSTEM (MLS)

5.4.1. SYSTEM OVERVIEW

MLS is another system for precision approach and landing by instruments. It is considered an alternative to ILS. Microwave beams are transmitted towards a sector of the approach which scan this sector across both the horizontal and vertical planes. This provides information on the azimuth, optimal angle of descent, distance, and details on reverse course in the event of an unsuccessful approach. Advancements in GPS navigation meant that the FAA cancelled the new installation of devices in 1994 (Landing Systems, 2025). It is currently not operational in the UK, although MLS has been tested at Heathrow (ICAO, 2009).

5.4.2. PERFORMANCE METRICS

MLS operates within the frequency band between 5031 MHz and 5090.7 MHz, providing a range and coverage of ±40° azimuth to 20 NM; ±15° elevation at an accuracy of less than 3 m, both laterally and vertically (ICAO, 2003) (Niyonsaba & Vivek, 2019). The cost range is described as high, since a moderately sized ground system is needed alongside compact airborne receivers.

5.4.3. INFRASTRUCTURE REQUIREMENTS

For installation of an MLS system, protractor components, rangefinder components and onboard hardware are needed for operation. Each beam has a transmission power of ~25 W, but this can vary (Landing Systems, 2025).

5.4.4. APPLICATIONS AND BENEFITS

Like an ILS, MLS has no signal interruptions, because the microwaves are radiated into space on approach in a given time and not spread over many different directions (Landing Systems, 2025). The flight paths produced by an MLS system have a flexible geometry which facilitates a curved or segmented approach, unlike ILS. Also, due to its high capacity, MLS can support multiple aircrafts on their simultaneous approaches in all weather conditions (ICAO, 2004) (ICAO, 2023). These assets of the MLS render it useful for precision approach in aviation, enabling Category I, II, and III in low-visibility condition—as are commonly used by the US forces and other NATO countries (Strong., 1985).

5.4.5. CHALLENGES AND LIMITATIONS

A key issue with MLS is the cost of its installation (Niyonsaba & Vivek, 2019). Due to this, globally, there is minimal infrastructure for operational systems (Eurocontrol, 2025). The high installation costs mean that it is impractical for many airlines to invest in it; therefore, the global uptake was very low, leading to MLS being decommissioned in most regions (ICAO, 2023) (Eurocontrol, 2025). The subsequent adoption of GNSS-based systems also contributed to the low uptake rate of MLS (Niyonsaba & Vivek, 2019) (ICAO, 2023). Furthermore, the frequency band within which MLS operates is shared by other aviation systems; therefore, it can become congested, causing constraints in frequency planning and allocation (ICAO, 2021).

5.5. NON-DIRECTIONAL BEACON (NDB)

5.5.1. SYSTEM OVERVIEW

NDBs are ground-based, low frequency radio transmitters that are used as an instrument approach for airports and offshore platforms. An NDB transmits an omni-directional signal that is received by an Automatic Direction Finder (ADF), which is a standard instrument onboard aircrafts (Southern Avionics, 2025). NDBs do not include inherent directional information. They are radio transmitters at a known location, used as an aviation or marine navigational aid. NDBs contrast with directional radio beacons and other navigational aids, such as low-frequency radio range, VHF omnidirectional range (VOR), and tactical air navigation system (TACAN).

5.5.2. PERFORMANCE METRICS

The accuracy of an NDB is generally considered to be ±5° under optimal conditions, as specified by the International Civil Aviation Organization (ICAO) standards (International Civil Aviation Authority, 2023). This accuracy can degrade significantly due to various factors such as atmospheric conditions, terrain, coastal refraction, and electrical interference like thunderstorms. These factors can cause bearing errors, with deviations sometimes exceeding ±10° in challenging environments, particularly at longer ranges or during twilight periods (dusk and dawn) when ionospheric effects are pronounced.

NDBs operate within the frequency range of 190 to 1750 kHz (535 kHz in the USA) and provide a range of 15 to 100 NM at an accuracy of ±5° to ±10° (Advanced Navigation , 2025) (International Civil Aviation Authority, 2023). The size, weight, and power of an NDB system is minimal, which is reflected in the low-cost range needed for its operation (Southern Avionics, 2025).

5.5.3. INFRASTRUCTURE REQUIREMENTS

An NDB system has multiple requirements for its installation. Firstly, a transmitter is needed to continuously emit radio signals is all directions. An omnidirectional wire antenna, along with its tuning unit, helps to uniformly radiate the signals emitted, allowing some aircrafts to receive bearings from any given direction. Onboard the aircraft, an Automatic Direction Finder (ADF) is required. The ADF is an instrument that interprets the NDB signal to determine the bearing (Southern Avionics, 2025) (Advanced Navigation , 2025). Overall, this installation requires a transmission power between 25 and 1000 W.

5.5.4. APPLICATIONS AND BENEFITS

NDB signals are transmitted on an uninterrupted 24/7 basis and are designed to operate reliably in a range of environmental conditions (Southern Avionics, 2025) (Advanced Navigation , 2025). In this case, NDB systems are important as backup navigations aids in case of a GPS or VOR system failure (Advanced Navigation , 2025). The uses for NDBs cover multiple industries, including aerospace, automotive, marine, space, defence, and surveying. More specifically, they are useful for reliable navigation for helicopter pilots and ADF-equipped crew boats at offshore platforms and drill ships (Southern Avionics, 2025) (Advanced Navigation, 2025).

5.5.5. CHALLENGES AND LIMITATIONS

NDBs operate in the low to medium frequency bands which are highly vulnerable to lightening, precipitation and other atmospheric noise (ICAO, 2023). At night, ionospheric reflection could cause NDB signals to travel quicker and arrive at the aircraft by multiple paths (FAA, 2025), which can cause signal fluctuations 30–60 NM from the transmitter, leading to erratic ADF needle behaviour.

There is a lack of precision and no vertical guidance with NDBs, resulting in higher minimum descent altitudes and lower accuracy with approaches (FAA, 2022). Due to these factors, NDB may be decommissioned and replaced by Area Navigation (RNAV) (NAVAC, 2024) (UK Civil Aviation Authority, 2022).

Terrain and coastal refraction impact the signals. Mountains or coastlines can reflect or bend signals, resulting in erroneous readings. Thunderstorms can generate noise, causing the ADF to point toward the storm rather than the NDB.

The Automatic Direction Finder (ADF) equipment on the aircraft, used to interpret NDB signals, also lacks a failure flag. This means that pilots must continuously monitor the NDB's Morse code identifier to ensure reliability. Due to these limitations, NDBs are considered less accurate than modern navigation aids like VOR or GPS and are often used for non-precision approaches or as backup systems.

5.6. 5G LONG-TERM EVOLUTION (LTE) NEW RADIO (NR)

5.6.1. SYSTEM OVERVIEW

5G LTE NR is the latest iteration of cellular technology that was introduced in July 2016. Transmission signals can provide PNT information to users. This can allow for continuity of critical services to mitigate against any economic losses that may arise due to GNSS signal instabilities and outages (Rohde and Schwarz, 2023) (NAVAC, 2024).

5G NR capabilities are driven by features in the 3GPP Release 16 (3GPP, 2020) and beyond, designed for applications like IoT, autonomous vehicles, and industrial automation. Below is a concise overview of 5G NR's positioning location capabilities.

Positioning Techniques

5G NR supports multiple positioning methods, leveraging both radio access network (RAN) and core network features (3GPP, 2020):

- Enhanced Cell-ID (E-CID): Uses cell tower information, signal strength, and timing to estimate location. Accuracy is moderate (~50-100 meters)
- Time-Based Methods:
  - Time Difference of Arrival (TDoA): Includes Downlink TDoA (DL-TDoA) and Uplink TDoA (UL-TDoA), measuring time differences of signals between the device and multiple base stations

(Next Generation NodeB (gNBs)5). Accuracy can reach ~1-10 meters
  - Round-Trip Time (RTT): Measures the time for a signal to travel from the device to a gNB and back. Multi-RTT improves accuracy by using multiple gNBs (~1-5 meters)
- Angle-Based Methods:
  - Angle of Arrival (AoA) and Angle of Departure (AoD): Uses beamforming and MIMO to estimate angles of signal paths. Accuracy depends on antenna configuration (~1-10 meters)
- Carrier Phase Positioning: Measures phase differences in carrier signals for centimetre-level accuracy, suitable for high-precision use cases
- GNSS-Assisted Positioning: Integrates GNSS with 5G for enhanced accuracy, especially in outdoor environments (~1-5 meters)
- Sidelink Positioning: Enables device-to-device (D2D) positioning for scenarios like vehicle-to-everything (V2X), using direct communication between devices

Key Enablers

- Millimetre Wave (mmWave) and Beamforming: These higher frequencies and directional beams improve angle-based positioning and resolution, while larger bandwidths (up to 400 MHz in mmWave) enhance time-based measurements for better accuracy.
- Low Latency: Positioning updates in milliseconds, which is critical for real-time applications like autonomous driving
- Massive MIMO: Multiple antennas improve AoA/AoD accuracy and signal reliability
- Synchronisation: Precise gNB synchronisation (sub-nanosecond level) ensures accurate timing measurements
- Sidelink and Integrated Sensing and Communication (ISAC): Supports direct device positioning and environmental mapping

3GPP Evolution

- Release 16: Introduced DL-TDoA, UL-TDoA, multi-RTT, and AoA/AoD, with a focus on high-accuracy positioning
- Release 17 (2024): Enhanced sidelink positioning, low-power modes, and ISAC for joint sensing and communication
- Release 18 and Beyond (2025+): Target centimetre-level accuracy, AI-driven positioning, and non-terrestrial network (NTN) integration for global coverage

5.6.2. PERFORMANCE METRICS

5G LTE NR can achieve a rural to urban coverage and a range of 50 to 2,000 feet (15-600 metres) (GPS World, 2018) (Dgtl Infra, 2024). It operates in the UHF band between 470 and 698 MHz (Rohde and Schwarz, 2023). Base stations for 5G LTE NR weigh less than 31 kg with a related power consumption ranging from 6 to 9 kW. The power consumption may increase up to between 14 and 19 kW as demand increases for this service (Vicinity, 2024) (Cheng, Hu, & Varga, 2022). 5G LTE NR provides different levels of accuracy depending on whether the user is indoors or outdoors. Outdoor accuracy is sub-meter to 1-10 meters, depending on the method, environment, and gNB density. The carrier phase and multi-RTT can achieve <1 meter in ideal conditions. Indoors, the accuracy is 1-10 meters, which is improved by small cells, ultra-wideband (UWB) integration, or dense gNB deployments (3GPP, 2020). High precision use cases are associated with 5G LTE NR due to centimetre-level accuracy with carrier phase or hybrid GNSS-5G methods in controlled environments (3GPP, 2020). For the user of this system, the costs are low; however, the costs associated with the infrastructure needed for 5G LTE NR are high (Honcharenko, 2019).

5.6.3. INFRASTRUCTURE REQUIREMENTS

The transmission power of a typical 5G New Radio (NR) gNodeB (gNB) varies depending on the deployment scenario (e.g., macro, small cell, indoor), frequency band (sub-6 GHz or mmWave), and regulatory limits. Below is a concise overview (3GPP, 2024):

Macro gNB (Outdoor, Sub-6 GHz):

- Effective Isotropic Radiated Power (EIRP): 60–80 dBm (100–10,000 W), depending on antenna configuration
- Conducted Power: Typically 20–200 W per sector (e.g., 43–53 dBm per antenna port)
- Example: A macro gNB with 4x4 MIMO might output ~40–46 dBm (10–40 W) per port, amplified by antenna gain (15–20 dBi) to achieve high EIRP.
- Use Case: Urban/rural coverage, serving large areas

Small Cell gNB (Urban/Indoor, Sub-6 GHz):

- EIRP: 30–50 dBm (1–100 W)
- Conducted Power: 20–33 dBm (0.1–2 W) per port

5 A gNB (Next Generation NodeB) is the radio base station in a 5G New Radio (NR) network, responsible for providing wireless connectivity to user equipment (UE), such as smartphones or IoT devices. It is the 5G equivalent of the eNodeB (eNB) in 4G LTE networks (3GPP, 2020).

- Example: A small cell might use 24–30 dBm (0.25–1 W) per antenna, with lower antenna gain (5–10 dBi).
- Use Case: Dense urban areas, indoor environments like offices or stadiums

mmWave gNB (High-Frequency Bands, 24-52 GHz):

- EIRP: 40–60 dBm (10–1,000 W), due to high antenna gain from beamforming
- Conducted Power: Lower, typically 20–30 dBm (0.1–1 W) per port, as mmWave relies on massive MIMO and beamforming to compensate for path loss
- Example: A mmWave gNB with 256 antenna elements might have ~25 dBm per element, but beamforming boosts EIRP significantly.
- Use Case: High-capacity, short-range deployments (e.g., urban hotspots, stadiums)

Factors Influencing Transmission Power (3GPP, 2024):

- Frequency Band: Sub-6 GHz gNBs use higher power for broader coverage; mmWave gNBs use lower conducted power but high EIRP via beamforming.
- Antenna Configuration: Massive MIMO (e.g., 64T64R or 128T128R) and beamforming increase EIRP without raising conducted power.
- Regulatory Limits: Vary by region (e.g., the FCC in the US limits EIRP to ~75 dBm for macro cells; ETSI in Europe may cap at ~61 dBm).
- Deployment Type: Macro cells prioritise coverage, small cells focus on capacity, and indoor gNBs minimize interference.
- Power Efficiency: Modern gNBs use dynamic power allocation to reduce energy consumption, adjusting based on traffic load.

For 5G LTE NR positioning (e.g., DL-TDoA, PRS), gNBs transmit Positioning Reference Signals (PRS) at similar power levels to ensure signal detectability, but power allocation may be optimised for accuracy rather than throughput.

5.6.4. INSTALLATION REQUIREMENTS:

For 5G LTE NR system infrastructure, TV broadcasting infrastructure can be reused. This includes towers, amplifiers, frequencies, and antennas (Rohde and Schwarz, 2023). Macro base stations and sub 6 GHz MIMO units are also needed (Vicinity, 2024) (Honcharenko, 2019).

5.6.5. APPLICATIONS AND BENEFITS (3GPP, 2020)

5G broadcast involves directional communications via MIMO, which facilitates high bandwidth communications (GPS World, 2018). Also, 5G chipsets can be easily integrated for mass-market receivers (Rohde and Schwarz, 2023). The low-power, high accuracy nature of this system makes it applicable to wearables and sensors. 5G LTE NR is, therefore, useful for a range of applications, such as those in the industrial, automotive and public safety sectors. For example, in industrial settings, this system allows for asset tracking, robotics, and the development of smart factories. The automotive industry utilises this system for V2X, autonomous driving, and lane-level navigation. It can also be crucial to human life, as it can provide an accurate location for an emergency caller, enabling a quicker and more efficient emergency response. At the consumer level, 5G LTE NR is used for AR/VR and provides location-based services for navigation, which is widely available and used every day.

5.6.6. CHALLENGES AND LIMITATIONS

Due to the many directional communications via MIMO for high bandwidth communications, the processing complexity is high (GPS World, 2018). This can be amplified using higher frequency bands, since increased signal attenuation could occur. This causes limited penetration capabilities through obstacles like buildings, consequently reducing coverage in some areas or environments (Gonzales-Garrido, Querol, & Chatzinotas, 2023). Further signal interference (such as jamming and spoofing) could occur, as well as multipath propagation, which could occur in urban environments, where signals reflect off surfaces (NextNav, 2024). This can cause degradation of positioning accuracy due to resultant errors in the time of arrival and angle of arrival measurement (Microchip, 2020). 5G LTE NR have high infrastructure costs associated with them, since dense gNB deployments are required for high precision. When using higher accuracy methods like carrier phase, more power is required. A key limitation is that 5G LTE NR is not yet independent of GNSS and so cannot completely replace it (GPS World, 2018).

5.7. MSF/DCF77

5.7.1. SYSTEM OVERVIEW

The MSF and DCF77 time signals are longwave radio broadcasts used primarily in Europe to provide highly accurate time synchronisation for radio-controlled clocks, network time servers, and other precision timing applications. Both are maintained by national meteorology institutes and rely on atomic clocks for accuracy, but they differ in location, frequency, coverage, and signal encoding.

MSF (NPL, 2025)

- A source of accurate and reliable UK civil time through a standard frequency and time broadcast
- The MSF signal is transmitted from Cumbria (Anthorn Radio Station) by Babcock International under contract to NPL.

- The signal is monitored against the national time scale UTC (NPL) and corrections are provided where necessary.

DCF77 (PTB - National Metrology Institute, 2025)

- Legal time realised by Physikalisch-Technische Bundesanstalt (German national metrology institute)
- The DCF77 transmitter is the transmitting radio station Mainflingen (25km south-east of Frankfurt).

5.7.2. PERFORMANCE METRICS

MSF provides a UK-wide service from Cumbria and can be received throughout the majority of northern and western Europe at a frequency of 60 kHz (NPL, 2025). It provides a timing accuracy of ±1 millisecond (to UTC). MSF uses two signal formats to function.

1. On/Off carrier modulation is used, the effective radiated power being in the order of 15kW. A 100 ms pulse represents a binary "0," a 200 ms pulse a binary "1," and a 500 ms pulse marks the start of a new minute (pulse width encoded).
2. Time and date information is presented in BCD (Binary Coded Decimal) within the broadcast signal. Data content transmits time (hours, minutes), date (day, month, year), day of the week, and indicators for British Summer Time (BST) and leap seconds. Bits 53–58 may include extra-wide 300 ms pulses, and bits 1–17 use single or double pulses to encode UTC offset.

DCF77 operates 24 hours a day and provides a coverage of 1,900 km during the day; 2,100 km at night (Figure 30) at a frequency of 77.5 kHz, and an accuracy better than 1 millisecond relative to UTC (NPL) (PTB - National Metrology Institute, 2025) (Timetools Limited, 2017). DCF77 also uses two signal formats to function.

1. An amplitude modulated, pulse width encoded signal like MSF, but the same data signal is also phase modulated onto the carrier using a 512-bit long pseudorandom sequence (direct-sequence spread spectrum modulation). The effective radiated power is in the order of 35kW. (Piester, 2011).
2. Data content: Transmits time (hours, minutes), date (day, month, year), day of the week, daylight saving time (DST) status, and leap second indicators in Binary Coded Decimal (BCD). Since 2006, 14 bits (seconds 1–14) may carry weather data (Meteo Time GmbH) or warnings (Piester, 2011).

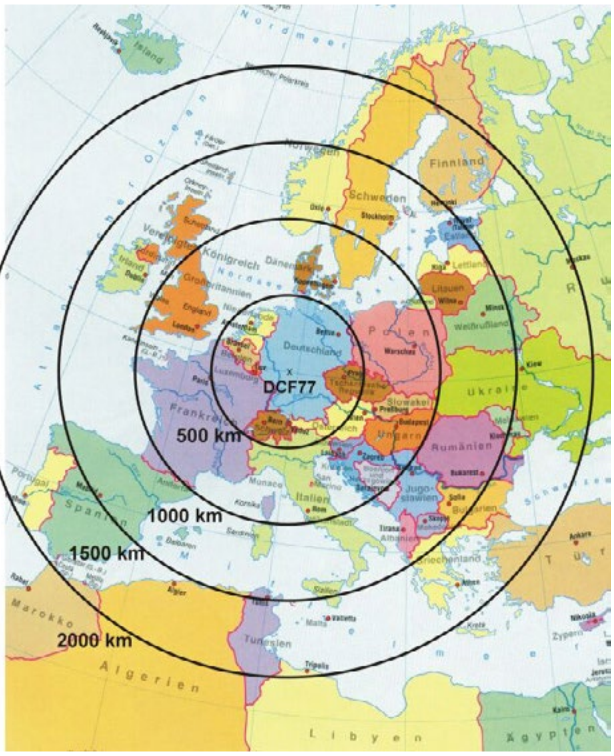


Figure 30: Coverage and range of DCF77 (PTB - National Metrology Institute, 2025)

5.7.3. APPLICATIONS AND BENEFITS

MSF is useful where GNSS signals are unavailable, since it provides a terrestrial backup for time synchronisation (NPL, 2025). It provides a highly accurate time signal which is maintained by atomic clocks (Galleon, 2003). Also, MSF is used as a provision of a precise time reference to synchronise computer networks and related servers using the Network Time Protocol (NTP), which is most important for telecommunications and data logging (Galleon, 2025).

The high accuracy DCF77 service is frequently utilised by private users as radio-controlled clocks, with increased usage for wristwatches and alarm clocks (Callea Design, 2024). The automatic operation nature of this service means that clocks and radio-devices will synchronise automatically (Callea Design, 2024). DCF77 is indoor-capable, meaning that longwave signals can penetrate buildings, and the reception is not impaired by obstacles. DCF77 provides a reliable service, since replacement transmitters and standby antennas are readily available to replace degraded infrastructure (PTB - National Metrology Institute, 2025).

5.7.4. CHALLENGES AND LIMITATIONS

Some reception problems may occur due to local interferences from electrical equipment and a reduced local signal due to screening by nearby metal work (NPL, 2025). Also, the issue of fading can occur at 600-1100 km due to ground and sky wave interference (PTB - National Metrology Institute, 2025).

The potential exists for short interruptions when changing over to replacement transmitters and during thunderstorms (PTB - National Metrology Institute, 2025). Over distances ranging from 600 to 1100 km, ground and sky waves may be of equal size, potentially leading to mutual fading (PTB - National Metrology Institute, 2025).

5.8. NEXT GENERATION POSITIONING (802.11AZ)

5.8.1. SYSTEM OVERVIEW

The IEEE 802.11az standard, also known as Next Generation Positioning (NGP), is an amendment to the IEEE 802.11 (Wi-Fi) standard, published in March 2023 (IEEE, 2023). It significantly enhances Wi-Fi-based positioning capabilities, particularly for indoor environments, by improving accuracy, security, scalability, and energy efficiency compared to prior standards like 802.11-2016 (Fine Timing Measurement, FTM). Devices are beginning to appear on the market (IEEE Standards Association, 2023).

802.11az uses the following positioning techniques:

- Time-Based (ToA/RTT): Uses Round-Trip Time (RTT) with Time of Arrival (ToA) and Time of Departure (ToD) timestamps to estimate distances between a Station (STA) and multiple Access Points (APs) (IEEE, 2023)
- Angle-Based (AoA/AoD): Supports Angle of Arrival (AoA) and Angle of Departure (AoD) measurements, especially in mmWave bands, using beamforming. This allows azimuth and elevation estimation for precise 3D positioning (IEEE, 2023)
- Multi-Path Resilience: Leverages MIMO and wide bandwidths (up to 160 MHz in Wi-Fi 6, 320 MHz in Wi-Fi 7) to mitigate multipath effects, improving accuracy in complex indoor environments

5.8.2. PERFORMANCE METRICS

802.11az can cover both the indoor environment between 30-50 m and the outdoor environments up to 100 m. It supports sub-6 GHz and 60 GHz frequencies, specifically the 5.9 GHz band, which allows for operation in the 2.4 GHz, 5 GHz and 6 GHz bands (IEEE Standards Association, 2023). 802.11az can achieve sub-1-meter accuracy typically ~0.1 meters (10 cm or ~4 inches) in optimal conditions, compared to 1–2 meters for 802.11-2016 FTM. In mm Wave bands, centimetre-level accuracy is possible due to the high temporal resolution from multi-GHz bandwidths (IEEE, 2023) (IEEE Standards Association, 2023). The cost, size, weight, and power required for this terrestrial RF system is minimal.

5.8.3. INFRASTRUCTURE REQUIREMENTS

802.11az can use two different frequency bands for its operation:

1. Sub-6 GHz is the primary band for most deployments as it offers sub-1-meter accuracy with wide bandwidths (160 MHz in Wi-Fi 6, 320 MHz in Wi-Fi 7).
2. mmWave (above 45 GHz) enables centimetre-level accuracy using beamforming and multi-GHz bandwidths which is useful for high-precision applications but limited by the range and penetration.

Wi-Fi 6e compatible applications along with Wi-Fi firmware updates are needed to support the 802.11az service (Segev, 2023). The infrastructure set-up needs a transmission power of less than 1W, which is required in a dense environment. In turn, this supports hundreds of devices simultaneously in crowded settings, like malls and stadiums, using trigger-based ranging and OFDMA (Orthogonal Frequency Division Multiple Access) from Wi-Fi 6. This reduces medium utilization to <10% in dense deployments making 802.11az a scalable and efficient service.

802.11az is considered energy efficient for two reasons. Firstly, it eliminates the FTM “bursts” characteristic of 802.11-2016, thereby reducing the power consumption by around 10 times. Also, battery life can be preserved because dynamic measurement rates (0.01 Hz to 10 Hz) can adapt to movement.

5.8.4. APPLICATIONS AND BENEFITS

802.11az has the potential to support more accurate indoor navigation through utilising MIMO technology. For example, it can be applied to micro-targeting for retail and warehouse uses as well as tracking asset locations, like tools and equipment (IEEE Standards Association, 2023) (GNS Wireless, 2025). The ability to provide location-based services helps provide personalised recommendations and targeted advertising to users based on their location within a venue (GNS Wireless, 2025). 802.11az also allows for secure authenticated and private positioning; for example, when using a smartphone to pay directly at the point of sale (IEEE Standards Association, 2023). Using 802.11az means first responders can receive accurate location information in emergency situations, enabling quicker and more efficient responses (GNS Wireless, 2025). This is also a scalable service, facilitating the simultaneous connections of hundreds of devices, thereby improving connectivity in dense environments such as stadiums (IEEE Standards Association, 2023).

5.8.5. CHALLENGES AND LIMITATIONS

The indoor environment can cause multi-path challenges since reflections within the space can degrade accuracy; however, this can be mitigated by MIMO or wide bandwidths. This service requires multiple APs (minimum three for trilateration) with 802.11az support, which may limit the adoption until the Wi-Fi 6/7 deployment expands. The mmWave can cause constraints due to the high accuracy of this band being limited by short range and poor penetration through walls. In comparison, 5G NR faces similar multi-path issues yet benefits from denser gNB deployments in urban areas and sidelink for device-to-device positioning—an attribute that 802.11az lacks. Overall, 802.11az is still under development; so it is not yet clear when forms of NGP will become widely available (GNS Wireless, 2025).

5.9. BLUETOOTH LOW ENERGY (BLE)

5.9.1. SYSTEM OVERVIEW

Bluetooth Low Energy (BLE) is widely used for positioning due to its low power consumption, cost-effectiveness, and compatibility with devices like smartphones and IoT gadgets. From a positioning standpoint, BLE enables location-based services through techniques leveraging signal characteristics and device proximity. Bluetooth LE allows users to produce locations based on the Angle of Departure and Angle of Arrival.

A Bluetooth beacon is a popular solution to asset tracking. The method involves tracking a tag's position through comparing the reference signal strength encoded in the beacon message with the strength of the received signal. The beacon's position is triangulated using 3 or more receivers to approximate its position (Pau, Arena, Engida Gebremariam, & You, 2021).

Key Positioning Techniques:

- Proximity Detection:
  - BLE beacons broadcast signals with unique identifiers
  - Devices detect these signals to determine proximity (e.g., "near," "far") based on signal strength (RSSI - Received Signal Strength Indicator)
  - Use case: Retail notifications when a customer is near a specific store section.
- Trilateration/Triangulation:
  - Trilateration: This uses RSSI to estimate distances from multiple BLE beacons (typically 3+). By calculating the intersection of distance circles, a device's position is estimated.
  - Triangulation: This uses the angle of arrival (AoA) or angle of departure (AoD) of BLE signals (introduced in Bluetooth 5.1) to determine direction and position.
  - Accuracy: Typically 1-5 meters, depending on environment and calibration
- Fingerprinting:
  - Involves creating a map of RSSI values at known locations in an environment (offline phase)
  - Devices compare real-time RSSI measurements to the map to estimate location (online phase).
  - This is suitable for complex indoor environments with obstacles; accuracy can reach 1-3 meters.

Advantages for Positioning

- Low Power: BLE's energy efficiency suits battery-powered beacons and devices.
- Ubiquity: This is supported by most smartphones, wearables, and IoT devices.
- Scalability: Beacons are inexpensive and easy to deploy in large numbers.
- Indoor Suitability: Works well where GPS struggles, like inside buildings.

5.9.2. PERFORMANCE METRICS

Bluetooth LE is a short-range service operating in the frequency band between 2400 to 2483.5 MHz (Bluetooth, 2023). With low power consumption, a long battery life and low overall cost, this service lends itself well to positioning (Pau, Arena, Engida Gebremariam, & You, 2021). The accuracy of Bluetooth LE can vary: AoA/AoD accuracy is less than 1 metre, whereas RSSI accuracy sits between 1 and 5 metres (Pau, Arena, Engida Gebremariam, & You, 2021) (Spachos, 2020) (Zafari, 2019) (Faragher, 2015).

5.9.3. INFRASTRUCTURE REQUIREMENTS

Bluetooth LE beacons (transmitters and anchors) and receivers (tags and user devices) are needed for this service to function. Alongside this hardware, positioning software is required (Pau, Arena, Engida Gebremariam, & You, 2021).

5.9.4. APPLICATIONS AND BENEFITS

Bluetooth LE is useful in many use cases across multiple sectors, such as industrial, tourism, and automotive. Seamless navigation—both indoor and outdoor—is useful for asset tracking in warehouses or retail scenarios where BLE can provide controlled and secure building access (NAVAC, 2024). BLE also facilitates proximity marketing which helps increase sales and retail traffic by sending promotions to visitor phones to attract a higher customer base. In the tourism sector, Bluetooth can be used in museums, airports, and other attractions to provide point of interest information to enhance visitor experience. For the automotive industry, BLE can provide passive keyless entry (PKE) to unlock a vehicle on approach (Bluetooth, 2022) (Pau, Arena, Engida Gebremariam, & You, 2021).

5.9.5. CHALLENGES AND LIMITATIONS

The method used with Bluetooth beacons does not provide the level of accuracy that is required for inventory management systems (Pau, Arena, Engida Gebremariam, & You, 2021). Location accuracy can be impacted by changes in the environment, such as humidity and movement of objects (Pau, Arena, Engida Gebremariam, & You, 2021). Also, the short-range nature of the BLE signals limits its uses in outdoor scenarios—a key factor limiting its potential to become a global service (NAVAC, 2024). Indoor multipath effects from signal reflections and signal interferences from walls, furniture or people can skew measurements and weaken RSSI, thereby reducing its accuracy (Zafari, 2019). BLE signals are vulnerable to spoofing, which impacts positioning integrity. Furthermore, BLE has calibration needs. RSSI-based methods require environmental calibration for reliable distance estimates (Zafari, 2019).

5.10. VHF (VERY HIGH FREQUENCY) DATA EXCHANGE SYSTEM (VDES) R-MODE

5.10.1. SYSTEM OVERVIEW

This is an emerging technology and a potential alternative PNT in the maritime domain. Maritime navigation traditionally relies on GNSS; however; VDES could successfully work alongside GNSS due to its ranging capabilities. VDES R-mode is currently at a low technology readiness level (TRL), and standardisations are not yet in place. Projects have been developed to further refine VDES-R user technologies as an alternative PNT (European Space Agency , 2024) (European Space Agency, 2024).

R-Mode ranging involves sending ranging sequences alongside the scheduled Automatic Identification System (AIS) and VDES messages. The Time of Arrival (TOA) method can determine distance between terminal (ship) and base station (shore). This system can operate in a harsh marine environment where there is a low signal-to-noise ratio (SNR) (Bronk, Koncicki, Lipka, Niski, & Wereszko, 2021).

5.10.2. PERFORMANCE METRICS

VDES R-Mode operates in the VHF maritime band covering channels within the 156.025-162.025 MHz range, channels 25 kHz wide with centre frequencies ranging between 161.800 MHz to 161.875 MHz (Wirsing, Dammann, & Raulefs, 2021). This service has a range of 100 km with the VHF bands and 300 km with medium frequency at an accuracy ranging from 10 to 100 metres (Lazaro, Raulefs, Bartz, & Jerkovits, 2021). The associated size, weight, and power required for VDES R-mode is low with a medium cost range.

5.10.3. INFRASTRUCTURE REQUIREMENTS

VDES R-mode requires shore-side and ship-side infrastructure, which are adaptions of AIS and DGPS infrastructure. The ships themselves need receivers to process the signals provided by the shore stations for positioning purposes (Lazaro, Raulefs, Bartz, & Jerkovits, 2021). The transmission power needed for this service ranges between 25 to 100 W. Also, VDES R-Mode utilizes ϖ/4-QPSK modulation for data transmission (Wirsing, Dammann, & Raulefs, 2021).

5.10.4. APPLICATIONS AND BENEFITS

VDES R-mode can be used as a GNSS contingency for navigation where GNSS signals are unavailable or compromised (Gutierrez, ESA-backed VAUTAP Advances VDES R-Mode for maritime PNT, 2025). Importantly, maritime safety is enhanced through the use of VDES R-Mode as it provides an alternative source of positioning data and contributes to the resilience of maritime navigation systems (Gutierrez, ESA-backed VAUTAP Advances VDES R-Mode for maritime PNT, 2025). Existing infrastructure can be used for implementation, since it uses VDES and AIS shore-based stations that are already present, eliminating the requirement for new and costly infrastructure (Lazaro, Raulefs, Bartz, & Jerkovits, 2021). Furthermore, as a result of operating within the VHF band, VDES R-Mode is less susceptible to signal interference, thereby providing more reliable coverage compared to higher frequency GNSS signals (Gutierrez, ESA-backed VAUTAP Advances VDES R-Mode for maritime PNT, 2025).

5.10.5. CHALLENGES AND LIMITATIONS

VDES R-mode is vulnerable to jamming attacks within its frequency band (Lazaro, Raulefs, Bartz, & Jerkovits, 2021). Also, it is currently at a low TRL and is not currently standardised, although there have been trials carried out in the Baltic Sea area (Interreg, 2021) (European Space Agency, 2024).

VDES R-mode uses GNSS signals to establish precise time synchronisation and positional data, enabling vessels to calculate slant range distances to other VDES-equipped stations or satellites. This dependency means that disruptions to GNSS, such as jamming, spoofing, or satellite outages, can degrade VDES R-mode performance, potentially compromising navigation accuracy. Additionally, VDES R-mode requires robust terrestrial and satellite-based infrastructure, including coastal base stations and satellite transceivers, to relay data and maintain connectivity, particularly in remote maritime environments where line-of-sight communication may be limited. The system's effectiveness thus hinges on the reliability and availability of these interconnected systems, possibly necessitating redundant or alternative systems to mitigate risks from infrastructure failures.

5.11. ULTRA WIDE BAND (UWB)

5.11.1. SYSTEM OVERVIEW

Ultrawideband (UWB) technology is a short-range, high-bandwidth wireless communication protocol that excels in precise positioning and time transfer due to its unique signal characteristics. From a positioning perspective, UWB offers superior accuracy compared to technologies like Bluetooth Low Energy (BLE), making it ideal for applications requiring centimetre-level precision. Its ability to transfer time with high precision further enhances its utility in synchronisation and location-based systems.

UWB operates across a wide swath of the spectrum, enabling it to deliver bandwidth at low power levels, predominantly at short ranges. It uses time-of-flight (ToF) information to calculate distance and direction (Schrock, 2021) (Viot, Bizalion, & Seegars, 2021).

Positioning Techniques:

- Time-Based Positioning Techniques - Time of Flight (ToF): Measures signal travel time between devices (1 ns ≈ 30 cm) (Pau G. &., 2021)
- Two-Way Ranging (TWR): Devices exchange pulses to compute round-trip time, with double-sided TWR (DS-TWR) improving accuracy by mitigating clock offsets (Ledergerber, 2018)
- Time Difference of Arrival (TDoA): Uses time differences in signal reception at multiple anchors to triangulate position
- Angle of Arrival (AoA): Determines signal direction using phase differences across antenna arrays, enabling 3D localisation

Advantages for Positioning:

- High Precision: Short pulses minimize multipath interference, distinguishing direct signals from reflections (Zand, 2019)
- Robustness: Performs well in cluttered environments (e.g., factories, offices)
- Low Latency: Supports real-time applications like AR or robotics (Pau G. &., 2021)
- 3D Capability: Enables precise 3D localisation for drones or inventory tracking

UWB's precise timing capabilities enable high-accuracy time transfer, critical for synchronisation and positioning.

Short pulses allow sub-nanosecond timestamping of signal transmission/reception. TWR and TDoA protocols facilitate clock synchronisation via timestamp exchanges (IEEE, 2020).

5.11.2. PERFORMANCE METRICS

UWB can cover a range of less than 10m at a frequency range between 3.1 and 10.6 GHz, achieving an accuracy of 10 to 30 cm (line-of-sight) (Ofcom, 2005). Additionally, the time transfer accuracy is between 1 and 10 nanoseconds, outperforming both BLE, which has an accuracy of microseconds, and Wi-Fi, which is accurate to the millisecond degree (Sang, 2021). The size, weight, and power associated with UWB is minimal, but the associated costs are medium to high (Viot, Bizalion, & Seegars, 2021).

5.11.3. INFRASTRUCTURE REQUIREMENTS

UWB anchors and tags are needed for service, so the infrastructure required is simple. There are currently no practical measurements that reflect the transmission power needed (Ofcom, 2005).

5.11.4. APPLICATIONS AND BENEFITS

UWB is a high precision service that is designed to function across a wide range of frequencies and just below noise floors to reduce the amount of interference with other signals (Schrock, 2021) (Viot, Bizalion, & Seegars, 2021). There is flexibility with this service as the update rate can be sacrificed for an improved range (Schrock, 2021). UWB's main uses include logistics, indoor and outdoor works, and smartphones (Apple U1 for spatial awareness and enhanced location accuracy) (Apple, 2021) (Schrock, 2021).

5.11.5. CHALLENGES AND LIMITATIONS

UWB is very short-range and NLOS (non-line-of-sight), which reduces its accuracy, although it is still better than that of BLE (Ofcom, 2005) (Stone, 2021). Additionally, beyond 50 to 100 m, the precision of UWB degrades (Abdulrahman, et al.). The implementation cost of UWB positioning systems is high due to the hardware requirements and dense infrastructure needs; the hardware required is more expensive than that required for BLE (Pau G. &., 2021) (Feasycom, 2024). Multipath propagation can occur as signals bounce off other surfaces (US Department of Transportation, n.d.). Signal interference can also occur due to the coexistence with Wi-Fi/5G, which can degrade UWB performance (Abdulrahman, et al.). The power consumption of UWB is higher than BLE for continuous use, and the clock drift requires periodic recalibration (Abdulrahman, et al.). UWB is not scalable because the synchronisation overhead increases with device count.

5.12. NEXTNAV RF POSITIONING AND TIME SYSTEM

5.12.1. SYSTEM OVERVIEW

NextNav, a commercial PNT provider, (NextNav, 2025) provides services specialising in 3D geolocation solutions that enhance traditional GPS capabilities, particularly in environments where GPS signals are unreliable. Its primary offerings, the Pinnacle and TerraPoiNT systems, deliver accurate, reliable, and resilient positioning for applications in public safety, critical infrastructure, commercial services, and emerging technologies like IoT and autonomous systems (NextNav, 2025).

NextNav owns 8 megahertz of low band spectrum that covers 2.4 billion MHz-POPs at 900 MHz (NextNav, 2025).

- Pinnacle – a service that provides 3D geolocation (NextNav, 2025). Pinnacle provides high-precision vertical (z-axis) positioning, achieving floor-level accuracy (within 3 meters, 94% of the time) using barometric pressure sensors in devices like smartphones, combined with NextNav's altitude reference network. Pinnacle leverages a terrestrial network of altitude stations and barometric pressure-based algorithms to optimize altitude data (Figure 31). It integrates with standard 2D location data (from GPS or other sources) to produce 3D positioning. It has been deployed nationwide in the U.S., covering over 4,400 cities and towns, addressing 90% of buildings taller than three floors. It operates in partnership with AT&T and FirstNet for public safety applications.
- Terrapoint – A full 3D PNT system designed as a terrestrial complement or backup to GPS, providing positioning, navigation, and timing in GPS-denied environments (e.g., indoors, urban canyons). Terrapoint utilises the Metropolitan Beacon System (MBS), a network of ground-based transmitters operating in the lower 900 MHz band (902–928 MHz). MBS transmits precisely timed signals, enabling receivers to use trilateration for high-precision 3D positioning. The signal is 100,000 times stronger than GPS, ensuring deep indoor penetration.

5.12.2. PERFORMANCE METRICS

NextNav's coverage extends 1-2 km indoors and through urban areas. It utilises a frequency band between 920 and 928 MHz and offers an accuracy of 1 to 3 metres for both horizontal and vertical positioning, surpassing GPS in challenging or harsh environments (Saines, 2023) (Nextnav, 2025). The associated size, weight, and power associated with NextNav receivers is minimal.

Figure 31: Pinnacle coverage map – 90% of buildings over 3 stories in the US (Nextnav, 2025)

5.12.3. APPLICATIONS AND BENEFITS

Pinnacle can be widely applied, because it uses barometric sensors that are already present in phones and tablets, thereby minimising the requirement for new infrastructure developments. Its implementation only requires simple software upgrades to devices which already have the barometric sensors. Pinnacle is available indoors and has a z-axis precision level. The network is maintained by NextNav, providing high availability (Figure 32), because data originates from a proprietary network operated and maintained by NextNav. Some uses extend to first responders locating victims, ensuring incident commanders' safety of personnel in the field, and service delivery for companies (Nextnav, 2025).

Performance Parameter (X days of GNSS outage)	1 day	14 days	100 days
Horizontal Accuracy (95%) m	11	11	11
Vertical Accuracy (95%) m	2	2	2
Availability (%)	99.96%	99.96%	99.96%
Continuity (per hour)	99.93%	99.93%	99.93%
Integrity (per hour)	100%	100%	100%
Time-To-Alarm (second)	60s	60s	60s
Network Timing Accuracy to UTC (3sigma) ns	9 =	*120*	*900 =*
Network Time synchronisation (ADEV)	9e-13	*3e-14*	*3e-14*
Network Timing Stability (ADEV)	4e-14	*2e-14*	*2e-14*
First time to provide services upon cold start-up (including system and receiver contributions)	10 sec (PN receiver only)		
	7 min (T-receiver only)		
	15 min (System + receiver T- only)		
	43 min (System + receiver: PN or T)		

Figure 32: NEXTNAV Key Performance indicators (European Commission, 2023)

Terrapoint is an assured PNT (APNT) solution, and the position, navigation, and timing elements of this service can be offered individually. It is long-range and low-cost, and the waveforms used are compatible with those used in GPS receivers. An overlay network can provide PNT information that is independent of the communication network, and it can also provide GPS interference detection (Nextnav, 2025).

5.12.4. CHALLENGES AND LIMITATIONS

NextNav is limited to licensed geographies and is US-focused, so it is not yet operational in the UK. Therefore, while the technology can be deployed in the UK, NextNav is not focussed on its deployment. The UK's 900 MHz band is primarily allocated for mobile communications like 4G and 5G, with no indication of NextNav's involvement. Terrapoint is dependent on the widespread deployment of the related infrastructure as well as the maintenance of it. This will require investment from various stakeholders, including governments agencies (NextNav, 2025). The systems are designed to complement the existing 5G infrastructure; however, ensuring compatibility with many different devices and networks will require vast amounts of testing and standardisation (Inside GNSS, 2025).

5.13. LOCATA POSITIONING AND TIMING SYSTEM

5.13.1. SYSTEM OVERVIEW

Locata, a commercial PNT provider, supplies precise positioning systems in environments where GPS is marginal or unavailable. It is not designed to replace GPS but instead acts as a local extension of GPS. Locata can synchronise transmitters to an accuracy of sub-billionth of a second without atomic clocks. LocataLite transceivers create a positioning network called LocataNet, which can operate in combination with or independent of GPS (Locata, 2025) (Locata, 2025) (Luccio, PNT by other means: Locata, 2023).

5.13.2. PERFORMANCE METRICS

Each LocataNet cluster can reach a range between 1 and 10 km at a frequency of 2.4 GHz (Locata, 2022). This provides a positioning accuracy of less than 5 cm and a timing accuracy of 1.7 ns (European Commission, 2023). The size, weight, and power associated with the ground system is moderate and considered low for the receivers. Due to the need for custom hardware, the cost range is considered high.

5.13.3. INFRASTRUCTURE REQUIREMENTS

For a functioning Locata service, LocataLite terrestrial transceivers are needed along with precision time nodes embedded in a LoS mesh (Locata, 2025). The transmission power for this set up is variable.

5.13.4. APPLICATIONS AND BENEFITS

TimeLoc allows Locata to achieve nano-second level synchronisation by utilising simple receivers with one-way ranging signals, as is the case with GPS (Locata, 2025). LocataNet can provide local control and regional coverage. This technology covers both transmission and receiver sides of the positioning network, which allows for the system to meet localised demand for availability, accuracy, and reliability. Locata provides flexibility, since the signal integrity is guaranteed—even in more demanding environments (Locata, 2025). The uses of Locata extend over multiple industries and sectors which are listed below.

Uses:

- Open cut mining
- Aviation
- Independent of GPS
- Indoors
- Urban areas
  - Military
  - Port automation
  - Warehousing markets

5.13.5. CHALLENGES AND LIMITATIONS

Locata involves large upfront and ongoing expenses, as it is on a network of ground-based infrastructure which is expensive to deploy and maintain. Also, the potential exists for inaccuracies which are often linked to issues with the infrastructure. Locata systems track devices and collect location data, which raises privacy concerns. Finally, environmental factors or other electronic devices can cause signal interference, thereby decreasing the integrity of Locata as a PNT service (Luccio, PNT by other means: Locata, 2023).

5.14. ELORAN

5.14.1. SYSTEM OVERVIEW

eLoran stands for enhanced long-range navigation and is built upon the foundation of Loran-C. Its main purpose is to provide a backup system for PNT. It is an internationally standardised PNT service (SAE International, 2018) used by a range of modes of transport (Heliwg, Offermans, Stout, & Schue, 2011) (Department for Science, Innovation, and Technology, 2023).

5.14.2. PERFORMANCE METRICS

eLoran covers continental areas with a radius of up to 1,200 km from the transmitter, and 1,800 km from the transmitter in coastal waters at a frequency between 90 and 110 kHz (Fischer & Courtois, 2018) (Ofcom, 2024). eLoran has a “default” positioning accuracy of 50 m and a timing accuracy of 300 ns or better, depending on infrastructure configuration. In the maritime sector, the harbour entrance approach (HEA) requirement is for 10 m, 95% of the time. For eLoran to achieve this, it must use Additional Secondary Factors (ASF) and differential reference stations (Lo, 2009). Some testing has shown that with respect to timing, accuracies of <100 ns are possible (Curry C. , 2014) (Li Y. H., 2020), and that the required positional accuracies are achievable (Heliwg, Offermans, Stout, & Schue, 2011).

5.14.3. INFRASTRUCTURE REQUIREMENTS

eLoran requires modernised control centres, transmitting stations, and monitoring sites to function (Heliwg, Offermans, Stout, & Schue, 2011). The transmission power for eLoran can be as much as 1 MW, equivalent to 60 dBW. High transmission power is needed to maintain a minimum signal to noise ratio of 10 dB (Ofcom, 2024). Differential eLoran reference stations correct for temporal variations in the nominal primary, secondary and additional secondary factors (PF, SF, ASF, respectively).

eLoran uses the concept of primary, secondary and additional factors to correct for various factors that impact the propagation of the transmitted signal from transmitter to receiver (Lo, 2009).

- Primary Factors – to account for the time of propagation (time of flight) of the eLoran signal through the atmosphere, accounting for the refraction for air
- Secondary Factors – Accounts for the difference in propagation time from an eLoran transmitter propagating over sea water
- Additional Secondary Factors – is a term to account for the extra delay on the arrival of the eLoran signal at the receiver due to propagation over a land path. Different land types (granite, sandstone, fields, mountains) can impact the signal, such that accuracy may vary from tens to hundreds of metres. It can also vary temporally.

These factors can be modelled and measured and the necessary coefficients either loaded into receivers, or transmitted over the differential link, to be applied to the position and time processing algorithm. In this way, the maritime compliant accuracies can be achieved.

5.14.4. APPLICATIONS AND BENEFITS

eLoran is GNSS independent; therefore, it can be used to complement GNSS to provide system robustness and reliance (GLA, 2006) (Heliwg, Offermans, Stout, & Schue, 2011). This was demonstrated by the General Lighthouse Authority (GLA) who trialled eLoran in 7 major ports along the east coast of the UK as backup GPS for maritime navigation purposes (GLA Research and Development, 2023).

These trials showed that eLoran, as a positioning and timing source, was accurate to less than 10 m, 95% of the time. eLoran could be used in telecommunications due to its ability to provide highly precise time and frequency references (Heliwg, Offermans, Stout, & Schue, 2011). The autonomous, unmanned, self-controlled, and self-supporting nature of eLoran makes it suitable for voice and internet communications (Heliwg, Offermans, Stout, & Schue, 2011). By operating at a low frequency, this system provides an extensive coverage area which reduces the need for many transmission sites. Additionally, low frequency operation means eLoran is more resilient to jamming and spoofing interference and able to penetrate buildings and dense foliage, consequently providing availability in challenging environments (GLA, 2006) (Ofcom, 2024). eLoran could be useful to many sectors and industries, including those listed below (GLA, 2006) (NLAI, 2020).

- Maritime navigation
- Aviation support
- Timing for critical infrastructure
- Emergency services and public safety

5.14.5. CHALLENGES AND LIMITATIONS

Currently, there is limited infrastructure for the deployment of eLoran. Trials in the UK ended in 2015, and there are no public plans for reactivation. Therefore, there are uncertainties surrounding the timelines for deployment and geographic coverage for eLoran (Fischer & Courtois, 2018). Signal interference may occur from other low frequency sources near a receiver, such as power lines, which is a dominant issue for land-mobile and handheld applications of eLoran (Fischer & Courtois, 2018). Also, space weather can cause ionospheric scintillation, disrupt power networks, and apply forces to satellites which can impact their orbit (Grant & Goward, 2022), which means that unless systems which provide services to eLoran systems, are protected, eLoran becomes a secondary impacted system.

The mapping and delivery of ASF coefficients can be problematic, and infrastructure is needed to update the values used in the receiver. Some tests have been done to explore this (European Space Agency, 2021).

5.15. 198 KHZ LONG WAVE

5.15.1. SYSTEM OVERVIEW

198 kHz is used by the BBC to broadcast BBC Radio 4. It carries radio data, including the time-of-day signal and tele-switch control signal for electricity meters like Economy 7. The signal is transmitted from Droitwich (Keep Longwave, 2024) (Mb 21, 2023).

5.15.2. PERFORMANCE METRICS

The 198 kHz service is a UK-wide groundwave. General specifications are listed below (Signal Identification Guide (SIGIDWIKI), 2025) (Laverty, 1999):

- Carrier Frequency: 198 kHz
- Modulation: Bi-phase phase-shift keying (PSK) of a 25 Hz subcarrier
- Data Rate: 25 bps (from Manchester encoding)
- Data Transmission: 30 blocks of 50 bits per minute, with each block transmitted over 2 seconds
- Data Block Structure: Each block consists of a 6-bit header (including a synchronisation bit and a 4-bit Block Application Code), 32 bits of user data, and a 13-bit CRC tail
- Synchronisation: The first bit of each block is a fixed logic 1 for synchronisation
- Data Payload: The 32 bits of user data can carry an array of information, including time codes and control signals for electricity meters
- CRC: A 13-bit CRC tail is used for error detection and correction
- Time accuracy is heavily dependent on the quality of the receiver equipment, specifically oscillator quality, but frequency distribution accuracy is 10^{-11} (Laverty, 1999).

5.15.3. INFRASTRUCTURE REQUIREMENTS

Low frequency radio receivers and a transmission power of up to 500 kW is required for 198 kHz.

5.15.4. APPLICATIONS AND BENEFITS

The low frequency signal allows for a high power and wide area coverage that is not easily susceptible to interference (Gutierrez, Brussels View: Bringing New A-PNT Opportunities to Life, 2023). The accurate time synchronisation characteristic of 198 kHz makes it an important service for applications with critical infrastructure. 198 kHz can have multiple uses and applications which are outlined in the list below (Gutierrez, Brussels View: Bringing New A-PNT Opportunities to Life, 2023).

- Marine navigation
- Air traffic control
- Precision agriculture
- Emergency response
- Military

5.15.5. CHALLENGES AND LIMITATIONS

Longwave transmissions were planned to be shut down in 2024, but this deadline has been extended to 2025 (Keep Longwave, 2024).

- Ionospheric Effects and Skywave Interference: LF signals like 198 kHz propagate via ground waves (reliable for up to 1000–2000 km) and skywaves, where signals reflect off the ionosphere. At night, the ionosphere's D-layer dissipates, enhancing skywave propagation, which interferes with ground wave signals. This causes phase shifts and amplitude variations, degrading timing and positioning accuracy. Skywave interference introduces errors in Time of Arrival (ToA) or Time Difference of Arrival (TDoA) measurements, critical for positioning. For example, during twilight (dusk and dawn), ionospheric transitions cause significant signal fluctuations, leading to bearing errors of ±10 degrees or more, as seen in NDB.

- The BBC Radio 4 signal at 198 kHz is known to suffer from skywave effects, particularly at ranges beyond 500 km, making it unreliable for precise PNT without advanced correction algorithms (International Civil Aviation Authority, 2023).
- Limited Transmitter Density: Effective PNT requires multiple synchronised transmitters for trilateration or triangulation. At 198 kHz, the number of available transmitters is singular, limiting the use for PNT, but it can be good for timing and frequency signal distribution (Laverty, 1999).
- Unlike GNSS or 5G NR signals, 198 kHz is not designed for PNT. Instead, it is primarily used for audio broadcasting, with timing tied to program schedules rather than atomic clocks.
- Receiver Complexity and Cost: Extracting PNT information from 198 kHz requires specialised software-defined radios (SDRs) or receivers capable of processing LF signals, accounting for ionospheric effects and compensating for lack of synchronisation. These receivers can be more complex than those for GNSS or cellular signals.
- Regulatory and Spectrum Constraints: The LF band, including 198 kHz, is heavily regulated for broadcasting and other uses (e.g., maritime communication, time signals). Repurposing these frequencies for PNT may face regulatory hurdles, especially in regions with competing spectrum demands.

5.16. SIGNALS OF OPPORTUNITY (SOOP)

Terrestrial Radio Frequency (RF) Signals of Opportunity (SoOP) refer to ambient radio signals, originally transmitted for purposes other than navigation, that can be exploited for PNT. These signals include AM/FM radio, cellular (e.g., 4G LTE, 5G), digital television (DTV), Wi-Fi, and other broadcast or communication signals. Unlike GNSS or systems like Locata or NextNav, which are designed specifically for PNT, SoOP leverages existing infrastructure, making it an alternative or complement in environments where GNSS signals are unreliable or unavailable, such as urban canyons, indoors, or GNSS-jammed areas. SoOPs lend themselves to uses for aircraft navigation due to the absolute positioning information that can be extracted from them. Also, SoOPs are widely available in areas of interest with a received carrier-to-noise ratio (CNR) of 20 to 30 decibels higher than that of GNSS (InsideGNSS, 2024)(Figure 33).

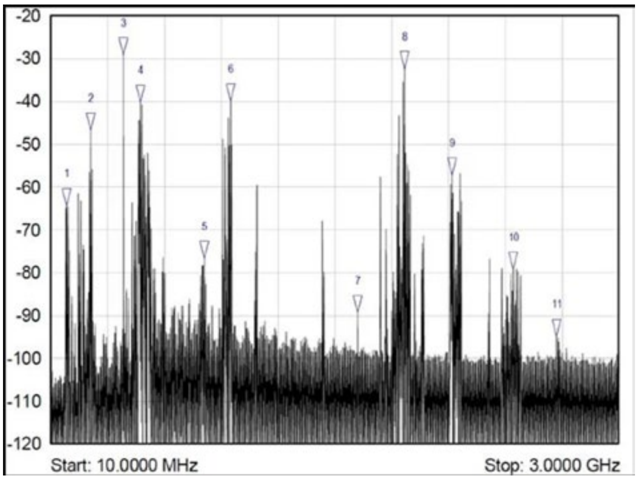


Figure 33: Between 10 MHz and 3 GHz, 11 signals present themselves as signals that can be utilised for PNT (Jones, 2018)

Signal Marker	Frequency	Level	Identity
1	93.72 MHz	-64.36 dBm	FM radio broadcast
2	219.3 MHz	-46.67 dBm	DAB radio
3	392.72 MHz	-29.10 dBm	TETRA
4	482.42 MHz	-40.24 dBm	Digital TV
5	817.3 MHz	-76.67 dBm	LTE (EUDD band)
6	954.84 MHz	-39.91 dBm	GSM (E-GSM band)
7	1.6246 GHz	-89.28 dBm	Iridium
8	1.8698 GHz	-32.37 dBm	GSM (DCS1800 band)
9	2.1209 GHz	-57.23 dBm	WCDMA (IMT band)
10	2.4439 GHz	-79.22 dBm	Wi-Fi (2.4 GHz band)
11	2.6711 GHz	-94.81 dBm	LTE (IMT-E band)

Figure 34: A table outlining the 11 signals that can be utilised between 10 MHz and 3 GHz for PNT (Jones, 2018)

5.16.1. METHODS FOR USING SOOP FOR PNT

Several techniques are employed to extract position and timing information from SoOP, each with specific signal processing requirements and applications:

- Time of Arrival (ToA):
  - Description: Measures the time it takes for a signal to travel from a known transmitter (e.g., a cellular base station) to the receiver. By using multiple ToA measurements from synchronised transmitters, a receiver's position can be calculated via trilateration.
  - Application: Used with cellular signals (e.g., LTE, 5G) or DTV signals, whereby transmitters are often synchronised with GNSS or other timing sources.
  - Example: ToA-based positioning with DTV signals exploits their broadband Orthogonal Frequency Division Multiplexing (OFDM) structure for precise timing (Navrátil, Karásek, & Vejražka, 2016).
- Time Difference of Arrival (TDoA):
  - Description: Measures the difference in arrival times of a signal at multiple receivers or from multiple transmitters to a single receiver. This method does not require strict synchronisation between the receiver and transmitters, reducing complexity.
  - Application: Differential TDoA (dTDOA) is used in cellular networks (e.g., IEEE 802.11 Wi-Fi) to eliminate the need for clock synchronisation, making it suitable for large-scale industrial networks.
  - Example: A dTDOA method proposed for asynchronous broadcast signals (e.g., TV/AM) achieves positioning without requiring round-trip communications (Coluccia, Ricciato, & Ricci, 2014).
- Received Signal Strength (RSS):
  - Description: Estimates position based on the strength of received signals, which decreases with distance from the transmitter. RSS is often combined with fingerprinting, where a database of signal strengths at known locations is used for position matching.
  - Application: Common in Wi-Fi and Bluetooth-based positioning systems due to their widespread availability in indoor environments
  - Example: Wi-Fi-based positioning uses RSS to estimate a user's location by matching signal footprints from access points (Guangteng Fan, 2024).
- Angle of Arrival (AoA):
  - Description: Determines the direction of the incoming signal using antenna arrays or beamforming techniques. By combining AoA measurements from multiple transmitters, a position can be triangulated.
  - Application: Used in 5G systems with phased array antennas, which support precise beamforming for both communication and positioning
  - Example: AoA is employed in military and defence applications to locate emitters (e.g., enemy radars) for intelligence purposes (CRFS, 2025).
- Doppler-Based Positioning:
  - Description: Exploits the Doppler shift caused by relative motion between the receiver and transmitter to estimate velocity or position. This is particularly useful for dynamic platforms like aircraft or drones.
  - Application: Applied in high-altitude aircraft using cellular signals, where Doppler estimates are critical for tracking signals in fast-moving environments.
  - Example: Radio Simultaneous Localisation and Mapping (SLAM) uses Doppler measurements from cellular signals to map transmitter locations and navigate in GNSS-denied environments (Marquand, 2024).
- Hybrid Methods:
  - Description: Combines multiple measurements (e.g., RSS, ToA, TDoA) or integrates SoOP with other sensors (e.g., Inertial Measurement Units or IMUs, odometers, or vision systems) to improve accuracy and robustness.
  - Application: A hybrid localisation method using GSM RSS, timing advance, and GPS ToA measurements which achieves better accuracy than standalone methods (Coluccia, Ricciato, & Ricci, 2014)
  - Example: Collaborative Opportunistic Navigation (COpNav) fuses SoOP with IMU and other sensors for robust PNT in complex environments.

5.16.2. BENEFITS OF USING SOOP FOR PNT

- Availability in GNSS-Denied Environments:
  - SoOP are robust in urban canyons, indoors, and areas with GNSS jamming or spoofing, as they use stronger terrestrial signals (e.g., cellular signals at -60 to -90 dBm vs. GNSS at -130 dBm) (Winter, Morrison, & Sokolova, 2023).

- Example: Cellular signals provided meter-level navigation on ground vehicles and submeter accuracy on UAVs in GPS-jammed tests at Edwards Air Force Base.

- Cost-Effectiveness:
  - Leverages existing infrastructure (e.g., cell towers, TV broadcast towers, Wi-Fi access points), eliminating the need for dedicated PNT systems
  - Example: Locata, a terrestrial RF-based system, uses a network of transceivers (LocataLites) to provide high-accuracy PNT without GNSS dependency (Rizos, 2019).
- High Signal Strength:
  - Terrestrial signals are significantly stronger than GNSS signals, making them less susceptible to interference and better suited for penetrating buildings.
  - Example: DTV signals, with their broadband nature, offer robust positioning in urban environments (Navrátil, Karásek, & Vejražka, 2016).
- Resilience to Weather:
  - Unlike GNSS, many SoOP (e.g., AM/FM, cellular) are unaffected by weather conditions like rain, fog, or snow, ensuring reliable PNT.
  - Example: Cellular signals have maintained navigation performance in adverse weather during NAVFEST experiments (Inside GNSS, 2024).
- Support for Timing Applications:
  - Synchronised terrestrial signals (e.g., LTE, 5G) can provide precise timing for applications like network synchronisation or financial transactions.
  - Example: LTE signals evaluated for time holdover demonstrated stability for PNT applications over extended periods (Winter, Morrison, & Sokolova, 2023).

5.16.3. LIMITATIONS AND CHALLENGES

- Limited Transmitter Density:
  - Reliable PNT requires multiple transmitters for triangulation or trilateration. In rural or remote areas, the density of SoOP (e.g., cell towers) may be insufficient.
  - Example: Cellular-based PNT struggles in areas with sparse base station coverage, limiting global applicability.
- Signal Synchronisation:
  - Many SoOP are not designed for navigation, lacking precise synchronisation. For example, AM/FM broadcast signals often have large clock offsets, complicating ToA or TDoA measurements.
  - Example: Asynchronous cellular signals exhibited discontinuous clock steering, frustrating online PNT estimation (Coluccia, Ricciato, & Ricci, 2014).
- Multipath and Interference:
  - Urban environments introduce multipath fading and shadowing, degrading signal quality and PNT accuracy.
  - Example: Wi-Fi signals in dense indoor settings suffer from multipath, reducing RSS-based positioning accuracy (Guangteng Fan, 2024).
- Signal Format Variability:
  - SoOP have diverse formats (e.g., OFDM for DTV, QPSK for cellular), requiring complex receivers to process multiple signal types simultaneously.
  - Example: StarNav's proposed device aims to sample multiple SoOP types but highlights the lack of commercial RF front ends for this purpose (Starnav, 2024).
- Dynamic Environments:
  - High vehicle dynamics (e.g., fast-moving aircraft) cause Doppler shifts and signal tracking issues, requiring advanced algorithms such as deeply coupled tracking loops.
  - Example: Traditional signal tracking loops failed during high-altitude aircraft tests, underscoring the necessity for specialised receivers (Marquand, 2024).
- Privacy and Security:
  - Using cellular or Wi-Fi signals for PNT raises privacy concerns, as tracking user locations may involve sensitive data.
  - Example: Internet radio advertising tracks listener metrics, highlighting privacy issues that extend to SoOP-based PNT (Makokha, 2021).
- Regulatory Constraints:
  - Spectrum allocation and interference management are complex, especially near international borders or in crowded spectrum environments.
  - Example: Meteorological uses of RF spectrum compete with commercial wireless services, risking interference with SoOP-based PNT (American Meteorological Society, 2017).

5.17. RADIO FREQUENCY IDENTIFICATION (RFID)

5.17.1. SYSTEM OVERVIEW

RFID has been commercially available since the 1970s and uses electromagnetic or electrostatic coupling in the radio frequency portion of the electromagnetic spectrum, thereby enabling the unique identification of objects, animals, or people. A device will read information through a wireless device or tag from a distance, so no physical contact needs to be made (Homeland Security, 2024) (FDA, 2018).

5.17.2. PERFORMANCE METRICS

RFID systems have a range spanning 4 inches to 33 feet, using the frequency band between 30 and 500 kHz (LF system), 3 to 30 MHz (HF system), 300 to 960 MHz (UHF system), and 2.45 GHz for a microwave system (Amsler & Shea, 2021). It can provide an accuracy of 20 to 25 cm for a passive UHF system and a few centimetres for an UWB system (Roberti, 2025). The size, weight, and power for an RFID system is considered minimal (FDA, 2018). RFID tags cost between $0.10 and $50, whereas the readers are more expensive, with prices ranging from $500 to $3000, indicating a medium cost range for this technology (Xminnov, 2024).

5.17.3. INFRASTRUCTURE REQUIREMENTS

RFID systems require tags and readers to operate. Transponders sit within the tags and use radio waves to communication identity and other information to nearby readers, active or passive (FDA, 2018) (Amsler & Shea, 2021). A scanning antenna is combined with a transceiver to create the RFID reader or interrogator. This device can have more than one antenna that emits radio waves and receives signals from tags. Readers can be mobile—being carried by hand or mounted to a post—or stationary—built into the architecture of rooms or buildings (Amsler & Shea, 2021). This system, overall, requires low transmission power (FDA, 2018).

5.17.4. APPLICATIONS AND BENEFITS

RFID provides a relatively low cost and scalable PNT service that is useful for everyday applications, such as car keys or medical history (Xminnov, 2024) (Homeland Security, 2024). Its scalable nature means it can adapt to the growing needs and changes to requirements (CMI Distribution , n.d.). Uses for RFID span a wide range of applications which are outlined in the list below.

Uses:

- Vicinity RFID-enabled documents allow documents to be read securely and accurately by authorised users from 20-30 feet away (Homeland Security, 2024).
- Healthcare (FDA, 2018)
  - Inventory control
  - Equipment tracking
  - Out-of-bed and fall detection in hospitals
  - Personnel tracking
  - Prevention of the distribution of counterfeit drugs and medical devices
  - Data provision for electronic medical record systems
- Other general uses (Amsler & Shea, 2021)
  - Livestock and pet tracking
  - Cargo and supply chain logistics
  - Vehicle tracking
  - Shipping
  - Manufacturing
  - Retail sales
  - Tap-and-go credit card payments

5.17.5. CHALLENGES AND LIMITATIONS

RFID is a short-range system, so it may interfere with other nearby devices (Amsler & Shea, 2021). Reader collision occurs when a signal from one RFID reader interferes with another. For example, in a hospital environment, RFID could interfere with pacemakers, implantable cardioverter defibrillators, and other electronic medical devices (FDA, 2018). Tag collision could also occur where too many tags confuse an RFID reader by transmitting the data simultaneously (Amsler & Shea, 2021).

5.18. OS NET CORRECTIONS

5.18.1. SYSTEM OVERVIEW

OS Net was established in 2003 and become widely available in 2006. The Ordnance Survey updated its geodetic infrastructure to create a positioning system that produces coordinates to accurately detail both natural and man-made features in Great Britain. OS Net is a national network of 114 permanent GNSS stations. The GNSS data is streamed real time to a central hub (Greaves, 2018) (Ordnance Survey , 2021).

OS Net provides 3 positional services: (Ordnance Survey , 2021)

- Real-Time Kinematic (RTK) GNSS provides accuracy to the level of a few centimetres.
- Differential GNSS (DGNSS) gives sub-metre accuracy.
- Receiver Independent Exchange Format (RINEX) refers to data for post-process applications.

5.18.2. PERFORMANCE METRICS

OS Net provides regional, UK-wide coverage at an accuracy better than 0.008 m in plan and 0.020 m in height (Ordnance Survey , 2021). The size, weight, and power associated with OS Net is minimal. This service is not commercially available but is instead a subscription model that users can buy and utilise (Ordnance Survey , 2021).

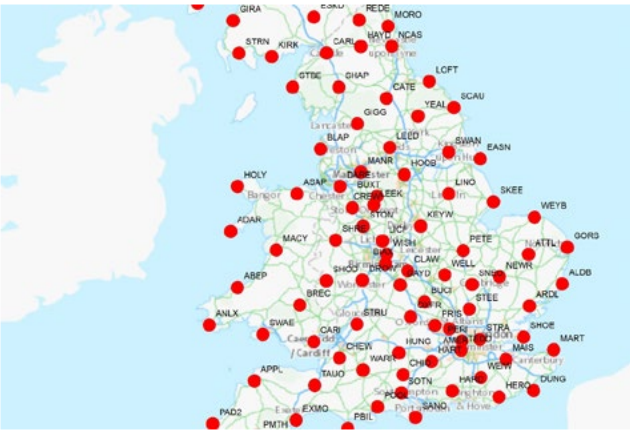


Figure 35: Location of OS Net stations across the UK (Ordnance Survey , 2021)

5.18.3. INFRASTRUCTURE REQUIREMENTS

The OS Net setup is comprised of GeoNet stations spread across the Great Britain landmass. The GeoNet stations are mounted (on structures like exposed bedrock) for maximum stability. The sites are chosen to achieve the longest foreseeable lifespan for the station and the lowest risk of disruption (Ordnance Survey, 2021).

5.18.4. APPLICATIONS AND BENEFITS

OS Net allows OS surveyors to quickly and accurately capture field data as the geospatial database is updated thousands of times per day. The continual streams of data sent to the hub of servers at OS Headquarters enables the real-time correction of errors to produce more accurate coordinates than GNSS. GNSS data from the OS Net stations is provided in RINEX format, which allows for maximum compatibility with the range of GNSS processing software users may have.

The RINEX data format is free and publicly available and also allows data from different manufacturers' receivers to be processed together (Greaves, 2018) (Ordnance Survey , 2021). Additionally, coordinates from ETRS89 (European Terrestrial Reference System) can be precisely transformed to OSGB36, National Grid and ODN height coordinates, allowing for a greater range of uses, including mapping and engineering (Ordnance Survey , 2021). Recently, the OS Net receiver stock has been updated, making it compatible with Galileo, BeiDou, GLONASS L3, and newer GPS signals like L2C and L5 (Greaves, 2018).

Further examples of OS Net use cases are outlined below (Ordnance Survey , 2021).

Uses:

- Agriculture – OS Net data supports ultra-precise positioning for farm machinery, which in turn improves crop yields and efficiency through more accurate seed sowing and fertiliser distribution.
- Construction – Due to the precise nature of OS Net data, construction zones can have improved safety, fuel efficiency, and accuracy when controlling and manoeuvring heavy machinery.
- Drones' ad UAVs – Centimetre-level precision in positioning enhances drone operations used for surveying, mapping, and autonomous navigation.
- Surveying – OS Net data means that surveying is more efficient, as there are no requirements for a base station or extra personnel.
- Asset management – The precise positioning that OS Net provides is important for positioning of critical assets, telecoms, and transport network companies. Furthermore, this aids routine maintenance operations, emergency repairs, and planning by making them more efficient.
- Street-level image correction – Highly accurate 3D imagery can be created using OS Net data, helping to deliver georeferenced data for enhanced mapping and analysis.

5.18.5. CHALLENGES AND LIMITATIONS

OS Net is commercially available as it is a subscription model (Ordnance Survey , 2021). While OS Net is a robust and critical infrastructure for precise coordinate determination, it faces several challenges and limitations, particularly in specific environments and use cases.

While OS Net can achieve positional accuracy of 1-2 cm with corrections, this is contingent on hardware quality and environmental conditions. Differences in phase centre offsets between OS Net antennas and user equipment can introduce errors if not properly accounted for in GNSS data processing. Additionally, atmospheric conditions (e.g., ionospheric or tropospheric disturbances) can degrade signal quality, particularly in remote or coastal areas.

OS Net's system of 115 stations ensures that most locations in Great Britain are within 75 km of a base station, although coverage may be less reliable in remote or rural areas with fewer stations. This can lead to reduced accuracy or slower correction data delivery in such regions. Applications like precision agriculture or environmental monitoring in remote areas may require additional local base stations, increasing setup costs and logistical challenges.

OS Net provides free RINEX data for post-processing, but this data is only stored for 45 days. Older data must be obtained from external sources like the EPOS (European Plate Observing System) service or the NERC (Natural Environment Research Council) British Isles continuous GNSS Facility (BIGF). This limited retention period can pose challenges for users requiring historical data for long-term projects or research (Ordnance Survey, 2025).

While OS Net data is freely available in RINEX format for post-processing, real-time RTK correction services are provided commercially. This can make high-accuracy services less accessible for smaller organisations or individual users without the budget for premium subscriptions.

Impact: The cost barrier may limit adoption in sectors like small-scale farming or local surveying, where budget constraints are significant.

As applications like autonomous vehicles and vehicle-to-infrastructure (V2I) systems evolve, OS Net must integrate with complementary technologies. OS Net's infrastructure may need significant upgrades or partnerships to support these emerging applications, increasing development costs, and complexity.
The OS Net system requires regular maintenance to ensure station stability and data accuracy. For example, GeoNet stations are mounted into bedrock for stability, but environmental factors like ground movement or equipment degradation can affect performance (Ordnance Survey, 2025).

5.19. COMMERCIAL CORRECTIONS

Commercial correction services have developed over the last 10 years to help compensate for errors in GNSS systems. The popularity around correction services has increased due to the need for higher level accuracy in the automative industry. Currently, 3 methods for correction exist:

1. Real-Time Kinematic (RTK), enabling a receiver to obtain correction data from a base station or local network
2. Precise Point Positioning (PPP)
3. Hybrid PPP-RTK is the most recent method for correction which combines RTK accuracy and quick initialisation times with the global access of PPP. It is reliant on a network of reference stations that sit within 150 km of each other, collect GNSS data, and calculate satellite and atmospheric corrections. The corrections are subsequently broadcast via the internet, satellites or phone towers.

	RTK	RTK-PPP	PPP
Accuracy after initialization	~1 cm	2 - 8 cm	3 - 10 cm
Initialization time	Immediate	Fast (< 1 min)	Slow (~20 min)
Coverage	Local	Regional	Global
Bandwidth requirements	High	Moderate	Low
Infrastructure density	~10 km	~100 km	~1000 km

Figure 36: Advantages and disadvantages of correction methods (Luccio, GPS World, 2020)

Traditional reference networks known as Continuously Operating Reference Stations (CORS) or virtual reference stations (VRS) are a source of DGPS and RTK corrections. CORS receivers can operate in remote areas and can be solar-powered, so they consume low quantities of power and have the ability to run remotely.

5.19.1. OSR AND SSR

GNSS correction services are based on the Observation Station Representation (OSR) or State Space Representation (SSR) of errors, which both use different techniques.

OSR relies on the transfer of corrected GNSS observations from the closest reference station to the rover. Focus is placed upon a geographic region, targeting uses in surveying, machine control, and agriculture industries. OSR provides centimetre-level accuracy up to 30 km; however, it is difficult to apply this to the mass market due to the requirement for bi-directional communication and a large bandwidth (Luccio, GPS World, 2020).

SSR uses a reference station network to model errors over a large area. The model is then transferred to the rovers which produce a local error model to further apply to GNSS observations. Accuracy of SSR ranges from 5 to 20 cm, continentally to globally, with convergence times between 10 seconds and 30 minutes. SSR corrections are broadcast and so can be distributed via internet and L-band satellite channels. Compared to OSR, SSR lends itself better to mass-market applications as the rovers rely on the same stream of GNSS correction data. The needs of this service are primarily driven by the automotive industry (Luccio, GPS World, 2020).

5.19.2. HXGN SMARTNET

HxGN Smartnet is an example of CORS/VRS. It is an open-standard RTK and DGNSS correction service which enables devices that are GNSS capable to quickly determine precise positions. It is provided continuously (24/7) through a highly available infrastructure set-up. A support team is provided and is constantly monitored to maintain integrity, availability, and accuracy (Hexagon and Leica Geosystems, 2025).

HxGN SmartNet was built to provide precise network RTK corrections that can be applied to any application across Great Britain. A total of 4,000 reference stations, based on Leica Geosystems technology, comprise the main infrastructure. Robust network RTK corrections means users can expect centimetre-level accuracy. This service is available to users through an affordable and flexible subscription option (Hexagon and Leica Geosystems, 2025) (SCCS, 2025).

5.19.3. TRIMBLE

Trimble receivers have been used for 40 years on every continent, operating 300 networks via 5,000 receivers. Trimble Positioning Services is a CORS/VRS system and provides 4 different centimetre-level correction services for a range of accuracies and applications (Trimble, 2025) (Luccio, GPS World, 2020).

1. The Trimble CenterPoint RTX provides the highest level of accuracy (~2 cm) for uses in agriculture, surveying, construction, mapping, and GIS.
2. Trimble FieldPoint RTX is used primarily for mapping and GIS purposes with an accuracy of ~10 cm. Uses include mapping asset locations and determining large boundary areas.
3. Trimble RangePoint RTX provides an accuracy of 15-50 cm and is used for agricultural purposes, helping farmers to achieve quality standards for broad-acre farming.
4. Trimble ViewPoint RTX can be used for both agriculture, and mapping and GIS purposes. When being used in the agricultural sector, there is an accuracy of 30 cm for broad-acre farming. In mapping and GIS, an accuracy of 50 cm is achieved.

5.19.4. OTHER ORGANISATIONS

There are a number of other significant organisations offering commercial PPP/RTK services, such as DDK Positioning (DDK Positioning, 2025), u-Blox (u-Blox, 2025), Topcon (Topcon Positioning, 2025) , and Premium Positioning (Premium Positioning, 2025).

5.20. TRNAV

5.20.1. SYSTEM OVERVIEW

Tualcom has developed TRNAV, a terrestrial navigation system that is based on communications technologies. It can operate independently of GNSS and is made up of a network of TRNAV ground stations at set locations. This allows for any platform with a Tualcom position finder to use the positional information provided. The system has been successfully implemented in regions in Turkey with plans to further expand this countrywide (Tualcom , 2024).

Data links are a key product line of Tualcom, enabling mesh network communication in the L, S, and C frequency bands, which are selected based upon the specific application requirements. Data link expertise has helped to address the issues of navigation in environments where GNSS is denied or where data jamming problems exist (Tualcom , 2024).

5.20.2. INFRASTRUCTURE REQUIREMENTS

Mobile terminal technical specifications (Tualcom, 2023)

- Transceiver unit dimensions: 15 cm x 20 cm x 4 cm
- Antenna height: 30 cm
- Weight: 3 kg max
- Centre frequency to be selected within a wide frequency band
- Output power: 10/60 W
- Antenna gain : 6 dBi.
- Power Supply: 24-32 VDC

Figure 37: TRNAV mobile terminal (Tualcom, 2023)

Platform terminal technical specifications (Tualcom, 2023)

- 1 Micro-D connector and 2 SMA connectors (one is optional GNSS antenna input)
- Dimensions: 62 x 75 x 30 mm
- Weight: 350 g Max
- Output power: 10/60 W
- Centre frequency to be selected within a wide frequency band
- Power Supply: 24-32 VDC

Figure 38: TRNAV platform terminal (Tualcom, 2023)

5.20.3. APPLICATIONS AND BENEFITS

TRNAV has a bi-directional communication capability which differs from GPS/GNSS unidirectional architecture (Tualcom, 2023). This characteristic, along with a high computational rate, allows TRNAV to perform time synchronisation and distance calculation by only communicating with the ground station. Consequently, TRNAV has a higher precision than GNSS. Also, the TRNAV system is designed with data link technology as its foundation. This allows for the ability to transfer many data types over the system, such as position, video, sounds, and text (Tualcom , 2024). TRNAV can work independently of GNSS as mesh communications and ad hoc networking properties allow the system to provide precise positioning information without a GNSS signal (Tualcom, 2023). There is evidence of effective implementation for uses in missiles, marine vehicles, and manned or unmanned aerial vehicles and land vehicles.

6. LOCAL SENSING PNT

Local sensing plays a pivotal role in modern PNT systems, providing critical PNT sensor data inputs to ensure accuracy and reliability, while enabling resilient operations across a wide range of applications and environments. Unlike systems that rely on external signals (space and terrestrial RF), local sensing leverages proximate environmental data through sensors integrated into the user equipment. These are sensors like inertial measurement units (IMUs), LiDAR, radar, cameras, and underwater devices. These sensors enable PNT systems to derive position, orientation, and timing information in environments where external signals may be degraded, denied, or unavailable, such as urban canyons, indoor settings, or contested areas.

Within a PNT system, local sensing enhances autonomy by enabling real-time environmental perception, obstacle avoidance, and precise motion tracking. When integrated into a system of systems, local sensing contributes to a layered, resilient architecture, complementing and augmenting external PNT sources. By fusing data from multiple local sensors with other PNT inputs, these systems achieve robust situational awareness and adaptability, supporting applications from autonomous vehicles and robotics to military operations and disaster response. This section explores the technologies used in local sensing in PNT systems, and their benefits and challenges. Figure 38 gives a visualisation of the sensor types covered in this section.

Figure 39: Local Sensing PNT Systems covered

6.1. QUANTUM TECHNOLOGIES FOR LOCAL PNT – AN OVERVIEW

Quantum Technologies (QTs) are a key element of achieving assured, resilient, PNT independent of external signals. The UK's National Quantum Strategy and its Quantum Strategy Missions define a 10-year ambition (to 2033) to become a world-leading quantum-enabled economy with quantum technologies being an integral part of digital infrastructure, driving growth and resilience (Department for Science, Innovation and Technology, 2023). This is strongly aligned with the UK's Resilient PNT Framework (Department for Science, Innovation and Technology, 2023), and two national quantum strategy missions frame the relevance of QTs to Local PNT (Department for Science, Innovation and Technology, 2023):

- Mission 4 aims that *by 2030 quantum navigation systems, including clocks, will be deployed on aircraft to provide next-generation accuracy for resilience that is independent of satellites;*
- Mission 5 aims that *by 2030 mobile, networked quantum sensors will have unlocked new situational awareness capabilities, exploited across critical infrastructure in the transport, telecoms, energy and defence sectors.*

QTs are devices and systems that *exploit quantum-mechanical effects such as superposition and entanglement* to deliver new capabilities in sensing, timing, communications and computing. For PNT this includes:

- Local PNT sensors and clocks that use quantum mechanical effects to measure motions, fields and time with exceptional stability;
- Quantum communications protocols that can be used to underpin new time transfer mechanisms; and,
- Quantum illumination systems that further the state-of-the-art in LiDAR and radar imaging.

These new technologies enhance the performance and resilience of local PNT systems, helping to provide trustworthy position updates and navigation solutions when external signals are unreliable or absent.

Quantum Technologies represent the next generation, and in some cases the emerging current generation, of systems in many areas of local PNT. This is not through a single type of technology, but a wide ecosystem of technologies, architectures, and implementations that are related by their use of quantum-mechanical effects but achieve these through fundamentally dissimilar means (for example, photonic systems compared with cold-atom systems). In some cases, quantum technologies are stand-alone replacements for existing systems (such as in magnetometry), but in most cases they work in a complementary, hybrid, regime with current state-of-the-art classical sensors, augmenting their capabilities. The benefits they provide also vary by sensor type, from SWaP reduction at a certain performance tier, to greater absolute sensitivity, to long-term stability and drift reduction. This section includes discussion of all QTs relevant to PNT, with details within the sub-sections for relevant sensor modalities. We also include a summary table below, Table 2:

Local Sensing Modality	Quantum Impact	Maturity
LiDAR	Quantum illumination may improve performance in adverse conditions where imaging is traditionally obscured, and SNR is poor.	Low
Barometric	Future potential for quantum fixed length optical cavity pressure sensors.	Low
Gravimetric	Quantum provides medium-to-high SWaP gravimeters and gravity gradiometers with ultra-low drift, low settling times, leading performance, and entanglement-based noise rejection for gradiometry. These significantly enhance gravity map-matching capabilities.	Medium
Magnetic	Low SWaP, low drift, self-calibrated high performance magnetometry through optically pumped and NV-centre magnetometers.	High
INS	Quantum accelerometers and gyroscopes with ultra-low drift, but with high SWaP. Pulsed and continuous regimes possible, with low and normal bandwidths respectively. Potential to increase GNSS-free holdover durations for navigation considerably, initially in hybrid configurations with classical INS.	Medium
Radar	Quantum illumination techniques at RF, with the potential to increase range and imaging resolution.	Low
Timing	Portable quantum optical clocks bringing performance roughly 2 orders better than caesium beam standards in a 3-4U rack mounted form-factor, swap-in replacement for current generation systems and potentially for hydrogen masers. Future pathways to shoebox and board-scale clocks, at similar or slightly greater performance. Initial COTS products available.	High
Timing	Next-generation reference-grade quantum optical clocks for SI second definition and metrology.	Medium
Time Transfer	Quantum protocols for secure time transfer, with potential benefits to achievable synchronisation precision through fibre or free space.	Medium

Table 2: Quantum technology impact across local sensing modalities.

Individually these technologies are important, but as part of an integrated system-of-systems they may have a considerable impact on PNT resilience and performance in fully local configurations. As PNT risks grow, this is an important contributor to safety and continuity of existing systems and platforms, and a potential enabler for highly PNT dependent future use-cases such as autonomy and deep-space navigation. High maturity technologies are already commercially available, and quantum is beginning to have a direct impact.

Quantum sensors are also expected to be a valuable market sector, with globally distributed demand. QED-C/Hyperion's 2025 survey estimates quantum sensing revenues at US $375 million in 2024, projecting US $915 million by 2028 (~25% CAGR) (Quantum Economic Development Consortium (QED-C), 2025), Fortune Business Insights forecasts the market to rise from $377 million in 2024 to 1.22 billion in 2032 (~16% CAGR) (Fortune Business Insights, 2025), IDTechEx estimates market size of $1.9 billion by 2046 (~9.0% CAGR) (IDTechX, 2025), and McKinsey estimates quantum sensing to have a market size of $7-10 billion by 2035 and $18-31 billion by 2040 (McKinsey Digital, 2025). Whilst these estimates vary there is a significant opportunity for economic growth and global supply chain presence for the manufacturers and integrators of quantum PNT technologies.

The UK is well placed to capture this value and has businesses fielding globally competitive quantum systems in almost all domains. This is further enhanced by world-leading research coordinated by the quantum hub structure, with both the UK Quantum Technology Hub in Sensing, Imaging and Timing (QuSIT) and the UK hub for Quantum Enabled Position, Navigation and Timing (QEPNT). The sub-sections that follow will articulate the roll, maturity, and key organisations within the greater context of PNT modalities.

6.2. LIDAR

Light Detection and Ranging (LiDAR) is an active sensing technology that measures distance by illuminating targets with laser light and timing the reflections (time-of-flight). A LiDAR system emits laser pulses or continuous modulated beams and uses the return time or phase shift to calculate distances. In so doing, it produces a 3D point cloud of the surroundings (Royo & Ballesta-Garcia, 2019) with a high-range accuracy (typically centimetric or better) (Dai, et al., 2022). Modern LiDARs operate at infrared wavelengths, commonly 905 nm or 1550 nm. While both are used in eye-safe systems, 1550 nm lasers offer enhanced eye safety due to the absorption characteristics of ocular tissues, allowing for higher power outputs within the bounds of eye-safety regulation, and hence longer detection ranges.

There are two broad classes of LiDAR: mechanical scanning and solid-state. Traditional mechanical LiDARs use moving parts (rotating mirrors, prisms, or the entire sensor head) to scan their laser beam over a wide field of view, typically 360° horizontally (Royo & Ballesta-Garcia, 2019). These spinning (multi-beam) designs are typically used in early autonomous vehicles and in surveying systems. They offer large coverage and high signal power at costs relevant to size and moving-part complexity.

In contrast, solid-state LiDARs have few or no moving parts. They steer beams electronically or with micro-mechanical elements, which improves robustness and allows a more compact form factor (Raj et al., 2020). Solid-state designs include MEMS mirror LiDAR (beam steering with MEMS tilting mirrors), optical phased array (OPA) LiDAR (beam steering via controlled interference from an array of optical antenna), and flash LiDAR (illuminating the field of view in a single broad flash and capturing the reflections on a sensor array) (Royo & Ballesta-Garcia, 2019). Hybrid approaches also exist, combining technologies into a single system.

LiDAR sensors range from compact single-chip devices to larger mechanical units. A LiDAR can be as small as a few centimetres and weigh 10s of grams (e.g., LiDAR modules in smartphones or ultra-lightweight drones), or as large as vehicle-mounted rooftop units weighing several kilograms. Mechanical 3D LiDARs often have a distinct cylindrical housing to cover 360°, whereas solid-state LiDARs may be flat or box-shaped to embed into vehicle bodywork or UAV gimbals. Flash LiDARs resemble a camera sensor with a lens.

Overall, the trend is toward smaller, more integrated form factors (Texas Instruments, 2025), with solid-state LiDAR enabling integration into tight spaces (e.g., behind automobile windshields or in handset devices).

6.2.1. PNT OUTPUTS

Positioning and Mapping: LiDAR primarily provides high-resolution spatial information – a 3D point cloud representing distances to surrounding surfaces. By comparing successive point clouds or matching them to a known map, LiDAR can support localisation (self-positioning). In simultaneous localisation and mapping (SLAM) applications, a LiDAR's data is used to build a map of the environment and track the sensor's movement within it, giving relative position and orientation updates (Chiang et al., 2023). Thus, LiDAR serves as a local positioning sensor, especially useful when GNSS is unavailable or to augment inertial navigation (Royo & Ballesta-Garcia, 2019). LiDAR point clouds can yield the sensor's 6-DoF pose (position and attitude) when matched against known environmental features, achieving lane-level or even centimetric localisation in mapped structured environments.

A LiDAR directly provides range measurements to objects and surfaces. Typically, this is a stream of range data points with associated angles (or 3D coordinates after calibration) and intensity returns (reflectivity). From these, the sensor or downstream algorithms can infer:

- Distances to obstacles or landmarks: enabling collision avoidance or mapping.
- Relative velocity of objects: Relative velocity of objects can be measured using Doppler-capable LiDAR systems, such as Frequency-Modulated Continuous Wave (FMCW) LiDAR. However, most current commercial LiDAR systems estimate velocity by analysing changes in successive point clouds over time. Coherent LiDAR systems can directly measure radial velocity of particles by Doppler shift (Crouch, 2019), although most automotive pulsed LiDARs do not directly output velocity per point.
- Orientation or attitude cues: while LiDAR does not inherently output the sensor's orientation, features in the point cloud, such as the detected ground plane or vertical structures, can be used to infer roll or pitch of the sensor or to aid an INS in determining orientation.
- Environmental features: some LiDARs perform on-board processing to classify or cluster points (e.g., identifying the road edge), but typically this is left to external processors. The high angular resolution of LiDAR results in geometrically detailed point clouds, with sufficient information for recognising and classifying environmental objects and features by shape.

In summary, a LiDAR sensor primarily contributes position and navigation data in the form of detailed range profiles of the surroundings. When fused into a PNT system, LiDAR data can improve positional accuracy and integrity by cross-checking other sensors. It excels at providing high-definition relative position information and can indirectly support orientation and velocity estimation when combined with algorithms or complementary sensors.

6.2.2. PERFORMANCE TIERS

LiDAR performance varies widely across consumer, automotive, and defence-grade systems. Key metrics include range, accuracy, resolution (both range resolution and angular resolution), field of view, and data rate.

- Consumer-Grade (Short Range): LiDARs are found in applications like consumer robotics, drones, or mobile devices. They offer modest range (typically 10–40 m) and moderate resolution. For example, a small 1D ranging module (like Garmin's LiDAR-Lite) can measure up to 40 m with ±2.5 cm accuracy and 1 cm resolution using a single beam (Garmin, 2017). A low-cost 2D scanning LiDAR for home robotics might have a 5–10 m range and angular resolution on the order of 1° (sufficient for room mapping). Update rates are typically 10–100 Hz. These units prioritise compactness and low power (<1 W) and weigh only a few tens of grams (Garmin, 2017). Angular resolution and point density are limited, but sufficient for local obstacle avoidance and mapping in confined areas.
- Automotive-Grade (Mid to Long Range): Automotive LiDAR can be split into ADAS-grade (advanced driver-assistance, in production vehicles) and autonomy-grade (higher performance in self-driving fleets). A typical automotive LiDAR detects objects at 100–250 m range (at 10% reflectivity) with high accuracy (±3 cm) (Dai, et al., 2022). Angular resolutions are on the order of 0.1° horizontally and 0.1°–0.5° vertically (Dai, et al., 2022). For instance, solid-state units like Luminar's Iris achieve ~0.05° resolution and ~250 m range on 10% reflective targets (Luminar Technologies, 2023). These sensors often output over a million points per second. High-end spinning LiDARs (mechanical 360°) in this tier may have 16 to 128 beams. Top-tier automotive LiDARs provide a long-range forward view (200–300 m) to support high-speed driving, and shorter-range wide FOV coverage for peripheral sensing. Range precision is typically centimetric or better.
- High-Performance/Defence-Grade: This tier encompasses specialized LiDARs used in defence, surveying, and research (for example, long-range mapping scanners or tactical LiDAR for target recognition). These systems push range and resolution further, often using 1550 nm lasers which allow higher power for longer reach (Texas Instruments, 2025). Ranges of >500 m for vehicles and up to several kilometres for large targets are possible with multi-aperture or amplified LiDAR (Rasshofer, Spies, & Spies, 2011). They can deliver sub-centimetre accuracy. Some surveying LiDARs achieve millimetre-level precision at short ranges for applications like rail or infrastructure monitoring. Angular resolution can be extremely fine (0.05° or better) to capture detail at a distance. These units are often heavier (several kilograms) and consume more power (20–50+ W) than lower-tier variants. They also may incorporate advanced techniques like geiger-mode or single-photon detection to extend range (detecting very weak returns).

Across all tiers, angular and range resolution on the order of centimetres is common, and even low-end LiDAR often quantizes distance in 1 cm increments (Garmin, 2017). Angular resolution varies widely, so low-end scanning LiDAR might only offer a few degrees, while high-end sensors achieve a few hundredths of a degree (Dai, et al., 2022). Finer angular resolution means higher point cloud density but also larger data throughput.

6.2.3. SIZE WEIGHT AND POWER, AND INTEGRATION

LiDAR SWaP characteristics correlate with their performance tier. Consumer 1D/2D LiDAR modules can be 2–5 cm in length, weigh 10s of grams, and have minimal low power consumption (0.5–1 W) (Garmin, 2017). By contrast, high-performance 3D LiDARs are larger: a 360° mechanical LiDAR with 64-beams could be 15–20 cm in diameter, 10–15 cm tall, weigh 1–3 kg, and draw 20–30 W (Velodyne Lidar, 2020). Newer solid-state LiDARs aim to reduce SWaP: many automotive-grade units are a few inches in size, <1 kg, and consume on the order of 10–25 W (Luminar Technologies, 2023). For example, MEMS mirror LiDARs are suitable for vehicle integration in headlamps or rooflines. Ongoing R&D in photonic integration is steadily reducing LiDAR SWaP, targeting chip-scale beam steering and receiver integration to bring high-end performance into smaller footprints.

LiDAR sensors produce a large volume of data. A high-resolution LiDAR can output millions of points per second, which demands significant processing for real-time use. Typically, a dedicated processing unit or FPGA (field-programmable gate array) in the sensor handles immediate tasks (timing pulses and accumulating returns). The raw point cloud is then sent out for further processing by the vehicle or system's computer. Tasks like object detection, SLAM, or sensor fusion with camera/radar are computationally intensive and can require GPU acceleration or specialized hardware. Lower-tier LiDAR (few hundred points per frame) can be handled by microcontrollers, but automotive LiDAR data (10^6 pts/sec) often requires automotive-grade SoCs or FPGAs for data processing and running perception algorithms (Dai, et al., 2022). Latency is another consideration. LiDAR data frames typically update at 10–20 Hz (mechanical spinning sensors) or up to 30 Hz (solid-state), so processing must keep pace to be useful for fast navigation.

Common interfaces for LiDAR include Ethernet, CAN (controller area network) or FlexRay, USB (Universal Serial Bus) or UART for lower-end devices, and SPI/I2C for very small modules. Many LiDARs also provide a synchronisation interface to coordinate multiple sensors and timestamp outputs for multi-sensor fusion. Integration into platforms often leverages middleware like ROS (Robot Operating System) drivers for robotics, or AUTOSAR drivers in automotive, to parse and use the data. The data format is typically a list of ranges/angles or XYZ coordinates. Some manufacturers have proprietary formats, but there is movement toward standardisation (OpenLR, 2025).

6.2.4. KEY MANUFACTURERS

In the UK, most LiDAR activity has been in integration and niche applications. BAE Systems and QinetiQ have developed LiDAR-based systems for surveying and defence, although they often use sensors from global suppliers. RIEGL UK (the UK arm of RIEGL, an Austrian manufacturer) supplies high-end survey LiDAR equipment domestically.

Small enterprises like Red Sensors (UK) offer 3D LiDAR and precision laser systems. Additionally, UK-based innovators are active in components: e.g., Phlux Technology is developing novel infrared photodetectors to improve LiDAR range at 1550 nm, and GeoSLAM produces handheld LiDAR mapping devices for indoor and underground use. Another UK contributor is Lumibird (originally Halo Photonics) which built a coherent Doppler LiDAR for wind sensing.

Manufacturers by tier:

- Automotive and High-Performance*:* The U.S. has prominent manufacturers like Velodyne Lidar (now part of Ouster), a pioneer of multi-beam spinning LiDARs, and Luminar Technologies, known for long-range 1550 nm LiDAR in production cars. Innoviz Technologies (Israel) supplies solid-state LiDAR to automotive OEMs (e.g., BMW), offering MEMS-scanning units. Valeo (France) was the first to bring automotive LiDAR (the Scala unit) to a production car (Audi A8). Other notable firms include Aeva (USA), which focuses on FMCW LiDAR for simultaneous velocity measurement, Cepton (USA) and RoboSense and Hesai (both of China), which are major suppliers for autonomous vehicles and robotaxis.
- Surveying and Mapping: RIEGL (Austria) and Leica Geosystems (Switzerland) lead in airborne and terrestrial survey LiDAR, offering high-precision long-range scanners for mapping. Teledyne Optech (Canada) is known for bathymetric and topographic LiDAR systems. Their products often form the backbone of geospatial LiDAR mapping services worldwide.
- Consumer/Industrial: Hokuyo and SICK (Japan/Germany) produce 2D and 3D LiDARs for industrial automation and robotics. Slamtec (China) offers low-cost LiDAR (like the RPLIDAR series) for hobbyists and entry-level robotics. Garmin (USA) provides the compact LiDAR-Lite module for drones and UAVs. In mobile devices, companies like Lumentum and Sony make tiny vertical cavity surface-emitting lasers (VCSEL) and sensor components used in smartphone LiDAR systems.

Across these tiers, consolidation is occurring (e.g., Velodyne and Ouster merging in 2023), as the industry matures. Leading suppliers differentiate by technology (pulsed vs FMCW, mechanical vs solid-state) and by targeting specific domains (mass automotive vs. niche mapping).

6.2.5. APPLICATIONS AND BENEFITS

LiDAR has broad applicability across land, air, sea, space, and subsurface domains, offering unique benefits for PNT:

- Land: The most prominent use is in autonomous ground vehicles (cars, shuttles, delivery robots). LiDAR provides detailed 3D perception to recognise obstacles (Figure 39), lane features, and a vehicle's location relative to road infrastructure (Figure 40). In self-driving cars, LiDAR complements cameras and radar to achieve reliable navigation. Its precise depth maps enable lane-level positioning and obstacle avoidance even in darkness. For surveying and mapping on land, tripod-mounted or vehicle-mounted LiDAR scanners capture 3D models of terrain and cities (used in surveying, construction, and archaeology). This mapping data itself becomes part of the PNT infrastructure (high-definition maps). LiDAR on trains or road maintenance vehicles can scan tracks and pavement for precise measurements.

Figure 40: A street-level view from an Ouster LiDAR sensor (Hesai, 2021)

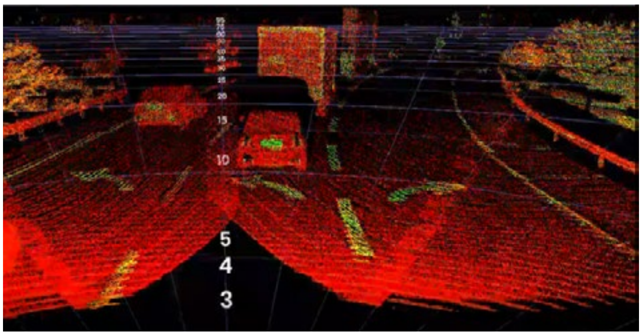


Figure 41: A view from the InnovizOne solid-state LiDAR solution (Hesai, 2021)

- Air: LiDAR systems are used on UAVs for terrain following and obstacle avoidance (allowing drones to autonomously navigate around wires or buildings). A drone equipped with LiDAR can also perform mapping of hard-to-reach areas like cliffs or disaster sites, aiding navigation and positioning where GPS might be unavailable (e.g., under canopy or indoors). Manned aircraft employ airborne LiDAR for wide-area mapping (e.g., scanning large swaths for topographic data, which indirectly supports PNT by providing detailed digital terrain models for navigation databases). In aerospace, coherent Doppler LiDAR is used for measuring wind vectors (important for aircraft takeoff and landing guidance). Spacecraft have used LiDAR for hazard avoidance and altitude determination during landings; for example, the 3D imaging LiDAR on the NASA OSIRIS-REx mission mapped an asteroid's surface to guide sampling.
- Sea: LiDAR can assist vessels in obstacle detection and docking. Autonomous surface vessels (from small robotic boats to larger ships) use LiDAR to detect and identify features like navigation buoys, rocks, or other vessels in their vicinity, with greater detail than what radar can provide at close range. LiDAR has been used in port automation and for mapping coastal areas (when mounted on low-flying aircraft for bathymetric LiDAR, using green 532 nm lasers to penetrate water and map seabeds in shallow water).

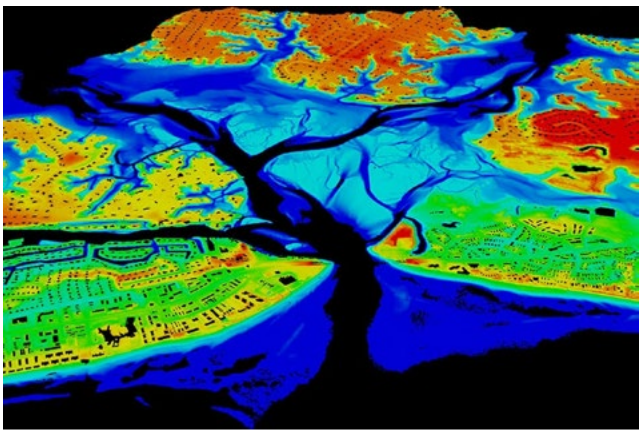


Figure 42: A LiDAR map of Lynnhaven Inlet, Virginia (National Oceanic and Atmospheric Administration, 2025)

- Subsurface: LiDAR is extensively used for mapping and navigation in tunnels, mines, and caves. Mobile mining machines or robots utilise LiDAR to avoid collisions and to map mine galleries for autonomous operation. Likewise, underground infrastructure (such as sewers and utility tunnels) can be mapped with handheld or drone-mounted LiDAR to create 3D models used for navigation. Indoors, warehouse robots and service robots rely on LiDAR for localisation (identifying walls, aisles, and obstacles in real-time). The clear benefit here is that LiDAR provides its own illumination and is immune to magnetic or radio signal loss. Furthermore, it can generate a real-time map to serve as the navigation reference in GPS-denied scenarios. LiDAR enables local reference frameworks for relative navigation.
- Space: LiDAR has been deployed in space for rendezvous and docking (e.g., on ATV and Dragon vehicles to dock with the ISS (International Space Station), where a LiDAR rangefinder provides distance and closing rate data). Future lunar landers are planned to use LiDAR for landing hazard detection. Additionally, satellite-based LiDAR (laser altimeters) like NASA's ICESat provides precise altitude measurements of Earth features.

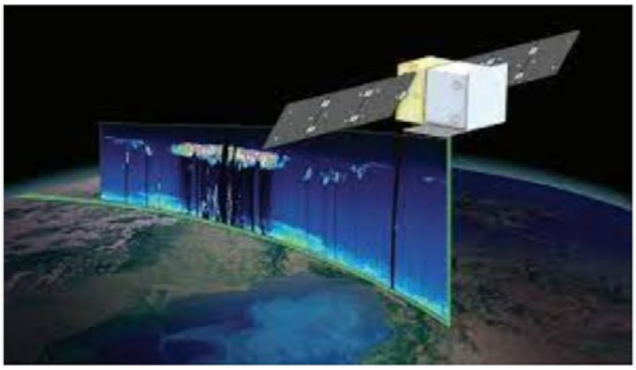


Figure 43: Next generation LiDAR for remote sensing satellites (NASA Goddard Spaceflight Center, 2020)

Across all these domains, LiDAR's main strengths are high precision distance measurement, rich 3D spatial information, and independence from external infrastructure (aside from power). It excels in providing local situational awareness, which is crucial for autonomous navigation and safety. By integrating LiDAR, the overall PNT system-of-systems can gain resilience. In a multi-sensor PNT stack, LiDAR often serves as the local reference sensor, anchoring other sensors to a truth with accurate distance measurements.

6.2.6. CHALLENGES AND LIMITATIONS

Despite its advantages, LiDAR faces several challenges and limitations that impact its use for PNT:

- Degraded Performance in Adverse Weather: LiDAR's laser beams can be scattered or absorbed by particulates in the air. Fog, heavy rain, snow, or dust dramatically reduce effective range as the light is attenuated and reflections from droplets cause false returns. Studies have shown that dense fog can cut LiDAR range down to a few meters or less (Rasshofer, Spies, & Spies, 2011). While using longer wavelengths (1550 nm) and adaptive algorithms can somewhat improve weather robustness, radar significantly outperforms LiDAR in these conditions (Texas Instruments, 2025).
- Sensitivity to Ambient Light and Reflectivity: Bright sunlight can introduce noise in LiDAR detectors, especially for 905 nm systems (which overlap with some solar infrared). Most LiDARs use narrowband filters and timing discrimination to cope, but strong sunlight or glare off reflective surfaces can reduce accuracy or produce spurious points. Target reflectivity also matters: very dark or absorbent materials (e.g., matte black cars or turf) return less light, shortening detection range. Conversely, retroreflectors (like street signs) can saturate sensors. Thus, a LiDAR's specified range might only be achieved for reasonably reflective targets; for very low reflectivity objects, the detection distance could be much shorter (Dai, et al., 2022). These variances mean PNT systems must account for uncertainty. An object might evade LiDAR detection if it is both distant and has low reflectivity.
- Occlusion and Limited Field of View: LiDAR, being line-of-sight, cannot see through solid obstacles. This creates occlusion shadows (e.g., a pedestrian hidden behind a parked car is invisible to the LiDAR until they step into view). For navigation, this means LiDAR alone cannot guarantee detection of all hazards; so strategies like multi-sensor fusion or multiple LiDAR placements (to cover blind spots) are used. Many solid-state LiDARs do not cover a full 360° (often 120° forward). While mechanical spinning types cover 360° horizontally, their vertical FOV will be limited (e.g., 30°). In environments like urban canyons or forests, limited FOV and occlusion can cause dropped features, making it harder for LiDAR-based localisation to track position continuously.
- High Power Draw and Thermal Management: High-performance LiDARs draw tens of watts. This can strain power-constrained platforms (like small drones or battery-operated robots). The heat generated must be managed. A hot LiDAR can suffer from noise or even shut down if thermal limits are exceeded. In automotive contexts, adding a 20–30 W sensor must be balanced against the vehicle's power budget and cooling systems—a tight trade-off for electric vehicles.
- Eye Safety and Regulations: LiDARs use lasers that must comply with eye safety standards (Class 1 for any consumer-facing use). This imposes limits on the laser power and beam divergence. Achieving long range within those limits is challenging and has driven the move to 1550 nm, despite increased cost.
- Interference: There are important considerations with respect to interference. While not as heavily regulated as radio, LiDARs can be constrained by interference, if many operate in close proximity (e.g., multiple autonomous cars). Most modern LiDARs use unique pulse patterns or offset frequencies to minimise cross-talk, but this is an area of concern in dense deployments.
- Integration and Calibration: To use LiDAR in a PNT system, it must be precisely calibrated (knowing the orientation and position of the LiDAR relative to the vehicle frame, etc.). Calibration errors can introduce biases in the perceived positions of points, which can degrade navigation solutions if not accounted for. Maintaining calibration, especially for units that experience physical stress and/or temperature variations, is non-trivial.

6.2.7. EMERGING SYSTEMS

A key trend is FMCW LiDAR (Frequency Modulated Continuous Wave), which is still in development but nearing the prototype phase. FMCW LiDAR can provide each data point with a radial velocity (like radar) by measuring Doppler shifts, and it offers the potential for interference immunity, since it uses coherent processing (Crouch, 2019). Companies like Aeva and Scantinel are working on FMCW LiDARs.

Another future technology is Optical Phased Array (OPA) beam steering, promising a fully solid-state, chip-scale LiDAR with no moving parts. Early systems exist; however, OPAs face challenges like beam sidelobes and limited optical power.

Several advanced LiDAR types remain in early-stage development and are not currently deployable for practical PNT use. Quantum LiDAR—which exploits quantum entanglement or single-photon interference to detect targets in low-SNR environments or against strong jamming backgrounds—is moving from the laboratory to field demonstrations.

Multispectral LiDAR (using multiple laser wavelengths) and polarimetric LiDAR (measuring the polarisation of reflected light) are also experimental. These offer the potential for material classification or camouflage detection but currently face significant challenges in complexity, size, and integration.

Geiger-mode and single-photon avalanche diode (SPAD) LiDAR systems have been demonstrated, especially in remote sensing and aerospace applications, where they enable long-range, low-power photon counting. However, their commercial availability for navigation applications is limited, and they are typically used in specialist survey or reconnaissance contexts.

6.3. BAROMETRIC ALTIMETERS

Barometric altimeters measure altitude by sensing air pressure, as atmospheric pressure decreases with height above sea-level. A pressure sensor (barometer) can thus serve as an altimeter when calibrated to a reference pressure or altitude. Early altimeters were mercury barometers and later aneroid barometers (or sealed flexible metal capsules that expand or contract with pressure changes).

In a classic aneroid altimeter (Figure 43), a partially evacuated metal wafer deflects as external air pressure varies, and mechanical linkages translate this motion to an altitude dial. Modern sensors emulate this principle using MicroElectroMechanical Systems (MEMS), shrinking the barometer into millimetre-scale silicon chips.

These MEMS barometric sensors typically use a microscopic diaphragm that bends under pressure. The deflection is measured via piezoresistive strain gauges or a change in capacitance between microfabricated plates. Capacitive MEMS barometers often exhibit better temperature stability than resistive types, improving accuracy over wide environmental ranges.

Common form factors range from MEMS pressure chips (~2×2 mm packages) in smartphones and wearables, to larger integrated altimeter modules for aviation. Consumer devices use low-power digital barometer chips mounted on circuit boards, usually with a small port exposed to ambient air. In contrast, aircraft altimeters may be stand-alone instruments with aneroid capsules and mechanical displays, or digital air-data units with internal sensors and electronics, such as temperature compensation circuitry and output interfaces in a rugged housing. These units often include an external port for connection to the vehicle's static pressure line. Overall, barometric altimeters span from legacy analogue gauges to miniaturized MEMS sensors, but all operate on the same physical principles (Bolanakis, 2017) (AVNET ABACUS, 2020).

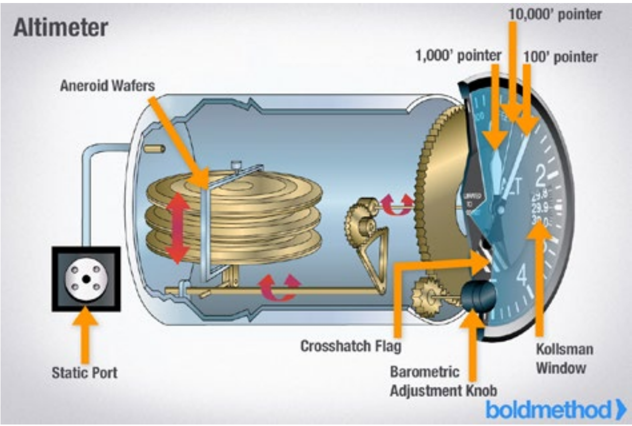


Figure 44: Altimeter overview (Boldmethod, 2024)

6.3.1. PNT OUTPUTS

Barometer or altimeter sensors provide a direct measurement of vertical position (altitude) relative to a reference pressure level. They sense atmospheric pressure and convert it to altitude based on an atmospheric model (e.g., the ISA barometric formula). This yields pressure altitude, which is the height above a defined datum (usually mean sea-level under standard conditions). In local PNT applications, barometric altimeters add the vertical dimension to positioning, which is often the most error-prone axis for GNSS. Furthermore, by integrating changes in position, it is possible to derive a local estimate of vertical speed, which can be useful in autopilot and hover systems (Ostroumov, 2022).

Barometric sensors can resolve extremely small altitude changes, thanks to their sensitivity to minute pressure differences. Modern MEMS barometers have internal resolution down to 0.001–0.01 hPa, equivalent to a few centimetres of altitude change. For example, Infineon's DPS310 MEMS barometer can detect pressure changes of ±0.002 hPa, corresponding to about ±0.02m in altitude. In practical terms, consumer altimeters in smartphones or wearables often report changes as fine as 0.1–1.0m in altitude (Infineon, 2020).

The absolute accuracy of barometric altitude is dependent on calibration and atmospheric models (including to correct for weather and temperature effects). In a controlled setting, consumer-grade MEMS barometers achieve ±0.5 to ±1 hPa absolute accuracy (approximately ±4–8 m error at sea level). With one-time factory calibration and compensation, a phone's barometer might indicate altitude within a few meters of truth after user calibration (e.g., setting local sea-level pressure). Aviation altimeters, when correctly set to local pressure, typically maintain altitude accuracy within tens of feet. Regulations allow an error on the order of ±80 feet at 10,000 ft altitude for certified aircraft altimeters. In practice, high-quality aircraft altimeters are often accurate to better than ±20–50 feet (≈6–15 m) at mid-flight levels (Federal Aviation

Administration, Department of Transportation, n.d.) (Thommen Aircraft Equipment, 2025).

Most important for aviation is that all aircraft use the same reference pressure to ensure relative accuracy between aircraft for separation, even if the absolute elevation above sea level might drift. With frequent calibration, barometric systems can hold altitude readings to ~±1–3m in many scenarios (for example, emergency caller location systems now aim for ~3 m vertical accuracy by calibrating device barometers with network data). However, uncorrected barometric readings will gradually diverge from true altitude as weather systems move through. For instance, a 1 hPa drop in ambient pressure (normal for a weather change) mimics roughly an 8-metre altitude increase if not recalibrated (Lin, 2008).

In summary, barometer sensors excel in relative vertical precision and smooth short-term stability, while their absolute accuracy is bounded by environmental calibration.

6.3.2. PERFORMANCE TIERS

Barometric altimeters are available in different performance grades, from basic consumer sensors to high-precision military or avionics units. Key differences lie in their accuracy, stability, and operational range:

- Consumer-Grade (MEMS Barometers): These are found in smartphones, tablets, watches, drones, and IoT devices. They use MEMS capacitive or piezoresistive sensing elements on a silicon chip for low cost and power. Typical accuracy is on the order of ±1 hPa (±8 m) without external calibration. With local calibration (e.g., using a known elevation or a reference pressure broadcast), their altitude error can be reduced to a few meters. Resolution is very high (0.01 hPa or better), yielding sub-meter incremental changes. However, their readings can drift with temperature and time (offset drift may be a few tenths of hPa over months). These sensors usually cover the pressure range ~300–1100 hPa (-500 to ~10,000 m elevation). Consumer barometers prioritise compact size and low power over extreme precision. Examples include Bosch BMP388 and Infineon DPS310 chips (Infineon, 2020) (Bosch Sensortec, n.d.).
- Aviation-Grade (Certified Altimeters): Aviation altimeters (civil aviation and aerospace) adhere to stringent standards (e.g., FAA TSO-C10b) for accuracy and environmental tolerance. Traditional analogue altimeters use multiple aneroid capsules and precision mechanisms to achieve ±10–30 ft resolution. Regulatory accuracy requirements allow small errors that increase with altitude (e.g., ±50 ft at 10k ft). Digital aviation altimeters and air-data computers use high-stability pressure transducers (often silicon strain-gauge or resonant quartz sensors) with multi-point temperature compensation. Aviation-grade sensors cover a wider pressure range than consumer equivalents to handle altitudes of -1000–50,000+ ft and are designed to be stable over -55 to +70 °C. Overall, aviation-grade altimeters offer better stability and known error bounds compared to consumer devices.
- Military and High-Precision Grade: Military aircraft, missiles, and precision applications use top-tier barometric sensors or hybrid systems. These often employ vibrating-cylinder or resonant quartz pressure sensors, which oscillate at a frequency modulated by pressure, yielding extremely stable readings. Such sensors can maintain accuracy on the order of 0.03–0.05% of full scale (equivalent to ~±0.3–0.5 hPa, or ~±3–4 m) over a wide altitude and temperature range. For example, Honeywell's Precision Altimeter (HPA) sensor specifies total errors within ±0.4 hPa across -40 to +85 °C (Honeywell, 2014). High-end altimeters often need no periodic recalibration due to their stability; one digital altimeter system (Thommen AD32 (Thommen Aircraft Equipment, 2025)) uses a vibrating cylinder transducer and guarantees meeting accuracy specs up to 80,000 ft without routine adjustment. These units can resolve altitude changes as fine as 1 foot and have very high update rates to support platforms capable of rapid vertical manoeuvres. Military-grade altimeters are also ruggedised against more extreme environments (e.g., very low pressures at high altitudes, high shock or vibration, rapid pressure changes).

6.3.3. SWAP AND INTEGRATION

Barometric altimeter sensors can be extremely compact and power-efficient, especially at the consumer level (AVNET ABACUS, 2020).

- MEMS barometer chips are a few millimetres in size and can weigh under a gram. For instance, a Bosch BMP388 chip is ~2 × 2 × 0.8 mm in package dimensions and adds negligible weight to a PCB. Power consumption on the order of microwatts of power enables always-on altitude sensing in battery-powered devices.
- Aviation-grade altimeters involve larger form factors. An analogue cockpit altimeter is typically a 3-ATI size instrument (~8–9 cm diameter dial, 15–20 cm depth), mainly for ease of reading, and weighs 0.5–1.0 kg, including casing and mechanism. Modern digital altimeter units (often part of an Air Data Computer) come as rugged modules. For example, a Honeywell HPA sensor module (Honeywell, 2014) is a small rectangular box (~10 × 7 × 3 cm) weighing about 140 g. These modules consume tens of milliwatts to a few watts.

Barometer sensors typically provide either a digital or analogue output that must be integrated into a larger PNT system.

- MEMS barometers for IoT or phones commonly feature digital interfaces like I²C (Inter-Integrated Circuit) and SPI (Serial Peripheral Interface), allowing microcontrollers or application processors to read pressure and temperature registers directly. These sensors often include onboard ADCs and temperature compensation, outputting calibrated pressure values – minimizing processing needed from the host. Integration involves reading the sensor at the desired rate (which can range from 1 Hz for slow-moving users up to ~50–100 Hz for UAV control loops) and converting pressure to altitude in software.
- Aircraft altimeters integrate differently. Traditional analogue altimeters are standalone and require no electronic interface – the pilot reads the value off the dial and manually sets the reference pressure. If the aircraft has an automated reporting system (Mode C/S transponder), an encoding altimeter converts the mechanical altitude into an electrical code (Gillham gray code) for transmission. Modern glass cockpit systems and autopilots use digital air data computers (ADCs). These units take static pressure (usually pitot pressure) via plumbing, use internal pressure transducers to compute altitude, and then output the altitude data over avionics buses. Common interfaces in aviation include ARINC 429 data buses carrying pressure altitude and baro-corrected altitude messages, as well as ARINC 429 or RS-232 maintenance ports for calibration and Built-In-Test.

Barometric sensors must be exposed to ambient air pressure to function, so their placement and packaging are important. Consumer devices have tiny port holes and a waterproof, breathable membrane to protect the sensor. In drones and aircrafts, the sensor is usually fed by a static pressure port positioned to minimise airflow disturbances. The sensor or instrument must be sealed to protect against the infiltration of water and contaminants, and they are designed to be insensitive to orientation or acceleration.

Temperature compensation is critical, and precise altimeters include temperature sensors and calibration curves to correct the pressure reading across the operating range. Integration into a PNT system-of-systems involves sensor fusion. This can be done in an Extended Kalman Filter (EKF) or something similar, whereby the barometer reading corrects drift in an INS' vertical channel or provides a constraint when GNSS vertical accuracy is poor. In terms of data processing, barometric altimeters have minimal requirements and can be adequately handled by a simple microcontroller.

6.3.4. KEY MANUFACTURERS

There are numerous manufacturers of barometric altimeter sensors across different performance tiers: Consumer/IoT Grade: Bosch Sensortec (Germany) is a leading supplier of MEMS barometric pressure sensors (BMP180/BMP280/BMP388 series) used in many smartphones and wearables. Other notable makers include STMicroelectronics (Italy/France) with their LPS22HB/LPS33 series, Infineon (Germany) with the DPS310/DPS368 sensors, and MEMS suppliers like Alps Alpine and TE Connectivity (MEAS). NXP (formerly Freescale) also produces MEMS barometers (e.g., MPL3115A2). These companies focus on high-volume, low-cost production and integrate features like on-chip temperature compensation and digital interfaces to simplify integration.

- Aviation and Industrial Grade: Honeywell (USA) produces a range of precision pressure transducers and barometric modules (such as the Honeywell HPB/HPA series). U.S. firm Paroscientific (part of Rugged Controls) produces Digiquartz resonant pressure sensors, which serve as calibration standards and are used in high-end altimetry and weather buoy systems. In Europe, Thommen (Switzerland) provide air-data instruments and altimeters for aircraft. TE Connectivity offers barometric sensors such as the MS5607 and MS5611. Other global players include Setra Systems (USA) which makes capacitive barometric sensors for weather and avionics, and Keller AG (Switzerland) for industrial pressure modules.
- UK Manufacturers: The UK's presence in this area includes Druck Ltd. (now part of Baker Hughes), which designs high-performance piezoresistive pressure sensors and calibrators used in aerospace and meteorology, and Meggitt (Parker Meggitt), which produces aviation altimeters.

6.3.5. APPLICATIONS AND BENEFITS

Barometric altimeter sensors provide valuable vertical positioning information across a wide range of applications, often complementing other PNT technologies:

- Aviation: Barometric altimeters are a cornerstone of aircraft navigation. Every manned aircraft uses a barometric altimeter to determine altitude above sea level for en-route navigation and terrain clearance. Critically, air traffic separation in the vertical dimension relies on barometric readings. All aircraft set a common reference (e.g., 1013.25 hPa / 29.92 in Hg at high altitudes), so that indicated altitudes are consistent for maintaining safe vertical spacing. Barometric readings are also used in executing altitude hold in autopilots and are referenced in approach procedures (e.g., decision altitudes). Even with GNSS available, aviation mandates barometric altitude for primary altitude reporting, because it is locally referenced and directly indicates pressure levels. In addition to aircraft, rockets and high-altitude balloons use barometric sensors for staging events or altitude triggers due to their simplicity and self-contained nature.

- Unmanned Aerial Vehicles (UAVs) and Drones: Most drones include a MEMS barometer on their flight controller for altitude control. The barometric altimeter enables a drone to hold a steady height above ground (in combination with or in lieu of laser or sonar altimeters) and to execute smooth take-off and landing. It provides a drift-free reference for vertical velocity and position when GPS altitude is coarse or when flying indoors.
- Smartphones and Wearables: Many modern smartphones and wearables contain barometric sensors to augment GNSS positioning. The main benefit is providing vertical location, e.g., distinguishing which floor of a building a user is on, or tracking elevation gain during exercise. Mapping applications and emergency services use phone barometer data to get a more accurate vertical coordinate than GPS alone can typically provide.
- Wider GNSS Augmentation: Barometric altitude is often integrated into navigation solutions to augment GNSS for vertical positioning, which is beneficial for any platform or domain. For example, in autonomous land vehicles, altitude changes from a barometer could aid map matching on hilly roads. Overall, barometers serve as a low-cost augmentation to improve navigations solution quality.

6.3.6. CHALLENGES AND LIMITATIONS

Barometric altimeters face several challenges and limitations (AVNET ABACUS, 2020) (Ostroumov, 2022):

- Dependence on Weather and Calibration: Barometric altitude is fundamentally tied to ambient pressure, which varies with weather systems. A barometric altimeter alone cannot distinguish between a drop in pressure due to climbing in altitude versus a drop due to an approaching low-pressure weather front. This means calibration is required to maintain accuracy. Temperatures also affect air density and, consequently, altimeter readings; so these must be calibrated, typically via a compensation loop.
- Altitude vs. Pressure Ambiguity: A barometric sensor by itself gives pressure. However, conversion to altitude requires assuming or knowing the pressure at a reference altitude. This means that whilst a well-calibrated altimeter will always provide good relative altitude measurements, absolute altitude requires calibration to a height above sea level.
- Environmental Factors and Errors: Barometric readings can be affected by factors other than weather. Dynamic pressure errors occur if the sensor is exposed to airflow or rapid movement; for example, due to wind or propeller wash if sensor placement is poor. MEMS sensors can also exhibit hysteresis and systematic errors with extreme temperature cycles due to package stress. Humidity or water ingress can damage sensors or alter readings. Rugged altimeters include provisions like moisture traps and heating elements to prevent such issues.
- Limited Operating Range and Varying Resolution: Most barometric altimeters have practical limits on the altitude or pressure range they can measure accurately. Consumer sensors often specify a range of ~300–1100 hPa, covers from slightly below sea level up to about 9,000–10,000 m altitude. Above that, the sensor may saturate or lose accuracy. Specialized altimeters are needed for very high altitudes (e.g., for stratospheric balloons). The sensors also have altitude-dependent resolutions; so at very high altitudes, the pressure change per metre is much smaller than near sea-level, increasing the impact of noise in the system and degrading resolution.

6.3.7. EMERGING SYSTEMS

Barometer and altimeter technology is well established, very mature, and widely deployed across consumer and professional domains for PNT. Incremental improvements to all sensor tiers are expected, such as extended pressure ranges (Bolanakis, 2017). Networked concepts are being developed to improve vertical positioning and calibration for human navigation and autonomy (Hager, 2025).

Novel approaches such as graphene-based pressure membranes are under development (Romijn, 2021), as are for quantum fixed length optical cavity pressure (primary developed by NIST towards a new SI definition for pressure), although these are currently low TRL (Hendricks, 2018) and not fieldable. Quantum gravimeters, which can provide relative altitude measurements, are discussed later in this report.

6.4. GRAVIMETERS AND GRAVITY GRADIOMETERS FOR MAP-MATCHING PNT

Gravimeters and gravity gradiometers are instruments that measure Earth's gravitational field with high precision. Gravimeters typically measure the local acceleration due to gravity (a scalar), while gradiometers measure spatial variations in gravity (the gradient of the gravity field). Traditional gravimeters often use free-fall or spring-mass principles, such as a weight on a quartz spring deflecting under gravity. Emerging systems leverage cold-atom interferometry: clouds of ultra-cold atoms are released in free-fall, and laser pulses create matter-wave interference that can be used to create highly accurate measurements of acceleration. For a cold-atom cloud in freefall, this yields a measurement of gravity. In a quantum gravity gradiometer, two atom clouds are dropped simultaneously at a spatial difference, acting as two quantum gravimeters with common-mode noise exclusion due to entanglement, and the gravity gradient is calculated from the difference in the accelerations they measure (Crossley, 2013) (Stray, 2022) (Vovrosh, 2022).

6.4.1. PNT OUTPUTS

For PNT, these instruments can be used to obtain absolute position fixes against gravitational anomaly maps or to provide local gravity estimates as input to inertial navigation systems. By tracking changes in experienced gravity, they can also act as a relative altimeter, as experienced gravity is proportional to distance from the centre of the Earth; however, the sensitivity requirements for this and the dominant impact of tides, as well as local variations in the gravitational field, mean that current systems are not used this way in practice (Crossley, 2013).

The Earth's gravitational field is not uniform; it has spatial variations (anomalies) due to geology, terrain, and structures. If a vehicle carries a gravimeter or gradiometer, it can measure the local gravitational acceleration or gradient and match that measurement to a stored gravity reference map onboard in a manner analogous to terrain matching or any other map-matching technique. This yields a position update or localisation constraint. In essence, gravity becomes a passive navigation signal, available everywhere and impossible to jam or spoof (since it's a natural field). This is valuable for platforms that necessarily operate in GNSS denied environment or that require passive sensing, such as sub-surface and underground. Position fixes obtained this way may be used as a method to periodically reset the drift of an inertial navigation system without requiring external signals (Stray, 2022).

6.4.2. PERFORMANCE TIERS

Gravity sensors span a range from classical mechanical devices to cutting-edge quantum instruments, with performance expressed in microgals (μGal) or in SI units of m/s^2 ($1\ \mu Gal = 1 \times 10^{-8}\ m/s^2$). Key performance metrics include sensitivity (noise floor), accuracy, and stability (drift).

- **Mechanical Gravimeters (Relative):** These use a spring or mechanical sensor and measure changes in gravity relative to a baseline. They are typically static or semi-static instruments. Modern survey-grade gravimeters (e.g., Scintrex CG-6) achieve repeatability around 5 μGal (one standard deviation) for static measurements. They often exhibit drift that must be calibrated by taking periodic readings at known reference points. Their resolution is excellent for geophysical surveying, but on moving platforms, their performance degrades due to vibration. Airborne or shipborne gravimeter systems (often based on stabilized platforms) can achieve 1–5 mGal accuracy, which is sufficient to map broad gravity anomalies. High-end mechanical absolute gravimeters (like the FG5) use laser interferometry in a laboratory setting and can reach 1–2 μGal absolute accuracy, but they require very stable operation and are not mobile in real time.
- **Gravity Gradiometers (Mechanical and Superconducting):** A gravity gradiometer measures the spatial gradient *g*, often reported in units Eotvos (E), where $1\ E = 10^{-9}\ s^{-2}$ (approximately 0.1 μGal/m). By differencing gravity between two points, common-mode noises like vehicle acceleration can be cancelled. A primary example is Lockheed Martin's Full Tensor Gravity Gradiometer (FTG), originally developed for the U.S. Navy's Trident submarines and later commercialised. These instruments use multiple accelerometers on a spinning disk to sense gradients in multiple axes and are deployed on survey aircraft and ships. They achieve sensitivities of a few tens of Eotvos in flight—which is sufficient to detect geological structures. Airborne gradiometers can resolve small, localised density variations that a gravimeter might miss and have a higher measurement rate. Superconducting gradiometers have achieved similar sensitivities in trials. Mechanical and superconducting gradiometers generally offer improved resolution in dynamic environments compared to scalar gravimeters but are larger and more complex devices.
- **Quantum Gravimeters (Absolute):** A new generation of gravimeters using cold atom interferometry to measure gravity is reaching commercial availability. These are highly sensitive and reduce issues of long-term drift as there is no variation in the properties of atoms. However, they are not perfectly 'zero-drift' devices, because their various sub-systems, such as laser systems, will exhibit aging, degrading measurement quality over time. Nevertheless, frequency recalibration is not required. Current commercial quantum gravimeters have comparable precision to the best mechanical meters, but with the promise of better usability and pathways to further improvements in performance. A commercial example is the Muquans (now Exail) Absolute Quantum Gravimeter (AQG). Such devices have achieved a sensitivity of 50 μGal per √Hz and can average down to 1 μGal stability over longer periods. However, these are primarily for static survey applications.

- **Quantum Gravity Gradiometers:** By combining two atom-interferometer gravimeters vertically, quantum gradiometers measure gravity difference and inherently cancel vibrations. The University of Birmingham demonstrated the first outdoor quantum gravity gradiometer in 2022, which achieved a sensitivity of 20 E in 10 minutes, equivalent to about 1.4 μGal accuracy for each of its two sensors. Exail's Differential Quantum Gravimeter (DQG) simultaneously measures absolute gravity and the vertical gradient. They report resolution better than 1 E and the ability to detect very small, buried objects (a 40 cm pipe at ~2 m depth). Quantum gradiometers represent an emerging technology area, with proven performance in controlled environments; however, they remain several years away from on-platform application for PNT.

In summary, static laboratory instruments (whether mechanical or quantum) can reach the single-digit μGal or even sub-μGal level of accuracy, whereas field-deployed devices suffer more noise. Gradiometers trade absolute sensitivity for better noise rejection in motion, making them appropriate for airborne or marine surveys, as well as map-matching. It is also worth noting that the quality of positional data will be directly related to how feature-rich an area is. If there are almost no gravitational features, there will be little to use for localisation.

6.4.3. SWAP AND INTEGRATION

SWaP vary widely between technologies, which impacts how they can be integrated into PNT systems. Traditional gravimeters are relatively compact: a modern field gravimeter like the CG-6 is a small box (~20 cm in size and ~5 kg mass) that runs on hot-swappable batteries (Scintrex, n.d.). High-end absolute gravimeters and gravity gradiometers are larger and more power-hungry. The FG5 absolute meter, for example, is 150 kg, occupies ~3 m^3, and consumes ~500 W of power. Similarly, Lockheed's FTG airborne gradiometer is a substantial payload (hundreds of kilograms), including multiple accelerometer assemblies on a stabilized platform and high-speed spinning disks. These require significant power for the gyroscopes or rotors and active stabilization (GEOExPro, 2022).

Quantum devices currently tend to be physically large due to lasers, vacuum systems, and electronics. As of 2025, a typical cold-atom absolute gravimeter might be rack-sized and weigh tens-to-hundreds of kg, with power requirements in the hundreds of watts. Gradiometers are inherently larger, since they require vertically stacked systems with reasonable spatial separation (e.g. 1 m), resulting in tower-designs that are often 2 metres tall (Vovrosh, 2022).

Integration and processing requirements: Using gravimetric measurements for navigation demands significant data processing. The gravity data itself is low-bandwidth (typically 0.1–1Hz samples), but to extract a useful position fix, the system must compare measurements to a map. This is usually done via a correlation or filtering algorithm. Since gravity maps are only known at finite, potentially coarse resolution, the navigation system might need to maintain multiple hypothesis positions and update their likelihood based on the measured gravity sequences. This can involve running an onboard particle filter or parallel Kalman filters over the map within the INS' position uncertainty region. Such processing needs a stored gravity database and some local computational capability. A vehicle using a gravimeter for navigation would also need a high-quality INS to separate vehicle acceleration from gravitational acceleration in real time. In practice, integration will require high-quality supporting PNT systems and capable software that can extract good PNT data from noisy measurements and manage non-unique matches.

6.4.4. KEY MANUFACTURERS

The field of gravimetry and gradiometry is highly specialized, with a small number of manufacturers:

- Scintrex Limited (Canada) – A leading manufacturer of relative gravimeters. Their CG-5 and newer CG-6 Autograv are widely used for land and marine surveys. Scintrex instruments feature the quartz spring sensor technology and built-in digital controllers (Scintrex, n.d.).
- Micro-g LaCoste (USA/Canada) – Known for absolute and relative gravimeters. They produce the FG5-X absolute gravimeter, which is considered a primary standard (used in metrology labs and geodesy) with ~2 μGal accuracy. Micro-g LaCoste also offers the A-10 portable absolute gravimeter (Micro-g LaCoste, n.d.).
- Lockheed Martin (USA) – Lockheed produce the Full Tensor Gradiometer for airborne and marine mineral exploration, and the smaller Falcon partial-tensor system which is deployed in helicopters (Lockheed Martin Corporation, 2013).
- iMAR Navigation (Germany) – Developed a series of strapdown gravity gradiometer (iCORUS) aimed at airborne use, including to support PNT (iMAR Navigation & Control, n.d.).
- Quantum gravimeters & gradiometers: Exail (formerly iXblue, France) has developed the first commercial quantum gravimeters for survey tasks and is developing quantum gradiometers for navigation (Exail, n.d.). A variety of established quantum technologies companies are actively developing gravity gradiometer systems and products, including AOSense (US) (AOSense, n.d.),

Inflegtion (US & UK) (Inflegtion, n.d.), CPI-EDB (formerly TMD, UK), Q-CTRL (Australia) (Q-CTRL, n.d.) and Delta-G (UK) (Delta-G, n.d.).

6.4.5. APPLICATIONS AND BENEFITS

Gravity-based navigation has the benefit of providing a passive means of position fixing or localisation in any environment, with varying gravitational features, contingent upon having map data. It may also improve traditional INS performance by providing a more accurate estimate of the local gravity vector. This benefit is true across platforms, although SWaP requirements and ruggedisation challenges limit realistic deployment (Crossley, 2013) (Stray, 2022) (Vovrosh, 2022).

- **Submarine and Underwater Navigation:** This is a primary application domain for gravity map matching and enables covert position-fixing in an environment inherently isolated from external navigation signals. It is the domain for which gravity gradiometers were originally developed. More broadly, any underwater vehicle (autonomous underwater vehicle or AUV and remotely operated vehicles or ROV) could use a gravimeter for periodic position fixes, enabling greater autonomy and longer submerged mission durations. It may also better enable navigation of complex sub-surface environments, such as under-ice exploration.
- **Underground Navigation:** Similarly to sub-surface environments, underground environments are naturally GNSS denied but usually have complex geographic features that enable map-matching based on gravitational/geological features. This may also benefit underground rail platforms, enabling more accurate positioning over fixed routes for which accurate route maps exist.
- **Aircraft:** Aerial gravimeters and gravity gradiometers have traditionally been used for geological survey and mineral discovery; however, these same features may be used for position fixing. Furthermore, aerial platforms cover sufficient distances to experience significant variations in the Earth's magnetic field. As a result, their INS must rely on a gravitational model of the Earth and the coarse-grained local estimates of gravity that it provides. The gravity estimate provided by a performant gravimeter or gravity gradiometer could improve this, resulting in better INS performance and improved resilience.

6.4.6. CHALLENGES AND LIMITATIONS

The advancement of gravity-based navigation systems is challenging for various reasons (Crossley, 2013) (Stray, 2022) (Vovrosh, 2022):

- Signal to Noise: Gravity anomalies that are useful for navigation are very small—often milliGals or less. Whilst measuring these anomalies is very achievable in a laboratory setting, it is challenging to achieve with the motion and vibration of a moving platform. Classical gravimeters are highly sensitive to vibration and tilt, so they need to be stationary or on a stabilised platform. Gravity gradiometers mitigate this by subtracting two sensors and excluding common-mode noise, but they, too, have a limited signal-to-noise ratio, which has restricted use in highly dynamic environments.
- Map Resolution and Errors: A gravity navigation system is only as good as the map it uses. Global gravity models (like EGM2008 or EGM2020) have accuracies in the order of mGal and resolutions of 10–20 km, which is too coarse for precise navigation. Higher-resolution maps can be made for specific regions (e.g., a naval operating area might be surveyed with airborne gravimetry to, perhaps, 1-2 mGal accuracy on a 1 km grid). Even in this scenario, natural temporal changes (e.g., groundwater movement, tidal effects) and survey errors mean that the map contains uncertainty. Additionally, not all areas are rich in gravitational features. Over featureless ocean basins or cratonic plains, the gravity profile might be very smooth with low contrast, which is not informative for positioning, although route-selection might mitigate this.
- Throughput and Update Rate: Gravimeters and gravity gradiometers are relatively low bandwidth sensors. A gravimeter might need tens of seconds for a stable reading (especially if averaging to reduce noise) as well as a gradiometer (such as the FTG of approximately 1Hz). This is very low compared to most local positioning or navigation sensors and is particularly bad if the platform is moving rapidly and variably between measurements, making it significantly harder to correlate measurements against map data. Quantum sensors have been demonstrated to operate at a similar rate. However, laboratory experiments are aiming to push this into the 10s of Hertz—which is still sparse relative to most sensors.
- SWaP: High-end gravimeters and gravity gradiometers are large and power hungry, significantly limiting platforms able to integrate them. The need for significant vertical space for gradiometers increases this challenge.
- Ambiguity and Depth vs Lateral Resolution: A fundamental issue in gravimetry is that a given gravity anomaly could be caused by different distributions of mass (the "inverse problem"). For navigation, this translates to potential ambiguity in inferring position vs inferring the cause of the anomaly. For instance, a gravity anomaly reading might indicate to someone that they are near a certain mass concentration, but not whether they

are directly over it or somewhat off to the side, combined with a different mass. Pure gravimeter readings create an iso-contour line on the map of possible positions that yield that value. The navigation system needs multiple readings over distance (or additional info) to triangulate a unique fix. Gravity gradiometers help reduce this ambiguity by being more sensitive to local variations. The combination of absolute gravity and gradient can, in theory, separate the size of an anomaly from its distance. Nonetheless, gravity-based fixes will always have a degree of uncertainty.

- Cost: Advanced gravity instruments are expensive (often ranging from tens to hundreds of thousands of pounds for a single unit, and up to millions for a full system). While cost might be justified for high-value platforms, it limits wider deployment.

6.4.7. EMERGING SYSTEMS

Gravimetry and gradiometry for navigation is bespoke and limited to few types of platforms. Classical systems, such as the Lockheed FTG, are mature and proven—although, in general, their use is overwhelmingly for survey rather than for navigation. However, the relevance of gravity navigation is growing due to more demand for sub-surface systems (especially for autonomous operation) and increasing issues around GNSS vulnerability.

It is possible that existing classical gravity sensors at various performance tiers may be applied to navigation in the future, particularly in conjunction with wider sensor suites, more advanced signal processing, and more detailed maps. Classical systems may develop towards better noise isolation, or work on integration with complementary stabilised platforms.

Quantum systems are likely the future of gravimetry, significantly addressing noise exclusion in a gradiometer configuration and vastly reducing system drift. These systems are between prototype and demonstration maturities (TRLs 2-5) and have headroom for large additional improvements to stability and measurement frequency (Stray, 2022).

It is worth noting that future satellite gravity missions may improve global gravity maps, which directly benefits gravity-aided navigation (Flechtner, 2021).

6.5. MAGNETIC SENSING

Magnetometry uses the Earth's magnetic field to aid in local PNT. It provides three forms of positioning and navigation output: absolute position by matching measurements to magnetic maps (outdoors from crustal anomalies, indoors from building fingerprints or beacons); heading from tilt-compensated vector measurements (converted to true heading using magnetic declination); and relative motion from changes in the field along a path (magneto-odometry).

Magnetic sensing is applicable across domains and platforms. Robots, autonomous land platforms and vehicles gain indoor fixes and odometry in sites or environments with rich magnetic signatures (such as steel-dense buildings). Maritime platforms use boom-mounted sensors and gradiometers for coastal updates and heading. Air platforms at low altitude can map-match to reduce, or potentially bound, their position uncertainty. Space platforms mainly use magnetometers for attitude determination, not position. Operational main-field models such as the World Magnetic Model 2025 (WMM2025), International Geomagnetic Reference Field (IGRF-14), and research models such as CHAOS-8 provide the reference context to derive heading information and perform integrity checks (WMM2025, 2024) (IGRF-14, 2024) (Kloss, et al., 2025).

For terrain-referenced navigation (TRN) outdoors, the useful signal is the crustal anomaly field (natural variations in the Earth's crust). Global anomaly grids such as EMAG2v3 give worldwide coverage and route-specific surveys improve resolution where higher accuracy is needed. In practice, systems remove the modelled main field, correct for altitude and attitude, and correlate total-field or gradient measurements against an anomaly grid to produce a position estimate and a confidence measure from the correlation peak. Airborne trials show tens-to-hundreds of metres horizontal position accuracy and significant long-term drift reduction from magnetic TRN fused with INS dead reckoning, albeit in favourable terrain and with good map quality (Meyer, Saltus, & Chulliat, 2017) (Saltus, et al., 2023) (Lee & Canciani, 2020) (Q-CTRL, 2025).

For indoor navigation, buildings contain stable ferromagnetic features that create repeatable patterns in the measured field. Once mapped, these fingerprints give absolute fixes of >2 m with COTS tri-axial sensors, especially when combined with inertial odometry and other local methods to bridge ambiguous, feature sparse areas.

Magnetometry is passive and infrastructure-light; integrity is managed with disturbance monitors (e.g. 50/60 Hz energy) and cautious use during elevated geomagnetic activity indicated (Chen, Chen, Chen, & Liu, 2021) (Ouyang, et al., 2023) (NOAA, 2025).

6.5.1. PNT OUTPUTS

- **Absolute position updates:** Outdoors, TRN produces discrete position fixes by matching measurements to a magnetic anomaly map. Fixes are provided only when the correlation is strong and unambiguous; the system reports both the position and a covariance derived from the peak height/width of the match. Availability depends on the strength of local anomalies and their uniqueness, altitude, and map resolution. Global grid maps can be used, and route surveys raise availability where when they are too coarse. Indoors, a site 'fingerprint' map gives room-scale fixes at practical rates when the environment has clearly identifiable magnetic features. Accuracies of 0.5–2 m are typical with commercial tri-axial sensors integrated in a system-of-systems with other local sensors to bridge navigation in areas where the magnetic profile is ambiguous (Meyer, Saltus, & Chulliat, 2017) (Saltus, et al., 2023) (Lee & Canciani, 2020) (Chen, Chen, Chen, & Liu, 2021) (Ouyang, et al., 2023).

- **Heading aids:** Tri-axial vector measurements provide magnetic heading once tilt-compensated by an IMU, with conversion to true heading carried out using a contemporary declination model (World Magnetic Model or IGRF). In well integrated systems and good circumstances sub-degree performance is achievable. However, this does not hold for magnetically disturbed areas, and in such cases a system should raise a disturbance flag and attempt to estimate a realistic uncertainty.
- **Relative motion (magneto-odometry):** Changes in the measured field along a path can be turned into short-baseline speed and displacement measurements. Using two sensors on a fixed baseline (for example, fore and aft on a vehicle) improves observability and reduces bias. The outputs of such systems are time-stamped measurements with associated confidence ratings, allowing a PNT filter to weight them against inertial measure data and physical or illumination based odometry (Ouyang, et al., 2023) (Zhang T. a., 2023).
- **Gradiometric constraints and integrity:** A pair (or array) of sensors forms a gradiometer. The gradient suppresses common-mode noise and disturbances, and sharpens matching, especially outdoors or in large indoor spaces. As in other gradiometry regimes (e.g. gravimetric gradiometry) this results in less ambiguous and more resilient map matching (Saltus, et al., 2023).

6.5.2. PERFORMANCE TIERS

Magnetometry performance depends on sensor noise and stability, map quality, and the 'texture' of the environment. There is a diversity of sensor types, and under different integration and processing scenarios some can cross between performance tiers, which are described in general below.

- **Embedded / indoor arrays (Hall, AMR/GMR/TMR, magneto-inductive):** Low SWAP-C mass manufactured COTS tri-axial sensors and modules support update rates of 50–200 Hz with noise typically in the region of 1–3 nT/√Hz and dynamic ranges around ±100-±1000 μT. In mapped, magnetically textured, buildings absolute fixes can have a precision of 0.5–2 m at room scale, especially when fused with inertial dead-reckoning. Short-baseline magneto-odometry constrains drift between fixes and a fore-aft sensor pair, or small sensor array, improves observability and reduces bias. Heading accuracy is typically 1–3° once calibrated. These devices suit handsets, UGVs, and small UAVs, including dense arrays for gradiometry in larger spaces (Chen, Chen, Chen, & Liu, 2021) (Ouyang, et al., 2023) (PNI Sensor, 2025).
- **Vehicle-grade vector/scalar for land, sea and air (fluxgate tri-axials; compact scalar OPM; matched gradiometers):** Fluxgates provide tens of pT/√Hz noise at 1-100 Hz with good bias stability. Earth-field optically pumped magnetometers (OPM) achieve ≤1–3 pT/√Hz at 100–500 Hz in compact heads. These instruments deliver sub-degree magnetic heading after calibration and support outdoor terrain-referenced navigation (TRN) with tens-of-metres horizontal updates where anomaly gradients are strong, and maps are good. Dual-head gradiometers suppress common-mode disturbance and improve map matching and can be integrated on marine booms and airborne wingtips. Typical use cases are coastal and low-altitude, harbour manoeuvring, and drift reduction for transport aircraft or UGVs operating over magnetically textured areas (Saltus, et al., 2023) (Lee & Canciani, 2020) (Bartington, 2025) (QuSpin, 2025).
- **Survey-grade scalar magnetometers and arrays (Overhauser; OPM arrays):** Overhauser magnetometers provide sub-0.1 nT time-domain sensitivity at moderate rates and very low drift; OPM arrays extend bandwidth and enable compact gradiometry. These systems are used to build or refresh regional anomaly surveys along intended routes and as high-stability scalar channels during operations. When paired with good maps, they improve the availability and confidence of TRN updates, with the limiting factor mainly being map resolution and altitude, not sensor noise. This tier is common in marine towed bodies and aerial survey pods. Superconducting Quantum Interference Device (SQUID) magnetometers are not used as onboard PNT sensors, whilst they are technically highly mature their current role is limited to high-sensitivity survey/gradiometry that improves the anomaly maps later used for TRN (Gemsys, 2025).

6.5.3. SWAP AND INTEGRATION

Embedded tri-axial magnetometers (Hall, AMR/GMR/TMR, magneto-inductive) are packaged as chip-scale sensors or small modules. Individual sensing elements are a few millimetres across, while common PCB modules are ~20-40 mm per side, <10 g and use <100 mW of power, with 50–200 Hz update rates. Vehicle-grade fluxgate tri-axials are hand-sized, either cylindrical or box-shaped and typically 5-20cm per side with a weight of 50-200g, drawing <2 W.

Optically pumped magnetometers (OPMs) separate a compact sensor head from small control electronics. The sensor head is typically <5 cm per side and <30 g, and the electronics module is slightly larger with a power draw of <5 W. Overhauser systems for survey/scalar reference are portable but comparatively large, typically comprising of a ~1 kg sensor/boom assembly and a ~2 kg console, with backpack-class volume and battery operation. These orders of magnitude illustrate practical envelopes by class rather than prescribing specific designs, which vary considerably and may be designed for integration with specific platforms (PNI Sensor, 2025) (Bartington, 2025) (QuSpin, 2025) (Gemsys, 2025) (Q-CTRL, 2025).

Mechanical integration is shaped by magnetic cleanliness rather than structural considerations. Installations on vehicles and vessels commonly employ standoff locations, such as booms, masts or wingtips, to reduce hard-/soft-iron effects from the platform. For gradiometry configurations or arrays baselines can vary considerably and are typically adapted to platform size, short on UGVs and longer on marine booms or aircraft.

Electrical and thermal behaviours differ by class. Embedded sensors run directly from low-voltage rails and interface over I^2C/SPI/UART, OPMs and multi-head systems use Ethernet for data output and control. Temperature changes drive bias and scale-factor drift, so characterisation over temperature and correction is standard practice. OPMs work with hot vapour gas contained in vapour cells, these require minutes-scale warm-up times and stable heat paths, making thermal stability a more important integration factor.

Calibration must be carried out on a per-platform basis as the local magnetic environment is a major factor for performance. Hard-/soft-iron calibration and alignment to the IMU/navigation frame are required, with re-calibration needed if platform loadout changes and for routine maintenance. For gradiometers, calibrating the baseline vector and lever arm to the navigation origin is necessary for consistency and integration with other sensors. These steps bound heading bias, improve indoor fingerprint repeatability, and stabilise outdoor correlation against anomaly maps (Renaudin, Afzal, & Lachapelle, 2010) (Vasconcelos, Elkaim, Silvestre, Oliveira, & Cardeira, 2011).

If OPM data is to be integrated in a fused navigation solution from a wider PNT system-of-systems time synchronisation is important, but no different or more stringent to that for other sensors. Embedded devices deliver time-stamped samples at the sensor's measurement rate, and OPMs and gradiometer rigs increasingly support PPS-disciplined or PTP-synchronised streaming to make latency and jitter more predictable and hence improve fusion.

Normal integration architectures for platforms are well established. Handsets and wearables contain embedded magnetometers and are widely used for ad hoc surveys and indoor navigation. They are low-cost, but orientation variability and local disturbances can limit performance, and necessitate good tilt compensation. Land systems favour multiple embedded sensors placed away from motors and batteries, with a short fore-aft baseline to improve magneto-odometry. Maritime installations use boom-mounted fluxgates or scalar heads with below-deck electronics, and gradiometers to help near harbours or other magnetically active environments where common-mode interference is stronger. Air platforms use wingtip/boom mounting to reduce airframe bias.

6.5.4. KEY MANUFACTURERS

The magnetometer supply chain is diverse and global, with many manufacturers including relatively new entries in areas such as OPMs.

Embedded tri-axial vector sensors (Hall, AMR/GMR/TMR)

- Asahi Kasei Microdevices (Japan) – Supplies low-power magnetometers for handsets and wearables widely used in indoor fingerprinting and mobile mapping.
- STMicroelectronics (Switzerland) – Produces integrated tri-axial compasses for embedded and industrial platforms used in indoor navigation stacks.
- Infineon (Germany) – Offers AMR/TMR devices for consumer and automotive applications suitable for dense array deployments.
- TDK InvenSense (Japan/USA) – Provides compact sensor modules for mobile and robotics use where SWaP is constrained.
- QST (China) – Manufactures low-cost magnetometers commonly used in consumer devices and ad hoc survey kits.
- PNI Sensor (USA) – Supplies repeatable, low-power tri-axial modules (magneto-inductive/TMR) used on UGVs/UAVs for indoor positioning and magneto-odometry.

Fluxgate sensors and gradiometers

- Bartington Instruments (UK) – Provides low-noise tri-axial fluxgates and matched gradiometers for land/sea/air platforms supporting heading aids and outdoor TRN.
- SENSYS (Germany) – Delivers fluxgate arrays and systems for survey and UXO work, applicable to regional anomaly mapping.
- Foerster (Germany) – Produces industrial and survey-grade fluxgate instruments used in mapping and platform integration.

Scalar total-field (Overhauser)

- GEM Systems (Canada) – Supplies Overhauser magnetometers used for marine and land surveys and as stable scalar references.
- Geometrics (USA) – Provides proton-precession and marine magnetometers for route surveys and coastal operations.
- Scintrex (Canada) – Manufactures survey-grade total-field systems used to build regional anomaly datasets.
- Marine Magnetics (Canada) – Focuses on marine towed magnetometers for coastal and harbour mapping.

Optically pumped magnetometers

- QuSpin (USA) – Produces compact Earth-field OPMs used as onboard scalar/vector channels and in small arrays for gradiometry.
- Twinleaf (USA) – Offers portable OPM instruments and accessories suitable for arrayed measurements and reference channels.

NV-centre diamond

- SBQuantum (Canada) – Develops compact NV-diamond magnetometer modules for mapping and pilot-scale gradiometry.
- Qnami (Switzerland) – Supplies NV-diamond components and modules used in high-resolution field mapping pilots.

SQUID survey/gradiometry

- Supracon (Germany) – Provides cryogenic SQUID systems used in specialist airborne/marine surveys that improve anomaly maps.
- STAR Cryoelectronics (USA) – Supplies SQUID magnetometers for high-sensitivity gradiometry; not used as onboard PNT sensors.

Survey and data providers

- Fugro (Netherlands) – Acquires and processes regional magnetic data used to enhance anomaly maps for TRN.
- CGG (France) – Provides multi-physics survey services and magnetic datasets that improve map resolution along routes.

6.5.5. APPLICATIONS AND BENEFITS

Magnetometry adds passive, infrastructure-light inputs for local PNT. It enables absolute position through map-matching outdoors and indoors, heading through tilt-compensated vectors, and relative motion from changes in magnetic texture. These observables are useful on land (UGVs and vehicles), at sea (coastal operations and harbour manoeuvres), and in the air (low-altitude drift resets), while spacecraft primarily use magnetometers for attitude rather than position. Contemporary field models support heading transforms; global anomaly grids and route-specific surveys underpin outdoor map matching. Hence, magnetometers are a universally relevant data source for PNT, whether addressing positioning, improved dead reckoning, or even just integrity bounding (WMM2025, 2024) (IGRF-14, 2024) (Kloss, et al., 2025) (Meyer, Saltus, & Chulliat, 2017) (Saltus, et al., 2023) (Lee & Canciani, 2020).

Indoor GNSS-denied navigation: Buildings contain stable ferromagnetic features that create repeatable fingerprints. Once mapped, these support room-scale fixes of ~0.5–2 m with commodity tri-axial sensors at practical update rates, especially when inertial dead-reckoning bridges low-texture areas. This can be used for indoor navigation, and is unaffected by lighting, smoke, dust and similar factors making it a relevant counterpart to optical systems often used indoors (Chen, Chen, Chen, & Liu, 2021) (Ouyang, et al., 2023) (Zhang T. a., 2023).

Subsurface, steel-dense and maritime domains: In corridors, tunnels, ships and platforms where RF is attenuated or multipath-dominated, magneto-odometry and gradiometry constrain drift and suppress common-mode disturbance. At sea, boom-mounted sensors and gradiometers support coastal terrain-referenced navigation and improve repeatability during harbour manoeuvres. Regional surveys can raise fix availability beyond what global grids allow (Saltus, et al., 2023).

Air and ground outdoor TRN: Low-altitude aircraft and ground vehicles can take periodic magnetic fixes to bound INS drift over long durations. Accuracy and fix rate depend on anomaly gradient strength, altitude, and map resolution, route surveys improve both. During elevated geomagnetic activity (for example, Kp ≥ 5), systems must inflate covariances and, at storm levels, defer absolute fixes – preserving integrity but limiting availability (Lee & Canciani, 2020).

Heading and integrity aids: Tilt-compensated magnetic heading provides an independent cross-check on gyrocompassing or GNSS course-over-ground.

6.5.6. CHALLENGES AND LIMITATIONS

Magnetometry is constrained by environmental variability, map fidelity, platform-induced bias, and sensor behaviours. These limits affect availability, accuracy and integrity.

Space weather and diurnal variability: Magnetometry is sensitive to space weather. During geomagnetic disturbances the field becomes less stable, reducing the contrast needed for map matching and introducing heading estimation errors. A common policy is to enlarge the reported uncertainty when activity rises (for example, Kp ≥ 5) and to pause absolute fixes in storm conditions (NOAA, 2025).

Maps, altitude and ambiguity: Maps and altitude set the ceiling on performance outdoors. Global anomaly grids provide coverage but lose detail with height and in low-relief regions, which increases ambiguity. Targeted route surveys can be conducted to improve map accuracy in key regions, improving fix availability along surveyed corridors. Where the crustal signal is weak or shielded (tunnels, basements), usable fixes may be rare (Meyer, Saltus, & Chulliat, 2017) (Saltus, et al., 2023) (Lee & Canciani, 2020).

Platform magnetic cleanliness and stability: Host platforms introduce sources of magnetic bias. Steel structures, batteries, cabling, motors and other features with strong magnetic signatures create 'hard-iron' and 'soft-iron' effects that change with configuration and temperature. 'Hard-iron' errors are fixed magnetic offsets from permanently magnetised parts of the platform, or from steady currents that shift the measured field equally in all directions, whereas 'soft-iron' errors are direction-dependent distortions (scale/orthogonality changes) from permeable materials that bend and amplify the external field. Routine calibration and re-checks after maintenance are necessary to keep heading and map-matching stable (Renaudin, Afzal, & Lachapelle, 2010) (Vasconcelos, Elkaim, Silvestre, Oliveira, & Cardeira, 2011).

Non-stationarity and interference: Indoors, non-stationary environments degrade fingerprints over time. Moving lifts, HVAC and layout changes alter the local pattern, and 50/60Hz mains-frequency interference can mask useful detail. Gradiometers help by cancelling common-mode disturbance, but periodic map refresh and robust descriptors remain part of through-life support (Chen, Chen, Chen, & Liu, 2021) (Ouyang, et al., 2023).

Operating limits: Magnetometers have predictable, well understood, operating limits. Embedded AMR/TMR/Hall parts drift with temperature and can saturate near strong fields. Fluxgate magnetometers suffer noise at very low frequencies, which appears as slow drift over seconds to minutes. Furthermore, because they work by periodically driving a core into saturation the drive waveform must be well controlled, if its amplitude or timing varies it shows up as bias or extra noise. OPMs require warm-up of the vapour cell and also rely on highly stable lasers (which can be influenced by temperature and other factors), they can also lose performance in large ambient gradients although mitigation strategies exist. Overhauser instruments are bulkier and slower, suiting survey and scalar reference roles rather than fast control loops as homogenous field around the sensor for accurate measurements.

6.5.7. EMERGING SYSTEMS

Progress in magnetic PNT is mostly incremental, particularly in established hardware areas and in mapping. On the modelling side, World Magnetic Model High Resolution (WMMHR 2025) supplements WMM2025 with higher-degree crustal terms and finer coefficient precision, improving heading transforms and main-field data. Mapping improvements, and increased availability of regional or route survey data, gradually raises the PNT performance ceiling for magnetic map matching. Rail, ports and coastal corridors are natural beneficiaries because traffic is constrained to repeatable routes where surveys can be refreshed efficiently. Hardware also plays a role here, and improvements in accurate miniature magnetometers (e.g. OPMs) decreases survey cost and may enable moves towards crowdsourced data in the future (WMM2025, 2024) (WMMHR2025, 2024).

On sensors, deployable OPMs are maturing beyond lab use. Compact heads with heater control and synchronised electronics support land vehicle and small-vessel arrays for gradiometry. Recent field deployments and UAV integrations underline that OPMs can operate in mobile and outdoor settings without shields when sited correctly, and demonstrations on flown air platforms show significant potential for improving integrity bounding over periods without GNSS (QuSpin, 2025) (Q-CTRL, 2025) (Mrozowski, et al., 2024) (U.S. Air Force, 2023).

NV-centre diamond devices have advanced from benchtop to portable vector instruments. Recent demonstrations show road-vehicle and trolley mapping with NV sensors and real-time vector/tensor imaging, indicating a credible future role in compact mapping systems, although use for PNT directly remains further away (Yu, et al., 2025) (Graham, et al., 2025).

As highly compact high-performance magnetometers become more available, and at decreasing price points, new use cases are emerging in various domains. In rail, the fixed right-of-way and strong magnetic signatures from infrastructure support reliable map-matching, and matching approaches have been validated on real track. In aviation, trials have flown OPMs on large transport aircraft, demonstrating integration with inertial systems and mission avionics, strengthening the case for magnetometry as a key PNT input on pre-surveyed low-level routes. In all cases, these demonstrations reinforce the role of magnetometry as a resilience contributor, raising availability and integrity as part of a wider system-of-systems, including in GNSS denied circumstances (Siebler, Lehner, Sand, & Hanebeck, 2023) (U.S. Air Force, 2023).

6.6. INERTIAL NAVIGATION SYSTEMS (INS) FOR LOCAL PNT

Inertial Navigation Systems (INS) determine a platform's motion and orientation using inertial sensors—accelerometers and gyroscopes—without external references. An INS continuously integrates accelerometer measurements (linear acceleration) and gyroscope measurements (angular rotation) to estimate the device's position, velocity, and attitude relative to a starting point. Modern INS are typically strapdown systems with three accelerometers and three gyros mounted rigidly in orthogonal axes. Computational algorithms (e.g., Kalman filtering) combine these sensor outputs into a continuous navigation solution, which is also often fused with other sensors, if available, to provide a PNT system-of-systems output. Key variants of INS are defined by the sensor technologies used for the gyroscopes and accelerometers, although gyroscopic errors—and hence performance—are dominant in INS systems and overwhelmingly define performance grades. This includes MEMS-based INS, Ring Laser Gyro (RLG) INS, Fiber-Optic Gyro (FOG) INS, Hemispherical Resonator Gyro (HRG) INS, and emerging cold-atom quantum inertial sensors (Barbour, 2011) (Groves, 2018) (Yazdi, Ayazi, & Najafi, 1998).

Accelerometers used in INS vary in design and performance. MEMS accelerometers are compact and low-cost, typically using capacitive sensing of a microfabricated proof mass on springs. Higher-end systems may use sprung mass (pendulous) accelerometers with electrostatic or piezoresistive readout, offering better stability. Vibrating beam accelerometers, now reaching navigation-grade maturity, use stress-induced frequency shifts in resonant beams to measure acceleration with excellent long-term bias stability.

Gyroscopes measure angular rate (rotation) about an axis; many designs (mechanical spinning gyros, optical gyros, vibratory MEMS gyros (Sobreviela-Falces, 2022)) exist. MEMS gyroscopes typically use a vibrating structure and detect rotation via the Coriolis effect. When the device rotates, the vibrating mass experiences a secondary oscillation that is proportional to the angular rate. Optical gyros (RLG and FOG) use the Sagnac effect: two light beams traveling in opposite directions around a closed path will experience a phase shift or frequency difference proportional to rotation. For example, an RLG uses a laser in a closed triangular or square cavity of mirrors; rotation causes one beam's path length to effectively differ, shifting the interference pattern at the detector. A FOG sends light through a long fibre coil; rotation produces a phase shift between the counter-propagating beams, detected as an interference signal. An HRG is a type of vibrating gyroscope with no light that consists of a thin hemispherical resonator that vibrates in a standing wave pattern. When the system rotates, the vibration pattern precesses and electrodes sense this drift to infer rotation (Groves, 2018) (Safran Electronics & Defense, 2025).

Quantum cold-atom systems exist at fieldable prototype maturities for both accelerometers and gyroscopes. The focus is on both achieving single-shot measurement accuracies greater than current systems, and—perhaps more importantly—vastly reducing long-term drift due to the 'identical' nature of atomic measurements (although some drift will remain due to aging of laser systems and other more traditional parts of the system).

From linear acceleration and rotational acceleration measurements, an INS computes velocity and, by double integration, position changes. A complete INS is formed from the combination of appropriate gyroscopes and accelerometers, and processing electronics.

6.6.1. PNT OUTPUTS

An INS provides a continuous estimate of position, velocity, and orientation (attitude) of the host platform. By starting from a known initial position and attitude, the INS updates these states by integrating the accelerations and rotation rates measured in the body frame. The output is a form of dead reckoning: the INS plots the vehicle's course based on its sensed motions. This yields full 3D position (latitude, longitude, altitude), velocity (often in north/east/down), and orientation (roll, pitch or yaw angles). High-end INS can also output gravity estimates, and when stationary, they can serve as accurate gyroscopic compasses (finding true north by sensing Earth's rotation). The outputs from an INS may be fed into navigation systems, or guidance and control systems for other onboard systems (Groves, 2018) (Barbour, 2011) (Titterton, 2004).

However, because an INS computes position by integrating sensor outputs over time, any sensor errors would cause the solution to drift over time. Bias in inertial sensors arises from several sources, including manufacturing imperfections (e.g., asymmetry in the proof mass or electrode layout), temperature-dependent drift, scale factor errors, and long-term ageing effects. Due to the nature of the double integration, a pure INS will suffer polynomial error growth over time, which would be faster for lower-grade sensors and slower for high-grade sensors. Nonetheless, within mission durations appropriate for an INS grade or when regularly calibrated to a true position (e.g., intermittent GNSS), an INS can be used for highly accurate local navigation. INS outputs are immune to external jamming or interference and typically have high update rates (100–1000 Hz), which is beneficial for capturing fast dynamics (Groves, 2018).

In practice, INS is fused with other PNT inputs, especially GNSS or other absolute references that can re-fix position and reset drift. The INS traditionally is used to bridge short outages; however, the relevance of fully local navigation is growing and with it the requirements for INS that maintain accuracy for long mission durations (10s of days). This is beyond the reach of almost all current commercial systems; therefore, new technologies, such as cold-atom based quantum systems, are seen as key to enabling this level of performance in the future.

6.6.2. PERFORMANCE TIERS

Inertial Navigation Systems (INS) are commonly categorised into performance tiers based on the error characteristics of their constituent sensors and their resultant rate of navigation drift over time for an intended deployed environment or platform. These categories range from consumer-grade devices with substantial drift and minimal cost, through tactical- and navigation-grade systems suitable for military or industrial deployment, to strategic-grade units offering extremely low drift and long-duration standalone performance. The upper envelope of strategic-grade sensors is being pushed further by emerging sensor technologies, such as quantum sensors, to meet the demands of future use-cases. These tiers are characterised by bias stability (typically measured in °/h for gyroscopes and µg for accelerometers), scale factor stability, and Allan deviation over defined averaging times (Barbour, 2011).

- Consumer-grade (Commercial/Embedded): These systems are typically found in consumer electronics such as smartphones, tablets, and gaming devices. They employ low-cost MEMS sensors with minimal calibration. Gyroscopic bias instabilities are generally greater than 1°/s, and accelerometer biases exceed 50 mg. Position error accumulates rapidly, requiring re-fixes on the order of seconds. These systems are unsuitable for dead reckoning but can be used for short-term motion sensing.
- Tactical-grade: Tactical-grade systems are employed in defence, industrial, and mid-performance unmanned platforms. These include precision-guided munitions, robotics, and airborne and ground-based autonomous systems. Gyro bias stabilities are typically ~1°/h, with accelerometer bias at around 1 mg. For example, MEMS units, such as the EMCORE SDI500 and Sensonor STIM300, achieve performance near or better than these thresholds (EMCORE, 2021) (Sensonor, 2024). This class is sufficient for short-term autonomous navigation with drift on the order of kilometres per hour.
- Navigation-grade: Navigation-grade INS are used in aircraft, maritime platforms, and medium-to-long-mission autonomous systems where extended operation without GNSS is required. These systems typically use FOG, RLG, or HRG gyroscopes with bias stabilities of 0.01°/h, and accelerometer biases in the 10–50 µg range. For example, the Northrop Grumman LN-250 (Northrop Grumman, 2025), Honeywell HG9900, and Safran Geonyx represent this performance level. Such systems can sustain navigation with tolerable drift (e.g., ~1 nmi/hour) for tens of minutes to several hours (Honeywell, 2023).
- Strategic-grade: Strategic-grade INS are suitable for mission-critical applications such as long-duration GNSS-free navigation and sub-surface navigation. They achieve gyro bias stability better than 0.001°/h and accelerometer bias near or below 1 µg. Technologies include electrostatically suspended gyros (ESGs) and ultra-stable HRGs. This category can sustain accurate navigation over many hours or days without external updates. iXblue's MARINS FOG INS and Draper's Silicon Oscillating Accelerometer (SOA) are examples of this class (Exail, 2023).
- Strategic-grade+: Emerging technologies such as quantum inertial sensors (Q-INS) based on cold-atom interferometry aim to further reduce bias drift over time. The goal of such systems would be to provide long-term bias correction, likely in a hybrid configuration with strategic-grade classical sensors. This would seek to extend tolerable holdover to many weeks or months or to provide highly accurate position (e.g., <10 m) for considerably longer (hours to days). This is an aspirational sensor category and candidate technologies are at best field deployable test units (TRL 6) (Carranza, 2020).

While these categories provide a useful structure, real-world systems may straddle boundaries. For example, some advanced MEMS now approach navigation-grade performance under laboratory conditions, with <0.1°/h gyro bias and sub-mg accelerometer bias (EMCORE, 2021) (Sensonor, 2024). Similarly, HRG-based systems can scale in performance without major changes in SWaP, blurring traditional distinctions. Overall, each tier reflects a trade-off between size, cost, and precision, with an approximate order-of-magnitude improvement in performance at each level (Advanced Navigation, 2022) (Groves, 2018).

6.6.3. SWAP AND INTEGRATION

The SWaP characteristics of INS vary depending on sensor technology and performance tier. Lower-end MEMS units are highly compact and power-efficient, while optical and strategic-grade systems are considerably larger and more demanding in terms of volume and energy. Integration requirements, both mechanical and computational, also differ significantly by class.

- A typical MEMS IMS can be built into a module measuring under 5 cm across and weighing tens of grams, with single-digit Watts power consumption (e.g., Advanced Navigation's Motus MEMS IMU occupies only ~16 cm^3 and weighs 26 g, drawing approximately 1.4 W of power (Advanced Navigation, 2025).
- FOG and RLG-based INS are larger and consume more power. Complete FOG or RLG INS can weigh low kilograms and draw 10–20 W of power due to laser sources, control electronics, and temperature stabilisation (e.g., the Northrop Grumman LN-200 IMU weighs 750g, has a volume ~2 l, and consumes 12 W (Northrop Grumman, 2025).

- HRG-based INS offer a compact alternative for high-end applications. HRGs are inherently rugged, with no moving parts, and exhibit performance scaling through internal design modifications rather than external size increases, thereby maintaining compactness at high grades. For example, Safran's HRG Crystal is embedded in systems like the Geonyx INS, which provides navigation-grade or better performance in a ~6 U package weighing 6.4 kg, with power draw under 17 W (Safran Electronics & Defense, 2025).
- Quantum INS currently exhibit very high SWaP demands, occupying full racks, weighing tens to hundreds of kg and drawing hundreds of watts. Significant miniaturisation efforts are underway and are likely to be achieved before commercial devices are available, but cold-atom systems may be limited in maximum compactness by relationships between vacuum chamber size and system performance. As a result, they are unlikely to achieve similar SWaP to other technologies in the near future.

Integration of INS into broader navigation or guidance systems requires both mechanical and computational alignment. Lower-end IMUs often output raw inertial data (angular rate and acceleration) and rely on an external processor to perform strapdown integration and sensor fusion. In contrast, tactical-grade and higher INS frequently include onboard digital signal processors or microcontrollers that execute strapdown algorithms and real-time Kalman filters. These filters estimate position, velocity, and attitude while correcting for sensor noise, bias drift, and scale factor errors, and may fuse additional PNT data, if available.

Advanced filtering techniques are essential to maintaining navigation quality over time. A standard implementation involves an Extended Kalman Filter (EKF) or Unscented Kalman Filter (UKF) to fuse inertial data with external sources such as GNSS, odometry, magnetometers, barometers, or velocity constraints. These algorithms are widely adopted in aerospace and robotics applications for their ability to manage non-linear sensor fusion and bound INS drift (Groves, 2018) (Mourikis, 2007).

Interface standards vary by domain. Common electrical interfaces include RS-232/422, CAN bus (automotive), SPI/I²C (for chip-scale sensors), USB (for development or COTS systems), and, increasingly, Ethernet for high-bandwidth or time-sensitive networking applications. Military and aerospace-grade INS often support MIL-STD-1553 or ARINC protocols. Power inputs are typically 9–30 V DC for vehicular systems or 28 V and 115 V AC for aircraft and naval systems. Mechanically, devices may be embedded as modules or packaged in rugged enclosures for frame-mounted installation.

6.6.4. KEY MANUFACTURERS

The inertial navigation system (INS) market is served by globally distributed manufacturers ranging from defence primes to specialised sensor developers, including OEMs and integrators. Many offer a tiered product range spanning tactical to navigation-grade performance. A non-exhaustive list of key manufacturers is presented below:

- Honeywell (USA) – A major supplier of INS across all tiers, from tactical to strategic, and across technology types
- Safran Electronics & Defense (France) – Offers tactical-grade MEMS units and high-end HRG-based systems, including the Geonyx (land/naval), Sigma 75 (aerospace), and BlueNaute (marine)
- Silicon Sensing Systems (UK/Japan) – Produces silicon ring MEMS gyros and IMUs such as the DMU11, DMU30, and CRS39, covering industrial to tactical-grade applications in aerospace and land vehicles
- Northrop Grumman (USA) – Provides optical systems including the LN-200 and LN-250 FOG IMUs (tactical/navigation-grade); has delivered strategic INS for missile and space programmes
- Exail (France) – Formerly iXblue, offers FOG-based INS systems such as MARINS and PHINS, spanning tactical to strategic-grade performance; widely used in naval and subsea GNSS-denied applications (Exail, 2023)
- Thales (France/UK) – Develops and integrates inertial systems across defence platforms
- Teledyne e2v (UK/France) – Supplies high-end accelerometers and oscillators for aerospace and space INS applications
- Collins Aerospace (USA) – Produces RLG-based INS for commercial and defence aviation
- VectorNav (USA) – Specialises in miniature MEMS INS with integrated GNSS
- Civitanavi Systems (Italy) – Designs FOG-based IMUs and INS used in land, aviation, and space
- Innalabs (Ireland) – Manufactures Coriolis Vibratory Gyroscopes (CVG) and FOG systems for tactical to navigation-grade solutions for defence and space
- Quantum Inertial Developers – Several firms are advancing quantum inertial navigation systems using cold-atom interferometry. Infleqtion (US/UK), formerly ColdQuanta, has led UK airborne trials of quantum accelerometers and atomic clocks in partnership with BAE Systems and QinetiQ. CPI-EDB (UK), formerly TMD Technologies, is developing ruggedised & platform-ready quantum accelerometer hardware. Q-CTRL (Australia) is developing cold-atom inertial systems and other quantum navigation hardware, as well as navigation

and control layers. AOSense (USA) has delivered prototypes of quantum inertial sensors to US defence. Exail (France) is developing strap-down cold-atom inertial systems.

6.6.5. APPLICATIONS AND BENEFITS

INS are foundational to PNT systems and will feature on almost all such platforms, albeit at different performance levels (Groves, 2018).

- Aviation and Aerospace: Commercial airliners use high-grade strapdown INS for continuous navigation and attitude reference, to provide orientation data, resilience against GNSS loss, and to cover periods of high-dynamics.
- Maritime and Subsea: Surface vessels use INS and complementary local sensors for resilience in navigation if GNSS in unavailable. Sub-surface vessels are fundamentally reliant on local sensors, especially INS, as they must navigate for mission durations without GNSS or other external positioning signals.
- Land Vehicles and Robotics: INS units are used in military ground vehicles and autonomous cars or robots. In military vehicles, they improve PNT resilience much as they do for sea or air platforms. In autonomous platforms and robots, an INS is fused with GNSS, LiDAR and other local sensors to provide stable pose estimation, including in urban canyons or other signal denied environments.
- Space Exploration and Satellites: In launch vehicles and spacecraft, inertial navigation systems (INS) provide the primary source of navigation and control during powered ascent and orbital insertion, when GNSS or celestial references are unavailable or unreliable. INS deliver real-time attitude, velocity, and acceleration data critical for thrust vectoring, staging, and trajectory correction. Interplanetary probes use INS during critical manoeuvres.
- Industrial and Survey: INS are used in surveying (e.g., INS with GNSS on aerial mapping systems to georeference data), in drilling, and in stabilization platforms. In virtual and augmented reality, MEMS INS enable tracking of head or device movements. The benefit, across this spectrum, is localisation without external infrastructure.

Overall, the chief benefit of an INS is resilient, self-contained navigation. It also offers high update rates and low latency, critical for control loops. Furthermore, an INS provides orientation (roll/pitch/yaw), not just position, which GNSS only provides with multiple antennas. For many platforms, knowing attitude is as important as knowing position; for instance, a drone needs attitude from INS to stay stable. For these reasons, INS are indispensable in aerospace and defence, and it has become increasingly important in any autonomous system that requires robust PNT (El-Sheimy, 2020).

6.6.6. CHALLENGES AND LIMITATIONS

INS have various challenges and limitations (Groves, 2018):

- Accumulating Drift: The most fundamental limitation is that INS errors grow polynomially with time, and integration of even tiny biases leads to unbounded position error. Drift is usually specified by gyro bias stability (deg/hour) and accelerometer bias (µg). Even the best INS will eventually wander without correction. Pure inertial navigation is inherently short-term unless aided. Techniques like periodic zero-velocity updates, map matching, or external resets are needed to manage drift for long durations.
- Bias Instability and Environment Sensitivity: Inertial sensors' biases can fluctuate with temperature, vibration, and aging. MEMS sensors are particularly sensitive to temperature changes, requiring calibration or compensation to maintain accuracy. Vibration is a similar issue, high-frequency vehicle vibrations can feed into inertial sensors, inducing bias shifts or noise. Similarly, linear accelerometers can be affected by lateral vibrations. Ruggedisation and stabilisation must address these issues for platforms deployed in more challenging environments.
- Alignment and Calibration: An INS needs a correct starting reference to provide an accurate navigation output. Initial alignment is the process of finding the orientation of the INS with respect to Earth's frame. High-precision INS often perform a gyrocompassing alignment to establish true north and level. This can be time-consuming (taking several minutes), affecting the feasibility of rapidly cold-starting such systems. In dynamic scenarios or on moving platforms, alignment is harder; sometimes external attitude references or special manoeuvres are used. If an INS is misaligned at the start by error, that error will translate into navigation errors until corrected. Calibration of the sensors (bias, scale factors) is also needed. Many INS have calibration tables and require careful factory calibration across environmental parameter ranges. Over time, recalibration might be needed as sensors age or if extreme events (like a severe shock) result in untrackable changes to biases. Lastly, the initial position fix is also crucial as INS require an accurate local gravity vector, typically relying on a lookup table derived from a model of the Earth's gravitational field. If there are significant errors in this initial fix, or if the position error drifts very far, the vector used may be increasingly inaccurate, thereby degrading performance.
- Mechanical Wear and Laser Lifetime: Different

technologies have specific issues. RLGs can suffer from laser lock-in at very low rotation rates. To counter this, RLGs employ a mechanical dithering mechanism, but this can introduce noise and can wear out. FOGs use broadband light to avoid lock-in, but FOG lasers and fibres can degrade over years.

- Filtering Complexity: INS navigation outputs rely on accurate filtering algorithms (such as the Extended Kalman Filter) to integrate raw accelerometer and gyroscope data into a stable navigation solution. However, the design and tuning of these filters are non-trivial, especially in systems that integrate multiple aiding sources (e.g., GNSS, barometers, odometry). Poorly tuned filters can amplify noise, suppress valid dynamics, or produce delayed or biased outputs. Additionally, high-dynamic environments introduce nonlinearities and time-varying noise that challenge standard linear filtering assumptions. Advanced approaches exist to address these challenges, but they also increase computational complexity and require careful state modelling. Ensuring numerical stability and real-time performance while maintaining estimation accuracy is a challenge in high-performance INS design.

6.6.7. EMERGING SYSTEMS

INS today is split between widely used commercial MEMS-based systems and specialized optical or HRG systems for high-end use. MEMS inertial sensors have seen significant improvements over the past decade, resulting in lower noise and better bias stability. The best MEMS gyros now approach tactical grade performance, and future systems are likely to improve this further, reducing SWaP at given performance levels and decreasing system cost. This means that for many mid-range applications (drones, autonomous vehicles, industrial machines) affordable MEMS INS are sufficient. On the other hand, the highest precision needs are still served by RLGs, FOGs, and HRGs; although requirements are becoming more demanding. Notably, classical INS has begun to plateau in performance.

Quantum inertial sensors promise order-of-magnitude improvements due to measurement sensitivity and resilience to bias drift. Due to the low measurement rate of these sensors, initial systems will necessarily be a fusion of classical and quantum sensors, with the quantum sensor serving as a co-device for drift correction. These systems are currently reaching TRL 6 with demonstration in field trials but will initially be high SWAP-C bespoke units.

Another future trend is chip-scale precision IMUs. There are efforts to create micro resonator optical gyros and NMR gyros, aiming to achieve up to strategic grade performance in a chip-scale package, although these are presently immature (Wright, et al., 2022) (Meyer D. a., 2014).

6.7. RADAR

Radar systems for local PNT encompass the use of radio-frequency sensing, active (monostatic/multi-static) or passive (illuminators-of-opportunity), to generate navigation data from time-of-flight, coherent Doppler, and angle-of-arrival measurements. Radar operating principles are straight forward and well understood; fundamentally they work by transmitting a known RF waveform and processing the resultant backscatter, which either directly or indirectly provides position and velocity data. These data support absolute position updates via terrain/feature correlation, body-frame velocity and drift from Doppler measurements, height-above-surface (AGL) from radar altimetry, and range/angle constraints to nearby hazards and landmarks that facilitate short-range localisation and integrity enhancements in poor visibility or cluttered environments. Radar systems are independent of ambient illumination and are tolerant to fog, dust, precipitation and glare, providing a resilient source of PNT data including when optical/LIDAR may struggle. Therefore, in Local PNT architectures Radar serves three roles: a primary positioning aid where suitable map data exist to enable Terrain Referenced Navigation (TRN), a direct kinematic sensor for velocity/track over ground estimation, and a safety sensor for obstacle and surface-proximity awareness including in low-visibility operations (Skolnik, 2008) (Richards, 2014) (RTCA, 1974) (Ward, Watts, & Tough, 2006)

Classical monostatic radars measure range by time-of-flight in pulsed systems or by beat frequency in Frequency Modulated Continuous Wave (FMCW) systems, with range resolution primarily determined by transmitted bandwidth, velocity derives from the coherent Doppler shift measurements with precision improving with integration time, and angle is estimated via beamforming/monopulse or Multiple-Input Multiple-Output (MIMO) Digital Beam Forming (DBF) with diffraction-limited resolution (or its virtual-aperture equivalent). These relationships define the PNT performance of Radar systems: bandwidth determines centimetric-class range accuracy at mm-wave, coherence and the Coherence Processing Interval (CPI) set Doppler precision for low-drift odometry, and aperture (physical or synthetic) controls bearing/heading accuracy and feature discrimination in radar-based localisation (Skolnik, 2008) (Richards, 2014) (Haimovich, Eldar, & Bliss, 2008) (Richards, 2014) (Grewal, Andrews, & Bartone, 2013).

The use-case for radar systems is tightly coupled with their frequency band, which ultimately expresses a trade-off between propagation, aperture and bandwidth, and in practice conforms to regulatory frameworks and certification/assurance standards for platform domains (vehicular, air, land).

Short-range/mmWave radars are single- or multi-chip MIMO devices providing dense range-Doppler-angle data at tens of Hz, enabling ego-motion estimation and obstacle perception in a compact formfactor. These operate at 76–81 GHz and are primarily for use in vehicles and robotic platforms (Patole, Torlak, Wang, & Ali, 2017) (Texas Instruments, 2021) (Hasch, et al., 2012).

Airborne radar altimeters work in the 4.2–4.4 GHz range and are FMCW or pulsed. They deliver decimetric-to-centimetric height-above-surface at >10 Hz within certified envelopes, forming the basis for terrain following/avoidance and TRN vertical constraints. Aviation standards prescribe interference tolerance, installation, and interface behaviour for safety-critical use (Skolnik, 2008) (RTCA, 1974) (Stimson, Griffiths, Baker, & Adamy, 2014).

Maritime navigation radars operate in the S and X bands (2-4GHz and 8-12GHz respectively) and are mechanically scanning or solid-state arrays. These offer situational awareness (target recognition and tracking) and surface-referenced navigation in open seas and harbour/coastal waters. If there is a feature rich coastal environment this can be used for TRN (Skolnik, 2008) (Ward, Watts, & Tough, 2006) (IMO, 2004).

6.7.1. PNT OUTPUTS

Radar contributes navigation observables that are directly integrated by a PNT filter or are transformed into absolute updates by correlation with prior measurements or stored maps. Hence, PNT data outputs are in the form of:

- Absolute position updates from terrain- or feature-referenced correlation (TRN).
- Body-frame velocity and drift estimation from coherent Doppler measurements and multi-beam geometry, enabling separation of forwards and sideways motion.
- Height-Above-Surface (AGL) from radar altimetry; and,
- Range/angle observations to obstacles and landmarks that improve short-range navigation integrity and contribute to collision avoidance.

These outputs are complementary to vision/LiDAR SLAM and acoustic systems covered elsewhere in this report, with radar being a very typical co-sensor as part of a platform's PNT system-of-systems (Skolnik, 2008) (Richards, 2014) (Grewal, Andrews, & Bartone, 2013).

In TRN, an altimeter or scanning radar provides vertical or slant-range profile of the terrain ahead or below the platform, this is correlated with a detailed elevation model/map to estimate horizontal position. Horizontal accuracy typically reaches the tens of metres when terrain variability and map fidelity is high. The correlation or fix rate depends on vehicle motion, terrain gradient and the correlation window, with update intervals of seconds being common in practice. In the maritime case, coastal or harbour operations can exploit shoreline features and radar landmarks (buoys, infrastructure) for feature-referenced fixes, which are particularly valuable in GNSS-denied littoral environments or areas with significant multi-path issues where fixes can aid dead reckoning. In autonomous car research, this has been shown to enable GNSS-comparable positioning in feature rich urban environments (Grewal, Andrews, & Bartone, 2013) (Stimson, Griffiths, Baker, & Adamy, 2014) (Richards, 2014) (Abu-Alrub & Rawashdeh, 2023).

Radars that measure the Doppler shift in their own reflected signals can calculate how fast something is moving relative to the ground. Using multiple beams lets them measure forward speed and sideways drift separately. This method works even if wheels slip or road texture changes, unlike wheel odometry or some camera-based methods. With today's systems, accurate speed measurements are routine, but the radar's angles must be well-calibrated to avoid drift in the results. These velocity estimates are especially useful to keep an inertial navigation system accurate between position fixes (Richards, 2014) (Patole, Torlak, Wang, & Ali, 2017) (Hasch, et al., 2012).

Airborne radar altimeters provide certified height above ground level at update rates typically >10 Hz, with decimetre to centimetre precision at nominal operating altitudes, in some cases these also provide rate-of-closure. This can be used to provide the vertical constraint used in TRN, terrain following/avoidance, and approach/landing profiles, with implement aspects governed by aviation standards (Skolnik, 2008) (RTCA, 1974) (Stimson, Griffiths, Baker, & Adamy, 2014)

Navigation and imaging radars deliver range, bearing and in MIMO systems elevation to nearby objects. Within a fused PNT system-of-systems, this data enhances short-range localisation integrity and supports rule-based proximity constraints (e.g. for manoeuvre planning, or for safety constraints for autonomous systems) (Skolnik, 2008) (Ward, Watts, & Tough, 2006).

Modern FMCW '4D imaging' radars can estimate platform motion by comparing incremental environmental scans, and examining changes distances, angles and speeds to objects or fixed references. This is similar to visual odometry methods, but more resilient to environmental conditions. This provides inputs to the navigation filter to contribute to the overall PNT fused solution and can be used as part of SLAM techniques.

To work well with other navigation sensors, radars need to be calibrated so that their position and angle on the vehicle are known (extrinsic calibration), and to account for internal timing delays between transmitting and receiving signals. They should also provide quality information with each measurement, such as signal-to-noise ratio, detection thresholds, confidence in a tracked object, or validity flags. If calibration is wrong, it can cause errors such as a small but consistent heading offset in velocity estimates or mismatches in terrain-referenced navigation updates. These errors can usually be detected by checking the consistency of the navigation filter.

Timing is also very important to radar systems. The radar should timestamp its data in hardware and stay synchronised with the vehicle's clock using IEEE 1588 Precision Time Protocol or IEEE 802.1AS gPTP. Most imaging radars send updates at 10–30 Hz, while altimeters send data at >10Hz. The small delays and slight variations in update rate (jitter) are significant to data fusion, and need to be accounted for to achieve an accurate PNT solution overall (RTCA, 1974) (IEEE, 2019) (IEEE, 2020) (IEC, 2024) (Richards, 2014) (Richards, 2014).

6.7.2. PERFORMANCE TIERS

The navigation performance of radar systems depends on frequency, bandwidth, antenna size, transmitter power, and processing design. They can be categorised into three broad tiers, from small, short-range, sensors to large, high-performance, systems, with each tier offering different trade-offs in range, accuracy, and resilience.

- **Short-Range / Small-Platform Radars:** This tier includes compact imaging radars for small UAVs, autonomous vehicles, and robotic platforms. They often operate at mm-wave frequencies (77–81 GHz) with wide chirp bandwidths of 3–4 GHz, enabling centimetre-class range resolution in good signal conditions. With coherent processing over tens of milliseconds, along-track velocity can be measured with precision better than 0.1 m/s, and cross-track motion is resolved via multi-beam geometry or scan-matching. Maximum ranges are typically 100s of metres and are primarily limited by power and small antenna apertures, with angular resolution of a few degrees unless improved via digital beamforming. When used for odometry, or SLAM, in feature-rich areas, position accuracies can reach 1–2% of distance travelled for systems of this grade, with loop closure correcting long-term drift. Terrain-referenced navigation on small UAVs may achieve ~100 m accuracy, improving with better map fidelity. These systems are low-SWaP (<1 kg, <10 W) but are more affected by rain than higher tiers due to attenuation and wet radome effects (Skolnik, 2008) (Patole, Torlak, Wang, & Ali, 2017) (ITU-R, 2005) (ITU-R, 2019) (Stimson, Griffiths, Baker, & Adamy, 2014) (Hasch, et al., 2012) (ITU-R, 2019).
- **Medium-Range / Mid-Grade Radars:** This category covers marine navigation radars, aircraft radar altimeters, helicopter Doppler radars, and high-resolution automotive radars on larger autonomous vehicles. Ranges typically extend to 1–30 km depending on target size and frequency band. An X-band marine radar with a 1–2 m antenna can detect land features or large vessels at 20–30 km, with ~1° azimuth resolution, smaller targets require closer range. Airborne radar altimeters in this tier operate up to ~2,500 ft (760 m) AGL, with decimetre to centimetre precision near the surface and sometimes also output vertical rate. TRN systems in this class can deliver horizontal fixes to within tens of metres when terrain variability and map quality are good. Doppler ground speed estimates are immune to wheel slip and surface texture and, when incidence angles are well-calibrated, maintain drift-free velocity aiding between position updates. SWaP is moderate (5–20 kg, tens to hundreds of watts), with good robustness to rain at X-band and reasonable angular resolution without requiring very large antennas (Richards, 2014) (Ward, Watts, & Tough, 2006) (RTCA, 1974) (Grewal, Andrews, & Bartone, 2013) (Stimson, Griffiths, Baker, & Adamy, 2014).
- **Long-Range / High-End Radars:** This tier includes terrain-following radars on combat aircraft, large-aperture surveillance radars, synthetic aperture radar (SAR) systems, and orbital radar altimeters. Maximum ranges can extend to tens or hundreds of kilometres; for example, an airborne SAR can map terrain from 30 km away with sub-metre resolution, and a planetary radar altimeter can measure height with decimetre accuracy from hundreds of kilometres in orbit. Navigation accuracy can be GPS-comparable in systems like TERPROM, maintaining errors in the 5–20 m CEP range after TRN updates. Angular resolution may be fractions of a degree using large physical antennas or synthetic aperture processing. These radars are high-SWaP, with antenna diameters of metres, 10s to 100s kg in mass, and kW power requirements. However, they can operate in all-weather conditions and offer the greatest level of capability for the platforms that can support them, typically for uses extending significantly beyond PNT (Skolnik, 2008) (ITU-R, 2005) (Ward, Watts, & Tough, 2006) (Stimson, Griffiths, Baker, & Adamy, 2014) (Richards, 2014).

Across all tiers, range resolution improves with higher bandwidth ($\Delta R \approx c/2B$), and angular resolution improves with larger aperture ($\theta \approx \lambda/D$) or equivalent virtual aperture via MIMO/DBF. Velocity accuracy benefits from longer coherent processing intervals and high SNR. Environmental robustness is band-dependent: mm-wave offers fine resolution in small form factors but suffers more attenuation from rain, fog, and atmospheric absorption, while lower frequencies (S/X-band) are more tolerant but require physically larger antennas for the same angular resolution. Multipath and sea/ground clutter can cause ghost targets and biases, mitigated through polarimetry, height-gating, and filtering in the perception layer (Skolnik, 2008) (ITU-R, 2005) (Ward, Watts, & Tough, 2006) (ITU-R, 2019) (Haimovich, Eldar, & Bliss, 2008) (ITU-R, 2019).

6.7.3. SWAP AND INTEGRATION

Radar systems for Local PNT vary widely in their size, weight, and power needs, and these directly influence how they can be installed and used, and correlate to their capabilities – there is strong overlap between SWaP bounds and performance tiers as described above. Antenna and bandwidth determine resolution and range, and must be balanced with platform limits on space, mass, power, and heat dissipation, while also meeting regulatory and EMC rules for the target platform domain.

- **Antenna Size and Placement:** Antenna aperture sets the radar's angular resolution and gain. At a given frequency, narrower beams require physically larger antennas, for example a 1° beam at X-band (~10 GHz) needs roughly a 0.5 m antenna. On small vehicles such sizes are impractical, so higher frequencies like mm-wave (76–81 GHz) are used, where the same beamwidth can be achieved with a few centimetres of aperture. Modern radars often use Multiple-Input Multiple-Output (MIMO) arrays or digital beamforming to create a virtual aperture from many elements, improving resolution without increasing physical size. Antenna placement is critical, forward-looking radars need an unobstructed forward view, altimeters must see directly downward, and maritime or perimeter systems may require 360° coverage. Poor siting or obstruction can cause detuning, multipath, or shadowing (Skolnik, 2008) (Patole, Torlak, Wang, & Ali, 2017) (Hasch, et al., 2012) (Haimovich, Eldar, & Bliss, 2008).
- **Processing Requirements:** Processing demands vary by application. A simple radar altimeter measures beat frequency or time-of-flight and outputs height with minimal computation. In contrast, imaging radars for odometry or TRN must handle fast Fourier transforms for range/Doppler, target detection, and often scan-matching or terrain correlation. These algorithms may run onboard, which is common for compact mm-wave modules that output object lists or velocity vectors, or on a host processor where raw radar 'cubes' are fused with other sensors. High-resolution SAR or wide-area mapping radars may need hardware acceleration to meet real-time navigation needs. Latency and timing consistency are crucial so the navigation system can use the data without estimator instability (Grewal, Andrews, & Bartone, 2013) (Richards, 2014).
- **Power, Emissions, and Environmental Factors:** Transmit power determines how far the radar can see and how well it penetrates clutter. Large ship or aircraft radars can operate at hundreds of watts or more; small UAV radars may be limited to ~10 W, constraining range. Solid-state designs improve efficiency and electronically steered arrays can manage duty cycles to save power. Spectrum regulations set frequency bands for each application, 77 GHz for automotive, 4.2–4.4 GHz for airborne altimeters and S/X-band for marine, and radars must avoid interference with other systems. Higher frequencies like mm-wave suffer significant attenuation issues due to wet-radome effects, while lower bands handle precipitation well but require bigger antennas (ITU-R, 2005) (ITU-R, 2019) (ITU-R, 2019) (RTCA, 2010) (IEC, 2002) (ISO, 2018).
- **Physical Integration and SWaP Envelopes:**
  - **Short-range mm-wave modules:** Typically under 100*100 mm (PCB scale), <150 g, and 3–8 W power draw depending on channel count and onboard processing (Patole, Torlak, Wang, & Ali, 2017) (Texas Instruments, 2021) (Hasch, et al., 2012) (NXP Semiconductors, 2025).
  - **Airborne radar altimeters:** Packaged as line-replaceable units for aviation with dual antennas, ~1–3 kg, 20–60 W depending on transmit duty cycle (RTCA, 1974) (RTCA, 2010).
  - **Maritime navigation radars (S/X-band):** Multi-kg mast-mounted antennas, below-deck units of a few litres volume, typically tens of watts for solid-state, 100W+ to 1kW+ for magnetron systems (IMO, 2004).
  - **UAV/UGV electronically scanned radars:** <1 kg, <50 W, with performance tuned by adjusting duty cycle and frame rate (Skolnik, 2008) (Navtech Radar, 2025).
  - **Fixed infrastructure scanners:** Multi-kg, 10s to100s W power draw, in IP-rated enclosures designed for continuous operation (Navtech Radar, 2025).
- **Sensor Fusion and Timing:** Radars are rarely used in isolation, they are fused with GNSS, inertial, vision, or acoustic systems – this is key to their effective integration into a PNT system of systems. Radar outputs (often 10–30 Hz for imaging radars, >10 Hz for altimeters) must be aligned to a platform's master timebase using IEEE 1588 PTP, IEEE 802.1AS gPTP, or PPS signals. In loosely coupled setups, radar data like altitude, Doppler velocity, or TRN fixes are passed into the navigation filter as measurements with associated uncertainties. Tightly coupled designs merge raw radar observables with IMU data to improve estimation of slip, yaw rate, and drift; this requires careful calibration of lever-arms, boresight, and timing delays to be effective. Sub-filter TRN modules run their own correlation and integrity checks before sending fixes to the master estimator, preventing errors from low-relief terrain or map mismatch (Grewal, Andrews, & Bartone, 2013) (Richards, 2014) (IEEE, 2019) (IEEE, 2020).

SWaP constraints determine which radar type is viable for a platform, from single-chip FMCW altimeters on small drones to multi-kilowatt radars on warships. Successful integration depends on antenna siting, managing power and emissions, meeting timing requirements, and ensuring the radar's outputs are compatible with the overall PNT system-of-systems and its data fusion.

6.7.4. KEY MANUFACTURERS

The radar manufacturing ecosystem relevant to local PNT spans avionics suppliers, maritime navigation vendors, mm-wave module providers for low-SWaP and automotive platforms, UAV/UGV radar companies and defence primes. Given the long-standing maturity of the sector and number of specialist suppliers the ecosystem is wide.

Airborne, maritime navigation and defence radar manufacturers

- Leonardo UK (UK): Airborne and land AESA radar families relevant to navigation and integrity monitoring.
- HENSOLDT UK: Kelvin Hughes SharpEye (UK) – Solid-state S/X-band bridge radars for coastal navigation and harbour operations, providing range/angle tracks for TRN.
- Raytheon Anschütz (Germany): IMO-compliant marine navigation radar integrated with ECDIS/INS over IEC 61162 interfaces.
- FURUNO (Japan): Marine radar systems widely deployed in commercial fleets.
- JRC (Japan): IMO-compliant marine radar sets with ECDIS integration.
- Collins Aerospace (USA): Certified radar altimeters for terrain following/avoidance and TRN vertical constraints.
- Honeywell (USA): DO-160-qualified radar altimeter systems for aviation navigation.
- Thales (France/UK): AESA radar families across air, land, and sea domains supporting mission navigation.
- HENSOLDT (Germany): Multi-domain AESA radar systems for defence platforms.
- Raytheon (USA): Integrated radar solutions contributing to platform navigation and integrity.

Automotive and mm-wave imaging radar manufacturers

- Texas Instruments (USA): MIMO transceivers and modules outputting range-Doppler-angle data for ground autonomy and odometry.
- NXP (Netherlands): mm-wave radar ICs and reference modules for ADAS.
- Infineon (Germany): 77 GHz radar sensors for automotive and robotics.
- Bosch Mobility (Germany): mm-wave radar systems for collision avoidance and velocity aiding.
- Continental (Germany): 4D imaging radar modules for autonomous vehicle navigation.
- DENSO (Japan): Integrated radar sensors for ADAS and ground autonomy.
- Arbe (Israel): High-resolution 4D imaging radars outputting dense point clouds.
- Uhnder (USA): Digital code-modulated radar technology for interference mitigation.

Low-SWaP radars for UAV/UGV and compact platforms

- Echodyne (USA): MESA electronically scanned array radars for sense-and-avoid and velocity aiding.
- IMSAR (USA): Lightweight SAR/MTI radar families for UAV and small manned platforms.

6.7.5. APPLICATIONS AND BENEFITS

Radar offers PNT advantages distinct from optical and acoustic sensors, maintaining range, range-rate, and angle observability in fog, dust, precipitation, glare, and darkness. When fused with INS and external aids these characteristics provide resilience in holdover, GNSS-denied, and low-visibility regimes, with certified behaviours in specific classes (e.g., radar altimeters) and well-understood error modes for integrity management (Skolnik, 2008) (Richards, 2014) (Grewal, Andrews, & Bartone, 2013).

Holdover and GNSS-Denied Navigation: Coherent Doppler and multi-beam down-look radars provide ground-referenced velocity and drift angle, constraining INS error growth between fixes. Where terrain or shoreline relief is available, TRN/FRN supplies periodic position updates by correlating radar returns with elevation or coastal maps, achieving tens-of-metres accuracy under good map and terrain conditions (Stimson, Griffiths, Baker, & Adamy, 2014).

Low-Visibility and Safety of Navigation: Radar supports hazard detection, collision avoidance, approach/landing profiles, and terrain following in poor visibility. Airborne radar altimeters in the 4.2–4.4 GHz band provide certified AGL at >10 Hz with decimetre precision; maritime S/X-band bridge radars maintain continuous situational awareness and integrate with ECDIS/INS for coastal navigation.

Infrastructure-Assisted and Cooperative PNT: Fixed FMCW scanning radars at ports, airfields, and industrial sites deliver 360° range-bearing tracks and reference points to stabilise navigation in cluttered environments. When several fixed radars are time-synchronised and positioned at different locations, their varied viewing angles provide independent range and bearing data. These independent measurements can be used to confirm or challenge position estimates from GNSS or vision systems, improving overall navigation integrity.

All-Weather Odometry and Localisation: Imaging mm-wave radars (76–81 GHz) deliver scan-matched odometry and landmark bearings that remain reliable in heavy rain, fog, and at night, bounding drift where camera- or LiDAR-based odometry degrades (Patole, Torlak, Wang, & Ali, 2017) (Barnes, Gadd, Murcutt, Newman, & Posner, 2020).

Integrity and Counter-Spoofing: Radar's active RF measurements provide diversity against GNSS spoofing and optical deception, with failure modes that are distinct from those of satellite or visual systems. Publishing SNR, track confidence, and covariance supports integrity monitoring and hazardously misleading information control in regulated domains.

Low-Emission and Passive Options: Passive and multi-static radar exploit illuminators-of-opportunity (e.g., broadcast, telecom) to obtain navigation observables without active illumination, reducing electromagnetic signature while preserving diversity in urban or contested environments (Colone, Cristallini, Lombardo, & Grüneberg, 2014) (Griffiths, Baker, Baubert, Kitchen, & Treagust, 1999).

6.7.6. CHALLENGES AND LIMITATIONS

Radar's PNT advantages come with constraints from propagation physics, scene characteristics, regulatory limits, and integration complexity. These factors affect the quality and integrity of radar observables and must be addressed in system design and error budgets to preserve radar's value within Local PNT architectures.

Propagation and Weather: Frequency choice drives robustness; mm-wave offers centimetric resolution but suffers high attenuation from gases and rain, and wet-radome effects that reduce SNR and bias range. S/X-band penetrates precipitation better but requires larger antennas for comparable bearing accuracy. ITU-R models should be used to adjust range/Doppler noise with weather (ITU-R, 2005) (ITU-R, 2019) (ITU-R, 2019) (Hasch, et al., 2012).

Clutter, Multipath, and Ghosts: Sea clutter increases false alarms and biases detection thresholds reducing TRN and hazard avoidance effectiveness. Urban/land environments suffer from multipath and ghost targets issues. These affect range/angle measurements directly and can cause mis-associations in fusion. Mitigation uses polarimetry, height-gating, robust CFAR, and model-based rejection before fusion (Richards, 2014) (Ward, Watts, & Tough, 2006).

Interference, Spectrum, and Certification: Protected bands and ETSI automotive limits constrain power, bandwidth, and duty cycle. Certified systems must meet interference-tolerance and performance standards (e.g., RTCA DO-155/DO-160), which shape achievable resolution, update rates, and operational envelopes (EN 301 091-1: Short Range Radar (76--77 GHz) --- Harmonised Standard, latest ed.) (IMO, 2004) (RTCA, 1974).

SWaP, Thermal, and Siting: High-channel-count MIMO/DBF increases compute and power demands, with thermal limits constraining duty cycle on small platforms. Antenna placement is critical to avoid detuning, shadowing, and angular bias; boresight stability is essential for Doppler and TRN accuracy (Patole, Torlak, Wang, & Ali, 2017) (Hasch, et al., 2012).

Calibration and Timing: Lever-arm, boresight, and group-delay errors bias velocity and position outputs. Asynchronous data paths can cause estimator inconsistency unless time-stamped via disciplined PTP/gPTP or PPS. These systematic effects require explicit bias states and controlled calibration (Richards, 2014) (Grewal, Andrews, & Bartone, 2013).

Data Association and Fusion Integrity: In busy environments, radar may generate false alarms, miss targets, or split/merge tracks, making it harder to match detections to real objects. Poor association can corrupt the navigation solution, so proven multi-target tracking methods and per-measurement quality flags are essential (Bar-Shalom, Li, & Kirubarajan, 2001).

TRN and Feature-Referenced Constraints: TRN works best with distinctive terrain and accurate, well-aligned maps. Performance drops in flat or smooth areas, or when maps are outdated; coastal FRN is also affected by shoreline changes and sea state (Ward, Watts, & Tough, 2006) (Stimson, Griffiths, Baker, & Adamy, 2014).

Security and Emissions Management: Active radar is detectable and jammable; emissions-managed operations may prefer passive/multi-static radar, but performance depends on illuminator availability and geometry (Colone, Cristallini, Lombardo, & Grüneberg, 2014).

6.7.7. EMERGING SYSTEMS

Near-term development in radar for Local PNT is evolutionary and centred on higher-fidelity observables, disciplined timing, and emissions-constrained operation.

Networked and multi-static sensing: Synchronised fixed-site and vehicle-borne radars can be combined into multi-static constellations to add geometric diversity in ports, airfields and urban canyons. The principal navigation benefit is availability and integrity, as this provides additional independent bearings/ranges and dissimilar failure modes. Improvement in nominal accuracy can also be achieved, but only if clocks and baselines are tightly controlled for synchronisation. Recent vehicular studies in coherent multi-static imaging and phase synchronisation demonstrate benefits, although there is a significant calibration burden for operational use (Advances in Bistatic Radar, 2007) (Tagliaferri, et al., 2024).

Integrated Sensing and Communications (ISAC): ISAC is the joint use of communication system signals for both data transmission and sensing, enabling shared spectrum, hardware, and infrastructure. In a Local PNT context, ISAC can provide range, Doppler, and angle measurements from the same waveforms used for communications, allowing navigation support without dedicated radar hardware.

Standardisation efforts to support this are now moving beyond concept studies. In cellular networks, 3GPP Release 19 includes ISAC-relevant channel modelling for 5G-Advanced, setting a baseline for coexistence testing and performance evaluation. In the WLAN domain, IEEE 802.11bf ('WLAN sensing') was ratified on 28 May 2025, defining a formal framework for sensing using commodity Wi-Fi hardware. These developments make short-range, infrastructure-assisted PNT via communications carriers technically viable where transmitter geometry and timing are known (3GPP, 2025) (FirstNet Authority, 2024) (IEEE, 2025) (Liu, et al., 2022) (Sturm & Wiesbeck, 2011).

Passive Illuminators: Purely passive radar, particularly using existing broadcast or telecom signals and infrastructure as illuminators, is also advancing. Demonstrations in 2024 with 5G downlinks on moving platforms achieved practical detection and tracking, but navigation performance is constrained by illuminator geometry, waveform stability, and site-specific calibration. At this stage, this positions passive radar as an opportunistic aid (similar to a signal of opportunity) in a PNT system-of-systems (Maksymiuk, et al., 2024).

Module and processing advances: mm-wave '4D imaging' devices are trending to higher channel counts, better chirp linearity and on-device inference, yielding cleaner range/Doppler/angle tensors and more stable radar odometry in rain/fog/night. Improvements are incremental, delivering lower latency and tighter covariances for velocity/bearing, although they are conditional on calibration and integrity-aware fusion (Patole, Torlak, Wang, & Ali, 2017) (Abu-Alrub & Rawashdeh, 2023) (Alhashimi, Adolfsson, Andreasson, Lilienthal, & Magnusson, 2024).

Quantum radar: RF quantum illumination remains at very-low TRL (lab based, and not to be confused with wider quantum illumination, such as that in the optical domain, which is maker faster and more significant progress), and recent analyses increasingly suggest potentially limited performance benefits under realistic noise and loss scenarios (Pavan & Galati, 2024) (Zhao, Zhang, & Zhuang, 2025) (Barzanjeh, Pirandola, Vitali, & Fink, 2020).

6.8. SPEED LOGS & ODOMETRY

Speed logs and odometry measure an object's travel distance or rate of motion. On land, wheel encoders and odometers count wheel revolutions (or encoder pulses) to compute distance. Differential wheel speeds can also indicate heading. These are simple, low-SWaP sensors (PCB-sized, grams) with TTL/quadrature outputs.

Marine vessels use mechanical propeller shaft logs and pressure differential (pitometer) logs to measure speed through water. Faraday-law electromagnetic logs (EM logs) embed a coil in seawater and measures a motion induced voltage to derive speed. These units are solid-state but require calibration for water salinity and temperature (Wartsila, 2025) (NASA Marine, 2025).

Doppler-based sensors form a broad class of speed logs, including acoustic, ground-radar, aerial-radar, and laser. These all use the Doppler effect to measure velocity relative to a known or fixed medium (e.g., the seabed or the Earth's surface) through measurement of the frequency shift of a reflected signal (Honeywell, 2025).

Lastly, optical flow sensors estimate motion by tracking the displacement of features in sequential images—typically from downward facing cameras for use on UAVs and similar platforms. They provide short-range velocity estimates, particularly for indoor environments (Miller, Miller, Popov, & Stepanyan, 2019) (Miller, Miller, Popov, & Stepanyan, 2019).

6.8.1. PNT OUTPUTS

Speed log and odometry sensors primarily provide velocity (linear and sometimes angular) and distance travelled along the vehicle's path. These outputs are typically used to perform dead reckoning, integrating motion over time to estimate position in the absence of GNSS. Depending on sensor type and configuration, the outputs include the aspects outlined below.

- Wheel odometers generate linear displacement by counting encoder pulses and, in differential-drive vehicles, infer yaw changes from wheel speed differences. Output is typically provided as cumulative distance and incremental heading estimates (Hasler Rail, 2025).
- Shaft and pitot logs report speed through water for marine platforms. These are scalar measurements that require calibration against known current or vehicle movement for absolute positioning. Pitot systems convert pressure differential into a velocity reading (Wartsila, 2025).
- Electromagnetic (EM) logs produce scalar velocity (speed magnitude) by measuring induced voltage in water. Multi-axis EM logs can resolve vector components, if arranged appropriately.
- Doppler sensors—including radar, laser, and optical types—estimate ground-relative velocity. Radar Doppler sensors such as HRVS (Honeywell radar velocity system) yield range-rate (velocity toward or away from surface) and lateral motion vectors at high update rates (Honeywell, 2025). Laser Doppler systems (e.g., Advanced Navigation LVS) output

2D or 3D ground speed vectors based on frequency shift of laser scatter.

- Optical flow sensors (e.g., PX4Flow) detect apparent image displacement over time to estimate velocity in planar space, useful for UAVs and mobile robots in GPS-denied zones (Miller, Miller, Popov, & Stepanyan, 2019) (Beyeler, Zufferey, & Floreano, 2009).

In all cases, these sensors are referenced to the local contact medium—ground, water, or seabed—not to an absolute Earth-fixed frame. This makes them highly suitable for relative position estimation, although external updates are required to maintain absolute accuracy over long durations. Most units output real-time data at rates from 10–200 Hz, suitable for tight integration into inertial navigation systems (INS) or SLAM frameworks. For example, the OxTS Inertial+ fuses TTL wheel pulse inputs directly into its Kalman filter to constrain position drift when GNSS is unavailable.

Data formats typically include cumulative distance (e.g., in pulses or metres), instantaneous velocity vectors, and optionally derived heading changes (e.g., from odometry or Doppler angle of arrival). Marine sensors may output NMEA 0183 messages, while automotive and robotic platforms often use CAN bus, RS-232, or ROS-compatible messages.

6.8.2. PERFORMANCE TIERS

Speed measurement systems vary significantly in precision, robustness, and operating domain. Their performance is typically evaluated in terms of velocity and distance error over time or distance travelled, expressed as a percentage, based on a tier system.

Tier 1 - High-Precision Doppler and Hybrid Systems (~0.05–0.5% error)

This tier includes state-of-the-art Doppler laser sensors. These provide sub-percent accuracy under a range of environmental conditions and are used in high-performance platforms:

- Laser Doppler sensors (e.g., Advanced Navigation LVS) achieve high-resolution ground-relative velocity using coherent laser beams with errors as low as 0.05%, with high resilience to drift. They perform best under moderate lighting and texture and may degrade on reflective or featureless surfaces.

Tier 2 - Mid-Range Electromagnetic, Radar, and Optical Flow Systems (~0.5–2% error)

This tier captures systems offering solid performance but with constraints due to environmental sensitivity or calibration requirements:

- Doppler radar sensors (e.g., Honeywell HRVS) emit mm-wave signals and measure reflected Doppler shifts from the ground. These offer 1–3% distance error. They work in both air and ground applications, including UAVs and off-road vehicles (Honeywell, 2025).
- Electromagnetic (EM) logs, commonly used in maritime navigation, generate a voltage proportional to saltwater flow across embedded coils. Accuracy is typically within 1–2% of speed, though sensors require calibration for water salinity and temperature.
- Pitot logs, used in both marine and aviation contexts, measure fluid flow velocity by comparing dynamic and static pressures. When properly installed and calibrated, marine pitot logs can achieve accuracy better than 0.75% of the range in use. However, their performance can be affected by factors such as water temperature, salinity, and the presence of air bubbles.
- Monocular optical flow sensors (e.g., PixArt-based units or Artificial Worlds FlowNav) use onboard cameras to estimate apparent motion over textured terrain. Performance varies by surface quality and altitude, but sub-2% distance error is achievable in structured indoor or outdoor environments.
- Radar-based velocity sensors, when used in simplified configurations or with reduced beam steering (e.g. single-axis units)

Tier 3 - Basic Odometers and Low-Cost Flow Sensors (~3–10%+ error)

This includes legacy or low-cost sensors with limited correction mechanisms. Their accuracy often degrades rapidly in difficult environments (Honeywell, 2025) (Advanced Navigation, 2022) (Miller, Miller, Popov, & Stepanyan, 2019).

- Wheel odometry systems, commonly used in terrestrial robots and vehicles, rely on counting encoder pulses to compute distance. On ideal surfaces and well-calibrated systems, accuracy can approach 2–3% per km, but in real-world conditions (mud, gravel, ice), slippage and wheel lift-off can cause higher errors.
- Low-cost optical flow sensors, such as those found in consumer drones, typically offer only pixel-based motion estimates and are sensitive to lighting, surface reflectance, and camera vibration. Without depth knowledge or altitude feedback, scale drift is common, and overall accuracy is variable.

6.8.3. SWAP AND INTEGRATION

Speed and odometry sensors vary considerably in size, weight, and power (SWaP), driven by sensing modality and intended platform.

- Wheel encoders are ultra-low SWaP sensors commonly used in terrestrial vehicles and robotics. Optical or magnetic encoders weigh only a few grams, with power consumption in the range of tens of milliwatts (e.g., AMS AS5048A: 3.5mA at 5V ⭢ ~17.5mW) (AMS OSRAM, 2025).

- Compact Doppler radar modules (e.g., for speed-over-ground) weigh <100g and typically consume 1-5W, depending on range and output complexity. For example, the Sensonor STIM300 + radar package integrates well into UAVs and small vehicles.
- Laser Doppler Velocimeters (LDVs), especially those used in marine or aerospace applications, weigh 200–700 g and consume 5–10 W. For example, Satimo L-Vel (LDV) weighs ~500 g and consumes ~8 W. These are generally bulkier due to optics and alignment housing.
- EM logs, used in maritime environments, typically consist of a 30–60 cm long probe and weigh 500g–2 kg, depending on integration. Power usage is typically 1-5 W. An example is the Airmar CS4500, which weighs ~700 g and draws 80–250 mA at 12–24 V (≈1–6 W).
- Pitot-static systems, common in aerospace, can be large and robust to withstand external environments. A complete unit (tube + sensors) can weigh 0.5–3 kg, especially in larger aircraft or maritime vessels. However, power draw for the pressure sensor is minimal—typically <1 W (e.g., Honeywell HSC series pressure sensors).
- Optical flow sensors vary between lightweight drone-grade modules and higher-resolution land vehicle systems.
  - Compact units (e.g., PX4Flow) weigh 15–25 g and draw ~110 mA at 5 V (~0.55 W)
  - Larger systems using stereo cameras or event-based sensors can weigh >300 g and consume 5–10 W, depending on resolution and onboard processing (e.g., Intel RealSense + Jetson Nano stack).

Integration of these sensors into navigation systems often involves standard interfaces including TTL pulses, Serial Interfaces (RS-232/RS-422), Ethernet and the CAN Bus for automotive applications.

6.8.4. KEY MANUFACTURERS

Speed log and odometry systems are produced by a range of specialised OEMs and platform integrators. Notable manufacturers include:

- Land and Robotics Platforms:
  - Oxford Technical Solutions (UK): Provides high-precision inertial navigation systems (e.g., Inertial+) with direct wheel encoder integration for GNSS-denied dead reckoning
  - Bosch (Germany), ZF Friedrichshafen (Germany), and Continental (Germany): Major automotive suppliers producing ABS and wheel speed sensors repurposed for odometry in robotics and AV systems
  - Artificial Worlds (UK): Produces FlowNav, a visual-inertial optical flow sensor for indoor and GPS-denied robotic applications
  - PX4 Dev Team / Dronecode (USA/Switzerland): Maintains the PX4Flow open-source optical flow camera for UAV odometry, originally developed by ETH Zurich
- Radar and Laser Doppler Systems:
  - Honeywell Aerospace (USA): Manufactures the HRVS mm-wave Doppler radar velocity sensor for ground-relative speed in UAV and land platforms
  - Advanced Navigation (Australia): Offers the Laser Velocity Sensor (LVS), a compact high-accuracy 3D laser Doppler unit for aerospace and robotics use
  - Sensonor (Norway): Supplies compact IMUs such as the STIM300, often integrated alongside Doppler sensors for combined inertial and velocity measurement
- Marine Systems - Electromagnetic and Pitot Logs:
  - Valeport (UK): Manufactures electromagnetic (EM) speed sensors such as the Model 803, widely used in commercial and scientific marine platforms
  - Airmar Technology Corporation (USA): Produces the CS4500 EM speed log, a solid-state unit for use in small vessels and recreational marine applications
  - Wärtsilä (Finland): Supplies integrated speed log systems—including electromagnetic, Doppler, and pitot types—for large commercial vessels
  - Kongsberg Maritime (Norway) and Simrad (Norway): Provide a range of Doppler and pitot-based logs for commercial and offshore dynamic positioning systems
- Stereo and Optical Odometry Stacks:
  - Intel (USA): Offers the RealSense depth cameras, commonly used in visual odometry and SLAM pipelines for indoor and structured environments
  - NVIDIA (USA): Provides Jetson platforms (e.g., Jetson Orin) used in vision-based navigation systems incorporating optical flow and stereo depth

6.8.5. APPLICATIONS AND BENEFITS

Speed log and odometry systems are fundamental to resilient navigation across diverse platforms, particularly in environments where GNSS is unavailable or unreliable. Their applications span several key areas:

- GNSS-Denied Navigation – In environments where GNSS signals are obstructed or denied—such as urban canyons, tunnels, or underwater—odometry and speed log systems enable dead reckoning by providing continuous estimates of position and velocity. These systems are critical for maintaining navigation capabilities in such challenging environments (Gallo, 2023).
- Autonomy and Robotics – Autonomous vehicles and mobile robots rely on sensor fusion techniques, such as the Extended Kalman Filter (EKF), to integrate data from wheel encoders, inertial measurement units (IMUs), and other sensors. This integration enhances the accuracy of localisation and navigation, enabling reliable operation in complex and dynamic environments (Ogunsina, 2024).
- SLAM and Mapping Support – Simultaneous Localisation and Mapping (SLAM) systems benefit from odometry inputs which provide motion priors that improve the robustness and accuracy of mapping in unknown environments. The integration of odometry with SLAM algorithms facilitates real-time mapping and localisation, essential for autonomous exploration and navigation (Basheer, Thorsten, Ahmed, & Ayoub, 2024).

6.8.6. CHALLENGES AND LIMITATIONS

Speed log and odometry systems exhibit various limitations influenced by sensor modality, environmental conditions, and platform dynamics.

- Wheel Odometry – Accuracy is highly susceptible to wheel slip, especially on low-traction surfaces like mud, gravel, or ice; slippage leads to cumulative errors in position estimation. Studies have shown that wheel slip can significantly degrade odometric accuracy, necessitating compensation strategies (Reginald, Al-Buraiki, Choopojcharoen, Fidan, & Hashemi, 2025).
- Optical Flow Sensors – Performance is contingent on surface texture and lighting conditions. Reflective or featureless surfaces, as well as low-light environments, can impair motion estimation accuracy. Research indicates that variations in surface reflectance and illumination can lead to substantial errors in optical flow computations.
- Electromagnetic (EM) Logs – Accuracy depends on water conductivity, which is affected by salinity and temperature. Variations in these parameters can introduce measurement errors. Additionally, biofouling on sensor surfaces can alter readings, underscoring the need for regular maintenance (Star:Oddi, 2025).
- Pitot Tubes – These are vulnerable to blockages from ice, debris, bubbles, or insects, which can lead to erroneous airspeed readings (Katz, 2016).
- Doppler Radar Sensors: Their efficacy can diminish over surfaces with low reflectivity, such as calm water or smooth terrain, due to insufficient backscatter. Environmental contaminants like dust or moisture on the sensor can further degrade performance.

6.8.7. EMERGING SYSTEMS

Classic odometry is mature, but AI and sensor advances are emerging. Machine-learning algorithms now adapt odometry models on-the-fly (e.g., neural-network calibration compensating wheel slip or tire pressure) to reduce error. Hybrid fusion (e.g., EKF with RNNs) has achieved centimetre-level localisation (Huang, Ye, Yang, & Yu, 2025). Laser-ground-speed sensors (like LVS) are new and promise very high accuracy.

Future trends include real-time learning of scale factors, adaptive calibration to terrain (auto-adjusting wheel radius), and tightly coupled multi-sensor SLAM that uses vision/LiDAR with odometry. For marine domains, research into smart EM logs (auto-calibrating for salinity) and compact multi-beam Doppler arrays are underway. In summary, mature systems (wheel encoders, EM logs) are being augmented by ML-enhanced fusion and advanced optical or doppler units for next-gen autonomous PNT (e.g., domain-adaptive speed models, neural slip detection).

6.9. SIMULTANEOUS LOCALISATION AND MAPPING (SLAM)

Simultaneous Localisation and Mapping (SLAM) equips vehicles and robots with situational awareness, by building a map of an unknown environment while tracking the sensor's pose within it (University of Oxford, 2022). Classic SLAM families include filter-based methods (e.g., EKF-SLAM, FastSLAM) which perform sequential Bayesian updates, and graph-based methods (pose-graph optimization) that refine a global map via loop closures (Munguia R, 2021). Visual SLAM algorithms are often feature-based—detecting and matching key points—or direct/dense (using raw pixel intensities), trading sparsity for richer maps. For example, feature-based ORB-SLAM yields sparse point maps, whereas dense methods (e.g., KinectFusion) produce full 3D surfaces at higher compute cost.
All SLAM systems rely on loop closure detection to recognize revisited places and correct accumulated drift. Modern SLAM thus fuses sensing and odometry data to produce a consistent global map, minimizing drift by realigning trajectories when loops are detected (Macario Barros, Michel, Moline, Corre, & Carrel, 2022) (NavVis, 2025).

6.9.1. PNT OUTPUTS

A SLAM system outputs a platform's 6-DoF trajectory (relative to its start or map frame)—a continuous pose estimate—and a geometric map (sparse features, point cloud or occupancy grid) for the measured area. This map can be used for localisation (the system localises within the built map) and for path planning. The estimated trajectory generally has bounded drift due to loop closure: as the platform revisits known areas, accumulated error is corrected, yielding a self-consistent map. SLAM outputs may be fused or anchored to other systems: for outdoor use, SLAM can integrate GNSS fixes to obtain georeferenced (absolute) positioning, while in indoor/signal-free cases it provides relative position (University of Oxford, 2022) (NavVis, 2025) (Ran, Xu, Tan, & Luo, 2025).

6.9.2. PERFORMANCE TIERS

SLAM performance varies widely with sensor choice, environment, and computation. Monocular cameras are lightweight and cheap, but scale-ambiguous and sensitive to lighting. They yield meter-level accuracy outdoors and degrade in texture-poor or dark scenes. Stereo rigs recover scale and perform better in featureless scenes, at the cost of higher bandwidth and processing (rectification). RGB-D cameras (e.g., Kinect, RealSense) provide direct depth indoors; they give accurate short-range maps but fail in sunlight and limited range. Although 2D lidars (planar scanners) are robust and accurate (to the cm-level) in structured indoor corridors, 3D lidars (multi-layer scanning) excel in long-range, high-dynamic-range outdoor or underground mapping, though laser pulses can degrade in fog or dust. Acoustic sonar may be used underwater; single-beam sonar gives range-only cues; multi-beam sonar builds 3D bathymetry—but typically with coarse resolution. Computationally, real-time embedded SLAM runs on onboard integrated CPU/GPU processors (e.g., GPU-accelerated dense mapping), whereas high-end mapping may post-process data on the cloud or use edge compute (Macario Barros, Michel, Moline, Corre, & Carrel, 2022) (Ran, Xu, Tan, & Luo, 2025) (Sobczak, Filus, & Domańska, 2022).

6.9.3. SWAP AND INTEGRATION

SLAM's direct SWaP requirements are primarily the compute unit, which is generally small although it has the potential to be power-hungry for advanced systems. The primary SWaP requirements for the overall systems are driven by the sensors integrated on the platform which are used for SLAM. As well as processing requirements, SLAM has data storage requirements for the accumulated map data; but this is not typically large compared with modern flash memory, which can be in the order of terabytes in compact formats. Similarly, integration requirements are driven by the sensors used for a particular implementation, although sensor latency will affect the real-time performance of SLAM, and accurate timestamping and synchronisation of sensors will affect the quality of data fusion in multi-sensor configurations.

6.9.4. KEY PROVIDERS

SLAM development is driven by a combination of industrial vendors, academic groups, and open-source communities. Notable contributors include:

- Industrial Systems Providers:
  - NavVis (Germany): A global leader in mobile indoor mapping systems using LiDAR-based SLAM (e.g., NavVis VLX, M6), widely used in construction, manufacturing, and asset management
  - Clearpath Robotics / OTTO Motors (Canada): Develop autonomous mobile robots and platforms using SLAM for warehouse automation and logistics
  - Emesent (Australia): Specialises in autonomous LiDAR SLAM for underground and GPS-denied environments (e.g., Hovermap system used in mining and DARPA SubT)
  - SLAMcore (UK): A spin-out from Imperial College London, offering visual-inertial SLAM SDKs optimised for robotics, drones, and AR/VR use cases
  - Sevensense Robotics (Switzerland): Provides visual and LiDAR SLAM-based navigation systems for autonomous mobile robots in industrial and logistics environments
  - Cognicept (Singapore/UK): Offers remote SLAM monitoring and fallback support services for field robotics
- UK-Based Contributors:
  - SLAMcore (above)
  - Createc (UK): Provides SLAM-enabled radiation mapping systems and is active in nuclear inspection and defence applications
  - Roke Manor Research (UK): Applies visual SLAM and navigation technologies for defence and secure environments
  - QinetiQ (UK): Uses SLAM in their autonomy and robotics testbeds, including GPS-denied navigation scenarios
  - Oxford Robotics Institute (UK): A world-leading academic group with real-world SLAM deployments; creators of the "RobotCar" dataset and integration work with both visual and LiDAR-based SLAM systems

- Open-Source and Academic:
  - University of Zaragoza (Spain): Developers of ORB-SLAM and ORB-SLAM3, which are among the most widely used feature-based open-source visual SLAM systems
  - ETH Zurich (Switzerland), TUM (Germany), MIT, and Tongji University (China): All are major research centres contributing to dense SLAM, learning-based SLAM, and multi-sensor fusion
  - ROS Ecosystem: The Robot Operating System (ROS) and ROS2 include widely adopted SLAM frameworks such as:
    - Google Cartographer: Real-time LiDAR SLAM
    - RTAB-Map: Visual or RGB-D SLAM with loop closure and mapping
    - LIO-SAM / LeGO-LOAM: For tightly-coupled LiDAR-inertial SLAM on robotics platforms
    - Hector SLAM: Lightweight 2D laser SLAM used in UAV and indoor mapping
- Consumer Applications:
  - Google, Apple, and Microsoft use SLAM as a core component in AR platforms:
    - ARCore (Google) and ARKit (Apple) use visual-inertial SLAM to enable 6-DoF tracking on smartphones and tablets
    - Microsoft Azure Kinect and the HoloLens use SLAM for spatial mapping and AR overlay

Overall, a mix of commercial and open-source SLAM systems are used across autonomy and PNT applications, with numerous companies and research groups contributing globally.

6.9.5. APPLICATIONS AND BENEFITS

SLAM is key to autonomy and robotics and an effective approach to local navigation.

- Autonomy – Autonomous vehicles (ground, aerial, marine) use SLAM for real-time localisation and mapping, particularly when GPS is intermittent, unavailable or denied (Jarraya, et al., 2025).
- Infrastructure Inspection – SLAM can combine navigation with inspection by building detailed infrastructure maps which can be monitored for change detection or directly analysed for structural properties. Furthermore, SLAM improves ease of access to hard-to-reach areas by enabling robotic navigation (e.g., pipelines and tunnels).
- Search-and-Rescue – SLAM can be leveraged to explore dark or smoke-filled spaces and environments that may have unexpected or changing hazards (such as disaster zones) that could not feasibly be pre-mapped. Furthermore, maps generated may be conveyed to operators for safer human entry.
- SLAM enables map-based relocalisation: a platform can re-enter a known environment, recognise it, and recalibrate its position estimates based on the pre-existing map. This is important for autonomy and robotics where the platform is expected to operate and navigate for long durations without manual recalibration (Qin, Chen, Chen, & Su, 2020).
- Enhanced PNT resilience – In general, SLAM enhances system resilience; by providing bounded-drift pose and map redundancy, it allows for continued navigation even with partial sensor degradation or failure, and fusion methods (e.g., Visual-LiDAR odometry) improve robustness in complex scenes (Jarraya, et al., 2025).

6.9.6. CHALLENGES AND LIMITATIONS

SLAM has proved effective in many contexts but has limitations especially in non-ideal environments:

- Pose drift and loop closure – SLAM relies on loop closure to correct accumulated odometry errors, so missed or false loop detections can result in unbounded errors distorting the map. This can severely degrade accuracy.
- Dynamic environments and adverse environmental conditions – SLAM algorithms often assume and certainly benefit from static environments. In dynamic settings, moving objects (e.g., people, vehicles) can introduce erroneous data associations, leading to map inaccuracies. Furthermore, degraded environments can limit performance. Visual SLAM systems are susceptible to changes in lighting, low-texture areas, or complete darkness, which hinder feature detection and tracking. LiDAR-based SLAM, while more robust to lighting variations, can degrade in adverse weather conditions like fog, rain, or snow due to signal scattering and attenuation. Whilst not an adverse imaging condition, highly geometrically repetitive environments also pose problems for SLAM due to a lack of unique features.
- Scalability and computational load – large-area or long-term mapping requires more memory and loop closures, impacting memory and computational requirements. This results in decreasing performance over time, which can gradually degrade SLAM performance to below real-time.
- Sensor calibration and integration – Sensor misalignment or timing/synchronisation discrepancies can introduce significant errors in pose estimation and map accuracy. System performance is highly dependent on good calibration.

- High dynamics – SLAM algorithms may lose track on sharp turns as well as with high-speed and high-dynamics motion, although these limitations are ultimately in the underlying sensors.

6.9.7. EMERGING SYSTEMS

SLAM is a mature technology but has a continuous trajectory for improvement. Solutions like ROS2 Navigation/SLAM (Cartographer, RTAB-Map, ORB-SLAM3) and automotive-grade LiDAR SLAM run reliably on real platforms, and many have reached fieldable to fully deployed readiness (TRL 6+) in autonomous vehicles and mapping devices.

However, research is moving toward learning-based and multi-agent SLAM. Recent work integrates deep networks for feature extraction and loop detection, making SLAM more robust to dynamic scenes. For example, neural VO and deep loop-closure networks improve resilience in challenging conditions. Multi-robot SLAM (cooperative/swarm mapping) is also at high TRLs, enabling teams of robots to merge maps dynamically. Semantic SLAM (simultaneous mapping of objects or landmarks) and reinforcement-learning-driven SLAM are emerging, potentially promising more robust and intelligent local PNT.

Current SLAM provides reliable bounded-drift localisation with static scenes (especially on ROS2/AV platforms), while future SLAM will leverage AI and collaboration for dynamic, large-scale, and adaptive navigation (many of which are already at or beyond TRL 5–6) (Jarraya, et al., 2025).

6.10. VISUAL ODOMETRY AND VISION-BASED NAVIGATION

Visual navigation refers to the use of cameras and machine vision to estimate a vehicle's motion and position relative to its environment. A fundamental approach is Visual Odometry (VO), which involves estimating egomotion—the motion of a viewer or camera relative to an environment or scene—by analysing sequential camera images. VO algorithms typically track motion by matching distinctive visual features, such as corners and edges, across frames or by computing optical flow (i.e., the pixel-wise apparent motion of brightness patterns) (Cadena, et al., 2016). Monocular VO, which uses a single camera, recovers relative orientation and translation but without absolute scale. Stereo VO, leveraging two horizontally offset cameras, triangulates corresponding features to directly measure distance and resolve scale ambiguity (Mur-Atal & Tardos, 2017).

Optical flow methods alone are prone to accumulating drift errors over time due to small inaccuracies integrating frame-to-frame motion. Consequently, practical VO implementations primarily utilise feature-based approaches enhanced with robust outlier rejection methods, such as Random Sample Consensus (RANSAC), to increase resilience to errors (Mur-Artal, Montiel, & Tardon, 2015).

In structured environments, artificially placed fiducial markers, such as AprilTags or ArUco markers, can significantly improve localisation precision by providing known reference points. AprilTags, for example, allow camera pose estimation with centimetre-level accuracy in position and orientation precision within a few degrees, supporting precise robotic localisation (Wang & Olsen, 2016).

Depth sensing is critical for robust visual navigation, and several methods exist for its acquisition. Stereo vision uses disparity—the horizontal offset between corresponding points observed from two camera views—to compute depth, with closer objects presenting greater disparities. Calibrated stereo systems can accurately determine distance to visual features (Tippetts, 2016). Additionally, active sensing methods such as structured-light and time-of-flight (ToF) cameras provide direct depth measurements. Structured-light sensors project known infrared patterns onto a scene and determine depth from pattern deformation, while ToF sensors measure depth by timing the round-trip or phase shift of reflected infrared light pulses (Hansard, Lee, Choi, & Horaud, 2013). These direct depth measurements significantly improve navigation reliability, particularly for obstacle avoidance and accurate scale determination.

Modern visual navigation systems commonly employ hybrid approaches, such as combining feature-based VO with periodic fiducial marker detection or integrating direct depth measurements to minimise drift errors and enhance long-term accuracy (Campos, 2021). Another important and increasingly common integration is visual-inertial odometry (VIO), which combines visual data with inertial measurement unit (IMU) readings to significantly reduce drift. VIO systems use IMU data to predict motion between visual updates, improving robustness during rapid movement and transient visual disruptions (Qin, Li, & Shen, 2018).

6.10.1. PNT OUTPUTS

Vision-based navigation primarily provides relative position (odometry) and orientation (heading and attitude) of the vehicle or platform. By analysing sequential camera images, the system can determine both how far and in which direction it has moved relative to its previous position. For instance, NASA's Mars rovers employ stereo visual odometry to correct wheel-slip-induced position errors, achieving cumulative drive-path accuracy of better than 1% of the total traversed distance over challenging terrain (Maimone, 2007). In addition to odometry, cameras can estimate orientation by tracking how visual landmarks or horizon features shift within successive frames. Multi-camera setups or fisheye lenses can provide full 360-degree coverage, thereby significantly enhancing situational awareness and improving orientation estimates (Mur-Atal & Tardos, 2017).

A key strength of visual navigation is the ability to simultaneously localise and map the environment (Simultaneous Localisation and Mapping, or SLAM). Visual SLAM algorithms identify and track salient visual features, generating persistent maps of these features while continuously estimating the platform's pose relative to them (Cadena, et al., 2016). Such approaches provide not only accurate trajectory estimates but also detailed, usable representations of the surroundings. When the camera revisits previously mapped locations, known landmarks are recognised, enabling loop closure, which significantly reduces accumulated positional drift and ensures map consistency over time (Campos, 2021). For example, visual SLAM algorithms can recognise previously observed features such as specific architectural details or prominent landscape formations, resetting accumulated positional errors and bounding localisation uncertainty.

In essence, vision-based navigation systems implement inside-out tracking, estimating the platform's position and orientation based on observations of environmental features. This approach inherently provides relative position and orientation, but with the addition of known landmarks or fiducials, absolute position estimates can also be achieved. Systems that integrate vision with inertial measurements (such as VIO) further improve robustness and accuracy, with inertial sensors compensating for rapid movements and short periods when visual features are lost (Qin, Li, & Shen, 2018).

6.10.2. PERFORMANCE TIERS

Visual sensors used for navigation encompass a wide spectrum of performance characteristics, differentiated primarily by sensor resolution, frame rate, depth range, and sensor technology type. At the lower-performance tier, inexpensive monocular cameras (such as smartphone or webcam modules) typically offer resolutions between 640 × 480 (VGA) and 1280 × 720 (HD) with frame rates around 30 Hz. These affordable sensors (costing tens of pounds) depend heavily on ambient lighting and environmental texture, limiting their effective operational range and accuracy; drift errors without correction can typically reach a few percent of distance travelled (Campos, 2021).

Higher-performance machine vision cameras provide improved resolutions (e.g., Full HD at 1920 × 1080, and 4K at 3840 × 2160) and increased frame rates (60–120 Hz or higher), enhancing feature detection, tracking accuracy, and the ability to handle rapid movements. Elevated frame rates, particularly beyond 90 Hz, significantly reduce motion blur and improve visual tracking reliability on fast-moving platforms such as unmanned aerial vehicles (UAVs) or autonomous cars (Scaramuzza & Zhang, 2019).

Stereo camera systems introduce depth accuracy and measurable range to performance parameters. These are dependent on sensor resolution and stereo baseline (the physical distance between the two camera lenses). A typical stereo camera with approximately a 75 mm baseline and 800 p sensor resolution can achieve depth measurement errors below 2% within several metres in range, with depth accuracy typically deteriorating to around 5-6% at 10 m distance (Tippetts, 2016). Commercial examples, such as the Intel RealSense D435, demonstrate reliable depth perception typically up to 10 m, while smaller-baseline stereo modules may have effective operational limits of approximately 4–5 m (Keselman, 2017).

Certain stereo cameras optimize speed over resolution; for example, the Stereolabs ZED series can operate at 120 fps at VGA resolution (960 × 600) or 60 fps at full resolution (1920 × 1200), providing effective depth sensing capabilities ranging from approximately 0.5 m to 20 m (Stereolabs, 2023). These high-frame-rate stereo sensors are valuable in dynamic or high-speed scenarios.

Specialized event cameras constitute another high-performance sensor category. These sensors detect changes in pixel brightness asynchronously, achieving effective frame rates exceeding 10,000 Hz and dynamic ranges beyond 140 dB (Gallego, et al., 2022). Consequently, event cameras excel in high-speed tracking scenarios, severe lighting conditions, and rapid motion environments where traditional cameras (even at high frame rates) would suffer significant motion blur and tracking degradation. However, current event cameras generally offer lower spatial resolutions (typically VGA or lower) and require more sophisticated algorithms to interpret asynchronous pixel events.

Thermal infrared (IR) cameras, such as those employing long-wave infrared (LWIR) microbolometer sensors, present yet another important sensor class. Although typically lower in spatial resolution (e.g., 320 × 256 or 640 × 512 pixels) and moderate in frame rate (around 30–60 Hz), thermal cameras enable visual navigation in complete darkness by detecting thermal radiation emitted by objects. The effective detection range of thermal IR sensors varies with thermal contrast in the environment and optical specifications, but practical obstacle detection is commonly achievable at ranges of tens of metres (Teledyne FLIR, 2017).

Finally, sensor performance tiers also vary significantly in terms of size, weight, and cost. Simple monocular modules suitable for micro-drones or consumer devices can weigh only a few grams and cost under £50. Conversely, ruggedised automotive-grade or aerospace-grade stereo or multi-camera systems with global shutter sensors, high frame rates, and robust environmental protection typically weigh from hundreds of grams to kilograms and can cost from several hundred to thousands of pounds (Campos, 2021).

In summary, visual navigation sensors span a broad performance range, from low-cost monocular setups adequate for simple indoor navigation to advanced multi-camera, stereo, or hybrid setups (including RGB-D, event-based, and thermal IR systems) delivering enhanced depth accuracy, robustness, and operational range. Essential performance metrics guiding sensor selection include spatial resolution (influencing feature detection range and accuracy), frame rate (determining maximum practical platform speed), low-light sensitivity (affecting robustness in poor lighting conditions), effective depth measurement range (particularly for stereo and depth sensors), and sensor dynamic range (critical for handling challenging environmental lighting conditions).

6.10.3. SWAP AND INTEGRATION

Vision-based sensors generally offer low SWaP characteristics, although practical integration introduces challenges. Simple monocular camera modules, such as those commonly integrated into smartphones, may measure approximately 8 × 8 mm and weigh only a few grams, making them suitable even for micro-drones and wearable applications (Campos, 2021). Compact stereo systems can similarly offer small form factors; for instance, the Intel RealSense T265 visual-inertial tracking module, combining dual fisheye cameras with an integrated IMU and onboard processing, measures just 108 × 24.5 × 12.5 mm, weighs about 55 g, and consumes approximately 1.5 W (Keselman, 2017).

In contrast, higher-performance or ruggedised vision solutions, such as multi-camera rigs providing 360-degree situational awareness or industrial-grade stereo cameras, typically have larger physical footprints and higher power consumption. A multi-camera spherical rig suitable for automotive or industrial environments may weigh between 1–2 kg and require upwards of 10 W of power when including multiple image sensors, onboard processors, and protective enclosures (Gallego, et al., 2022).

Optical characteristics significantly influence sensor size and integration considerations. Wide-field-of-view lenses, often exceeding 150 degrees, are commonly employed to ensure continuous feature tracking during dynamic manoeuvres. Such lenses are typically compact; however, integrating additional optical capabilities such as zoom lenses, polarisation filters, or thermal imaging optics, increases both complexity and physical dimensions. For example, thermal cameras often require germanium lenses, which are larger, heavier, and more costly compared to conventional visible-spectrum optics (Teledyne FLIR, 2017).

Lighting conditions strongly affect visual sensor performance and integration requirements. Standard optical cameras rely on ambient illumination, which severely limits performance in low-light or dark conditions. Consequently, integration may necessitate additional illumination sources, such as infrared LED illuminators or structured-light projectors, increasing complexity, power draw, and overall system SWaP (Hansard, Lee, Choi, & Horaud, 2013).

Processing requirements present another critical integration challenge. High-resolution and high-frame-rate visual navigation sensors generate substantial data volumes, requiring significant onboard computing capabilities. Vision-based navigation solutions typically employ embedded vision processing units (VPUs) or FPGAs integrated into sensor packages to mitigate the processing load on primary computing units. For instance, integrated solutions such as Intel's T265 camera utilise embedded Movidius VPUs to efficiently perform visual-inertial odometry directly on-device (Keselman, 2017). Alternatively, some high-performance sensors stream raw data externally via high-speed interfaces (e.g., USB 3.0, Gigabit Ethernet, or MIPI CSI-2) to offboard computers equipped with dedicated GPUs or DSPs (digital signal processors), enhancing flexibility in algorithm deployment but increasing integration complexity and system-level SWaP requirements (Campos, 2021).

Environmental factors introduce additional integration considerations. Vision systems for field use typically require robust enclosures to protect against dust, moisture, temperature extremes, and mechanical shocks. Industrial-grade cameras frequently adopt IP65 or higher-rated protective housings, inevitably increasing system weight and size but ensuring reliable operation under harsh conditions (Gallego, et al., 2022). Additionally, precise calibration—both intrinsic (lens distortion, focal length) and extrinsic (camera alignment in multi-camera setups)—is essential. Calibration can drift due to environmental factors such as temperature variations or mechanical disturbances, necessitating periodic recalibration routines to maintain accurate navigation performance (Cadena, et al., 2016).

From an overall SWaP perspective, vision-based navigation sensors are typically advantageous, with compact, lightweight solutions consuming relatively low power compared to sensors such as scanning LiDAR. However, their integration demands—such as processing requirements, illumination, optical complexity, environmental robustness, and stability significantly—influence the practical SWaP characteristics and overall complexity.

6.10.4. KEY PROVIDERS

The visual navigation technology sector is supported by a robust ecosystem of manufacturers and solution providers across robotics, automotive, aerospace, and defence domains. At a global scale, several prominent companies produce vision-based sensors suited to PNT applications. Notably, Intel RealSense (US) manufactures widely adopted stereo depth and visual-inertial tracking cameras, such as the D435 and T265, extensively used in robotics applications for visual odometry and SLAM (Keselman, 2017). Teledyne FLIR (US/UK) offers advanced thermal and visible-spectrum machine vision cameras, such as the Boson thermal cores and Bumblebee stereo cameras, utilized in autonomous vehicles, drones, and industrial robots (Teledyne FLIR, 2017). Additionally, Stereolabs (US/France) is recognized for its ZED series stereo vision cameras, delivering high-resolution depth sensing and integrated inertial measurements suitable for autonomous robotics (Stereolabs, 2023).

In automotive and autonomous driving, Mobileye (an Israeli company, now a subsidiary of Intel) supplies vision-based Advanced Driver Assistance Systems (ADAS), pioneering monocular vision technologies for lane detection, pedestrian recognition, and road mapping, and extending these capabilities toward fully autonomous driving (Shashua, Levin, & Sinha, 2022). Sony (Japan supplies high-performance CMOS sensors (e.g., STARVIS series), extensively used in automotive and robotic cameras due to their superior low-light sensitivity and high dynamic range capabilities (Sony Semiconductor Solutions, 2023).

In specialised sensor markets, Prophesee (France) and iniVation (Switzerland) are prominent producers of event-based (neuromorphic) vision sensors, offering high-speed tracking capabilities in challenging lighting and rapid-motion environments (Gallego, et al., 2022). These sensors have demonstrated significant potential in drone navigation and high-speed robotics.

Within the aerospace and defence sectors, integrators commonly produce custom vision systems. Leonardo MW and BAE Systems (both of the UK) have developed advanced electro-optical and infrared (EO/IR) sensor turrets for aircraft, unmanned aerial vehicles (UAVs), and defence platforms, integrating day/night cameras with stabilization systems for navigation, surveillance, and targeting purposes (Leonardo, 2023).

Software-centric companies like Oxbotica and SLAMcore (both of the UK) focus on developing robust vision-based localisation and mapping algorithms, often collaborating closely with hardware manufacturers to provide integrated visual navigation solutions for robotics and autonomous vehicles (Oxbotica, 2023) (SLAMcore, 2023).

In the drone industry, companies such as DJI (China) equips consumer and enterprise UAVs with optical-flow and stereo-camera-based obstacle avoidance systems for navigation (DJI, 2023).

Global automotive OEMs, such as Tesla and Waymo (both of the USA), develop in-house multi-camera visual navigation systems to enable their self-driving capabilities. Notably, Tesla's autopilot system utilises eight cameras around the vehicle to achieve autonomous navigation and obstacle avoidance entirely based on vision and machine learning (Tesla, 2023).

Finally, space agencies such as NASA's Jet Propulsion Laboratory, have pioneered sophisticated visual navigation systems, prominently demonstrated in the Mars Perseverance rover's visual landing system, achieving highly precise planetary landings through terrain-relative navigation using onboard cameras (Johnson, 2022).

6.10.5. APPLICATIONS AND BENEFITS

Vision-based PNT is widely adopted and essential in various domains, particularly for autonomy.

In the autonomous ground vehicles (AGVs) and automotive sectors, cameras form a key part of navigation systems, providing precise ego-motion estimation and detailed environmental perception. Autonomous vehicles rely on vision-based localisation and mapping systems (visual SLAM and visual-inertial odometry) to supplement GNSS, particularly in urban environments where GNSS signals are unreliable due to multipath and signal occlusion (Shashua, Levin, & Sinha, 2022). Cameras support obstacle detection, semantic understanding of surroundings, lane identification, and dynamic object tracking, facilitating safe autonomous driving (Campos, 2021). Mobile robots employed in industrial environments, warehouses, and homes increasingly use visual SLAM methods to systematically navigate and perform tasks such as cleaning or inspection without relying on external localisation infrastructure (Cadena, et al., 2016).

In aerial platforms, UAVs may utilise vision sensors to provide resilience against GNSS loss and to enable indoor navigation. Downward-facing optical-flow sensors combined with altimeters allow drones to hold stable hover positions (Scaramuzza & Zhang, 2019). Stereo cameras and visual-inertial systems further enable obstacle detection, avoidance, and autonomous navigation through cluttered environments. Advanced event cameras are beginning to demonstrate capability in enabling agile UAV navigation at high speeds and in challenging lighting conditions (Gallego, et al., 2022).

In maritime and underwater scenarios, vision sensors enhance surface navigation through obstacle detection and docking manoeuvres. Cameras augment situational awareness close to shorelines, ports, or complex structures (Campos, 2021). AUVs and ROVs utilise visual odometry and SLAM as part of their PNT system-of-systems to navigate in clear-water environments and to perform specific tasks such as inspecting subsea infrastructure (Mai, 2018). Vision complements acoustic positioning systems by providing higher-resolution and closer-range navigation data.

In aerospace and defence applications, vision-based navigation provides critical capabilities for spacecraft attitude determination, planetary landing precision, and terrestrial autonomous navigation. Star trackers—a type of specialised camera—provide spacecraft with precise attitude information based on star-field recognition (Liebe, 2016). Planetary rovers, such as NASA's Perseverance rover, utilise visual odometry and visual localisation systems to safely traverse challenging terrain and accurately target scientific sites (Johnson, 2022). Defence systems, including cruise missiles and UAVs, use terrain-matching and scene-correlation methods (e.g., Digital Scene Matching Area Correlation, DSMAC) to maintain accurate navigation when GNSS signals are jammed or spoofed (Gallego, et al., 2022). These methods allow platforms to autonomously and accurately determine absolute positions based solely on onboard visual observations.

In robotics, industrial automation, and augmented reality (AR) applications, vision-based localisation methods support precise robotic manipulation, assembly tasks, and immersive user experiences. Robotic arms equipped with visual sensors can achieve millimetre-level positioning accuracy by recognising fiducial markers or known object features (Wang & Olsen, 2016). Consumer AR and virtual reality (VR) devices utilise inside-out visual SLAM to precisely track user movements in real time without relying on external beacons, enabling seamless and accurate user interactions within virtual environments (Campos, 2021). Additionally, pedestrian navigation systems that combine inertial sensors with smartphone cameras have demonstrated improved positional accuracy by identifying environmental landmarks for drift correction (Qin, Li, & Shen, 2018).

6.10.6. CHALLENGES AND LIMITATIONS

Despite their widespread applicability and low-SWaP advantages, vision-based PNT systems face several inherent challenges and limitations that constrain their performance in real-world scenarios.

A fundamental limitation is sensitivity to lighting and environmental conditions. Standard cameras rely on ambient illumination to detect features, and their performance degrades sharply in low light, shadowed, or high dynamic range scenarios. Sudden lighting transitions—such as entering or exiting tunnels—or extreme glare and reflections can saturate sensors or render features undetectable. In outdoor conditions, weather phenomena such as fog, rain, or snow can occlude the visual field or reduce contrast, impairing both monocular and stereo performance. While high dynamic range sensors, auto-exposure techniques, and thermal or event-based cameras mitigate some of these issues, they do not fully eliminate the risk of visual failure (Gallego, et al., 2022).

Feature-poor or repetitive environments also pose a challenge. Visual odometry and SLAM algorithms require sufficient distinctive features in the environment to match between frames. Homogeneous surfaces (e.g., blank walls, sand dunes, snowy fields) or highly repetitive structures (e.g., warehouse aisles, tiled corridors) can cause tracking failure or incorrect data associations, leading to drift or catastrophic loss of position (Cadena, et al., 2016). Fiducial markers or artificial features can alleviate this but are only practical in structured settings.

High-speed motion or dynamic scenes introduce additional complexity. Fast translation or rotation can induce motion blur, reducing feature detectability, especially in low-light scenarios. Rolling shutter effects in low-cost cameras further distort images during motion, affecting pose estimation accuracy. Event cameras and global shutter sensors address this by minimising motion artefacts, but adoption remains limited to high-performance systems due to cost and algorithmic complexity (Gallego, et al., 2022).

Monocular systems suffer from inherent scale ambiguity. Without external reference points, a monocular VO or SLAM system cannot recover the absolute scale of motion, only the relative movement up to an unknown factor. This ambiguity is particularly limiting for applications requiring metric accuracy. Fusion with inertial data, stereo vision, or recognition of objects with known size can partially resolve scale, but this requires careful calibration and consistent environmental features (Mur-Atal & Tardos, 2017).

Drift accumulation is a persistent concern. All dead reckoning systems accumulate error over time, and VO is no exception. Small inaccuracies in feature detection and pose estimation compound with distance travelled. SLAM systems address this through loop closure—detecting when a previously visited location is reobserved—but this relies on environmental conditions and consistent observability. In large or open environments where features are not revisited, drift remains uncorrected and can degrade localisation quality significantly (Campos, 2021).

Computational load and processing latency also constrain practical deployment. Visual SLAM and odometry algorithms processing high-resolution, high-frequency data in real time require significant computing resources. Embedded platforms must balance throughput, energy consumption, and heat dissipation. While dedicated vision processing units (e.g., Movidius Myriad, NVIDIA Jetson) and FPGAs are increasingly adopted, small-scale platforms such as micro-drones or wearable devices may struggle to meet processing requirements without offloading computation or sacrificing performance (Qin, Li, & Shen, 2018).

Robustness is further impacted by sensor fragility and calibration drift. Lenses can be obscured by dirt, rain, or mechanical damage. Occlusions—e.g., by pedestrians, foliage, or moving machinery—can disrupt feature tracking. Moreover, cameras require accurate calibration of intrinsic parameters (focal length, lens distortion) and extrinsic parameters (sensor position and orientation in multi-sensor systems). Temperature variation, vibrations, or mechanical shifts can invalidate calibration, thereby degrading accuracy, unless recalibration is performed (Scaramuzza & Zhang, 2019).

Environmental context also impacts algorithm robustness. Indoor environments tend to have abundant features and constrained motion, favouring vision-based navigation. Outdoor scenes, by contrast, may present large-scale variation, fewer close-range features, variable lighting, and moving elements, such as vehicles or foliage. These dynamic and unstructured characteristics complicate feature tracking and increase the risk of associating dynamic elements to static maps. Military applications further raise concerns about countermeasures: active illumination can be detected or jammed, and visual obscuration (e.g., smoke, camouflage, laser dazzling) can disable visual systems entirely, whereas RF or inertial sensors may remain unaffected (Gallego, et al., 2022).

As a result, vision-based navigation systems are rarely deployed in isolation. Most practical platforms employ sensor fusion—integrating cameras with IMUs, LiDAR, radar, or GNSS—to compensate for the weaknesses of individual modalities and improve robustness and resilience. Significant research continues in developing methods to improve visual SLAM reliability, such as learning-based feature selection, low-light enhancement using deep learning, and robust loop closure detection (Campos, 2021).

6.10.7. EMERGING SYSTEMS

As of 2025, vision-based navigation technologies are widely deployed across consumer, industrial, and defence sectors. Robust, open-source SLAM frameworks such as ORB-SLAM3 and VINS-Mono provide reliable visual and visual-inertial localisation on CPU-class hardware in real time, enabling integration into embedded platforms and robotics systems without the need for external signals (Campos, 2021) (Qin, Li, & Shen, 2018). Visual systems are used to supplement GNSS and wider local sensors across platform domains.

Looking forward, several key technology trends are poised to enhance the performance and scope of visual PNT. One is the increasing deployment of event-based and neuromorphic vision sensors in navigation tasks that demand high temporal resolution and robustness to lighting variability. Event cameras enable real-time motion tracking in dynamic scenes, operating effectively in environments with flickering, high-speed motion, or extreme illumination contrast. These sensors, when paired with efficient event-based SLAM algorithms and inertial sensors, are likely to see increased deployment in drone swarms, missile guidance, and edge-compute constrained systems (Gallego, et al., 2022).

Another emerging direction is multi-modal sensing. Cameras capable of simultaneously capturing visible, infrared, polarisation, and event-based imagery are being developed to improve robustness under diverse environmental conditions. Such integrated systems will reduce complexity for autonomous platforms and may perform better than separately integrated systems. For example, polarisation data can aid in distinguishing water from sky, and thermal sensors can detect obstacles or vehicles in darkness or camouflage (Teledyne FLIR, 2017).

High-definition prior maps—containing geolocated visual landmarks—are also enabling vision-based absolute positioning. This technique, already used in some automotive systems, allows vehicles to match live camera feeds with stored high-definition visual maps to achieve centimetric localisation. Future AR devices and pedestrian navigation systems may similarly use onboard cameras and pre-mapped interiors or cityscapes for real-time localisation.

Artificial intelligence and machine learning are further improving the resilience and adaptability of visual navigation. Deep learning-based approaches to feature selection, image enhancement, and motion estimation are enabling visual odometry even in previously challenging conditions, such as low-light, fog, or rain. Learned representations can help distinguish transient or dynamic objects from structural features, improving robustness and map consistency (Campos, 2021).

Finally, continued improvements in sensor hardware are expected to yield higher-resolution, higher-dynamic-range, and lower-power camera systems. By 2030, it is plausible that 4K resolution global shutter cameras with 120 Hz frame rates and full HDR will be available at low SWaP, making them deployable across all domains—from micro-UAVs to satellites and manned vehicles.

In summary, vision-based navigation is in a mature state but continuing to improve, with clear paths toward greater robustness, multimodality, and sensor performance. As vision becomes more resilient and deeply fused with inertial, radar, and mapping systems, it is increasingly likely to contribute to navigation systems across sectors and platform domains.

6.11. ACOUSTIC NAVIGATION

Underwater and maritime surface vehicles cannot reliably depend on GNSS signals due to signal attenuation underwater and reflection at the water-air interface. Instead, they predominantly employ acoustic navigation methods based on the acoustic time-of-flight (TOF) principle, measuring round-trip travel time to calculate distance (distance = sound speed × time) (Chutia S., 2017) (Melo, 2017).

Acoustic positioning systems are commonly classified as long-baseline (LBL), short-baseline (SBL), ultra-short-baseline (USBL), and single-beacon methods, each differing in infrastructure requirements and achievable accuracy.

LBL systems use three or more fixed transponders on the seafloor with precisely known locations. The vehicle interrogates these beacons, and by measuring the round-trip travel time to each, determines its position via trilateration. LBL configurations offer high accuracy over large areas, particularly in deep-sea operations, due to their large baseline geometry (Paull, 2014).

SBL systems determine the position of a tracked target such as a remotely operated vehicle, by measuring the target's distance from three or more fixed transducers. These transducers are deployed on a support platform, for example by being lowered over the side of a supporting surface vessel, or a fixed/floating platform from which tracking operations take place. This can be constrained by the hull or platform size (typically a few metres), a greater baseline improves accuracy. These systems offer faster deployment and moderate accuracy without seafloor infrastructure but are limited in range and degrade significantly in precision at longer distances (Bibuli, 2012) (Robert D. Christ., 2007).

USBL systems use a tightly spaced acoustic array (centimetre-scale) on the ship and calculate both range (via TOF) and bearing (via phase-difference) to a target. These systems output a vector fix (bearing and slant-range) to the responder beacon, and with additional depth information, resolve a full 3D position (Kinsey, 2006) (Paull, 2014).

Single-beacon systems provide only a single range measurement to a fixed or mobile transponder. Since these yield only a radial distance, they must be fused with inertial navigation, Doppler data, or vehicle manoeuvre models to resolve the vehicle's location, typically along an annulus around the beacon (Jalal, 2021).

Across all types, velocity estimation is commonly achieved through Doppler shift measurement. Doppler Velocity Logs (DVLs) estimate velocity relative to the seabed or water column by measuring the frequency shift in echoes from multiple angled beams (Saeedi, 2021) (Caiti, 2022).

To enhance positional estimates and suppress noise or latency effects, modern acoustic systems employ Kalman filtering, phase-difference methods, and coded wideband pulses (Paull, 2014) (Ribas, 2012). These filtering strategies improve tracking fidelity even under challenging environmental conditions, such as multipath propagation or variable sound speed profiles.

6.11.1. WHAT IT PROVIDES

Acoustic navigation systems provide absolute or relative positioning based on measured ranges and, where applicable, bearings to fixed or mobile acoustic transponders. Their output varies depending on configuration:

- LBL systems offer an absolute position fix within a local coordinate frame established by the geometry of the seabed-mounted transponders. By using multiple wide-baseline anchors and triangulating ranges, an AUV or ROV can determine its (X, Y, Z) position with very low drift over time, assuming the beacons themselves are georeferenced (Paull, 2014) (Kinsey, 2006).
- SBL and USBL systems provide relative positioning with respect to the surface platform or support vessel. SBL systems derive 3D position from time-differences between hull-mounted receivers, while USBL directly outputs range and bearing using phase-difference and TOF measurements. When fused with pressure/depth data, these systems resolve 3D location in a vessel-centred frame (Paull, 2014) (Bibuli, 2012).
- USBL outputs include slant range, bearing, and, when pressure/depth is available, 3D position in local coordinates. The bearing is determined by evaluating the phase difference of received signals across the transducer array, yielding an angular measurement from the array axis to the responder (Ribas, 2012).

In more advanced configurations, such as inverted USBL (iUSBL), the transceiver is located on the vehicle itself. This allows the AUV to track fixed or mobile targets (such as surface buoys) and home in on them. If the external transponder (e.g., a buoy) is GNSS-referenced, the AUV's local navigation can be corrected in an absolute (Earth-referenced) frame (Saeedi, 2021) (Jalal, 2021).

Velocity estimation is also enabled through acoustic systems. Two primary methods are used:

- Doppler-based velocity: DVL systems measure the Doppler shift of bottom or water column echoes across multiple beams, typically angled at 30–45°. This yields precise surge, sway, and heave velocities, which can be dead-reckoned over time (Caiti, 2022).
- Range-rate tracking: By differentiating successive acoustic range and bearing fixes, systems can estimate the vehicle's velocity vector or provide direct range-rate outputs, though this is typically less accurate than DVL (Paull, 2014).

All acoustic outputs feed into a navigation filter (typically Kalman or particle-based), which fuses them with inertial and DVL data to produce smoothed position and velocity estimates. This fusion corrects for inertial drift, compensates for latency between acoustic updates, and stabilises tracking in complex environments (Ribas, 2012) (Kinsey, 2006).

6.11.2. PERFORMANCE TIERS

The performance of acoustic positioning systems is primarily determined by their baseline geometry, acoustic frequency, and system architecture. The four main system types—LBL, SBL, USBL, and single-beacon—each present different trade-offs in range, accuracy, and infrastructure:

- LBL systems deliver the highest accuracy due to their use of widely spaced, fixed seabed transponders. With baseline spacings typically ranging from tens of metres to over two kilometres, triangulation yields strong geometric constraints for positioning. Positioning precision is commonly cited as 0.01–1% of slant range, equating to centimetre-level errors at 100 m and decimetre-level errors at kilometre scale. Crucially, because the transponders are anchored to the seafloor, LBL accuracy is largely unaffected by water depth. However, deployment demands at least three to four transponders per operation, each of which must be precisely surveyed and often deployed by ROVs or divers. LBL systems typically operate in the 10–30 kHz band, balancing moderate range with manageable transducer size (Kinsey, 2006) (Paull, 2014).
- SBL systems mount multiple acoustic transducers on a fixed structure, such as a vessel or platform. Their performance is inherently limited by the platform's geometry—baseline lengths are typically a few to a few tens of metres—making SBL less precise than LBL. Accuracy on the order of decimetres to metres is typical, especially at ranges of several hundred metres. In ideal shallow-water scenarios with large vessels, sub-metre precision can be achieved, but this requires careful calibration. SBL performance degrades significantly as the target range exceeds the baseline length, and vertical accuracy is notably sensitive to depth variations. Operating frequencies are generally in the tens of kHz, with mid-frequency pulses offering a balance between resolution and attenuation (Paull, 2014) (Kinsey, 2006).
- USBL systems combine multiple receivers in a compact array—often less than 20 cm across—and use phase-difference and time-of-flight to resolve both range and bearing. System performance spans from short-range "consumer-grade" USBLs (<500 m) to advanced deep-water units reaching 5–10 km. For example, USBL accuracy varies from ~1–2% of slant range in low-cost systems to ~0.04–0.5% in high-end commercial and defence configurations. In practical terms, this means decimetre-level errors at 100 m and metre-scale errors beyond 2–3 km. Frequency agility is common: advanced USBLs support wideband chirps over ranges such as 14–34 kHz to optimise between resolution and penetration. Infrastructure demands are minimal—typically one transceiver head and one responder—making USBL highly popular for real-time tracking in mobile operations (Kinsey, 2006) (Paull, 2014).
- Single-beacon configurations offer the lowest infrastructure requirements, using just one transponder as a range reference. However, they provide only a scalar range measurement, constraining position to a sphere or annulus around the beacon. Without bearing information, positional error can grow significantly unless vehicle motion (e.g., curved trajectories) or velocity estimates are used to resolve ambiguity. When integrated with dead reckoning or INS/DVL estimates, single-range methods can achieve moderate positioning accuracy—typically 0.1–0.5 m range resolution in calm conditions—but suffer from poor geometric observability and high error growth during linear motion. These systems are generally used in short-range applications with constrained paths (Saeedi, 2021) (Kinsey, 2006) (Jalal, 2021).

6.11.3. SWAP AND INTEGRATION

Acoustic positioning systems exhibit a wide range of size, weight, and power (SWaP) characteristics depending on their configuration and performance class:

- USBL systems are typically compact and modular. The transducer head varies from 10–20 cm diameter in micro-USBLs (e.g., for small AUVs and ROVs) to ~0.5 m for full-size shipboard arrays. These units are often pressure-rated for deep deployment and integrate internal inclinometers, compasses, and pitch/roll sensors. Processing electronics are housed in separate deck units (e.g., rackmounted or in portable cases), drawing tens of watts, though power consumption is dominated by short, high-power acoustic pings (Kinsey, 2006) (Paull, 2014).
- LBL transponders, by contrast, are larger and typically cylindrical, up to 1 m tall, with internal batteries or external connectors. They are designed for long-term seabed deployment, often lasting weeks or months on a single charge. Ping rates are low (~1 Hz), with average power consumption of only a few watts, making them suitable for fixed infrastructure or persistent monitoring. Deployment usually requires a frame or ROV, increasing complexity (Kinsey, 2006).
- SBL systems consist of multiple hull-mounted hydrophones wired to a topside processor. These systems are lightweight and draw minimal power but require stable, well-surveyed mounting arrangements. Performance depends strongly on hull geometry and transducer placement (Paull, 2014).

Modern systems increasingly use integrated configurations combining USBL with inertial navigation (INS) and gyrocompass units. For example, the iXblue/Exail GAPS series (Exail, 2025) includes a fibre-optic gyro and acoustic transceiver in a single 30–40 cm housing. These all-in-one systems offer faster setup and calibration while reducing cabling and alignment errors. Similar compact INS-USBL units are offered by Teledyne and Kongsberg (Teledyne Marine, 2025) (Kongsberg Maritime, 2025).

Latency and update rate are important constraints in acoustic systems. Because acoustic pulses propagate at ~1500 m/s, a 5 km round-trip yields over 3 s of latency before a position fix can be calculated. Update rates are thus limited to 0.3–1 Hz depending on range, system processing, and echo environment. This is insufficient for fine-grained control or rapid tracking on its own (Kinsey, 2006). The navigation filters (typically Kalman or particle-based) that integrate inertial sensors (accelerometers and gyros) and DVL inputs propagate high-rate estimates of position and velocity between sparse acoustic updates, correcting accumulated drift when valid acoustic measurements are received (Caiti, 2022) (Paull, 2014).

Vehicle interface protocols vary by vendor but commonly include:

- Serial RS-232/422 interfaces for basic control and NMEA/PD0 navigation outputs
- Ethernet (UDP/TCP) for high-rate raw data and real-time telemetry
- Pulse-per-second (PPS) or GNSS-synchronised timing inputs to align clocks and reduce timestamp drift
- Integration interfaces to vehicle autopilots or SLAM systems, often using ROS, proprietary SDKs, or middleware such as MOOS or DDS

Sensor fusion is standard practice. DVLs, using four or more beams angled from the vehicle's underside, provide 3D velocity vectors at high frequency (up to 10 Hz), with resolutions of 0.1–0.5 cm/s in clear bottom-lock conditions. Pressure sensors contribute absolute depth, and magnetometers or gyrocompasses provide orientation. In advanced vehicles, acoustic range measurements are used as inputs into Simultaneous Localisation and Mapping (SLAM) filters, particularly where beacons serve as static "landmarks" or where acoustic and optical sources are jointly processed (Ribas, 2012) (Saeedi, 2021).

Proper synchronisation is critical: vehicle clocks and acoustic transponders must be accurately aligned to avoid range errors due to timing offset. High-end systems use GNSS-disciplined oscillators or regular acoustic calibration exchanges to maintain alignment (Paull, 2014).

6.11.4. KEY MANUFACTURERS

The primary manufacturers of acoustic positioning systems for subsea and surface PNT applications include Sonardyne (UK), iXblue/Exail (France), Teledyne Benthos (USA), and Kongsberg Maritime (Norway). Each offers systems across LBL, SBL, and USBL categories, targeting scientific, commercial, and defence markets.

- Sonardyne provides a comprehensive suite of systems:
  - Ranger 2 USBL offers up to 11,000 m range, 1 Hz update rate and accuracy down to 0.04% of slant range, capable of tracking multiple targets simultaneously (Sonardyne, 2025)
  - Compact variants such as Mini-Ranger 2 and Micro-Ranger 2 support up to ~995 m range with 3 Hz updates and sub-metre accuracy (Sonardyne, 2025) (Sonardyne, 2025)
  - Compatt 6+ LBL transponders are widely used in offshore survey and construction, supporting wideband ranging, long-term deployment, and depths up to 7,000 m (Sonardyne, 2025)
- iXblue/Exail's GAPS systems integrate USBL with fibre-optic INS in a single housing (~30 cm); models like the M5 achieve ≤0.5% slant-range accuracy up to ~1 000 m (Exail, 2025).
- Teledyne Benthos offers versatile platforms (Teledyne Marine, 2025).
  - TrackLink and Trackit USBL systems provide short-to-mid range tracking, with models such as Trackit 2 supporting up to 1,500 m range and 0.5% of slant range accuracy.
  - Acoustic Transponders and Modems, such as the ATM-900 series, serve dual roles in positioning and telemetry.
- Kongsberg Maritime manufactures the HiPAP family of USBL systems, widely adopted in naval and deep-ocean industrial use. With configurations supporting long range (>10 km) and ultra-high precision using fibre-optic baselines, HiPAP systems are deployed for high-end survey, tracking, and subsea dynamic positioning applications (Kongsberg Maritime, 2025).
- Additional industry contributors include Evologics (EvoLogics, 2025), LinkQuest (LinkQuest Inc, 2025), and Nautronix (owned by Imenco).

6.11.5. APPLICATIONS AND BENEFITS

Acoustic PNT is indispensable wherever radio-frequency solutions such as GNSS are unavailable or degraded—especially in underwater environments. Key subsea applications include offshore energy, scientific survey, archaeology, defence, and autonomous operations. Each domain exploits distinct configurations (LBL, USBL, SBL, or beacon-based) to meet its operational, spatial, and cost constraints.

In offshore oil and gas, LBL systems are the primary choice for high-accuracy underwater positioning during subsea construction, infrastructure inspection, and asset deployment. When fixed seabed transponders are georeferenced via surface GNSS buoys or vessels, absolute positioning can be achieved at depths exceeding 2,000 m with centimetre-to-decimetre accuracy. These high-stability solutions are essential for precise placement of manifolds, wellheads, and pipelines under dynamic sea states and low visibility conditions (Chutia S., 2017).

Autonomous Underwater Vehicles (AUVs) use USBL extensively for mid-range georeferenced survey and mapping. AUVs conducting bathymetric, magnetic, or sonar-based survey missions typically receive USBL fixes from a tracking ship or buoy. This allows for systematic coverage of broad areas, with navigation updated by a navigation filter combining USBL-derived position, INS, and DVL measurements. This fusion ensures accurate localisation over missions spanning kilometres and lasting hours (Caiti, 2022) (Kinsey, 2006).

Remotely Operated Vehicles (ROVs) performing inspection, maintenance, or intervention tasks (e.g., on pipelines, cables, or docking stations) rely on SBL or USBL for close-in positioning. Dynamic positioning systems on support vessels use acoustic data to hold station over a worksite. During recovery or docking, ROVs often home in on fixed transponders using short-range USBL or ToF methods (Jalal, 2021).

Beyond industrial use, scientific and archaeological missions benefit from the repeatability and precision of acoustic PNT. LBL and USBL are employed in hydrothermal vent exploration, wreck mapping, and sample return operations, where sub-metre accuracy enables data registration across repeat dives (Melo, 2017). Acoustic SLAM techniques also support terrain-relative navigation in structured environments, allowing for accurate track reconstruction and revisit planning (Ribas, 2012).

Acoustic PNT also supports cooperative navigation between multiple platforms. Acoustic modems are frequently dual-purpose, acting both as communication nodes and transponders. This allows AUVs to share position data, coordinate paths, or operate in formation. “Swarm” configurations, where AUVs act as moving LBL nodes for each other, are under investigation for scalable and infrastructure-light deployments (Saeedi, 2021).

6.11.6. CHALLENGES AND LIMITATIONS

Despite their proven utility, acoustic navigation systems face well-documented physical and operational limitations stemming from the nature of underwater acoustics and system design. A major constraint is multipath propagation, wherein acoustic pulses reflect off the seafloor, surface, or structures before reaching the receiver. These reflections introduce spurious echoes, particularly problematic in shallow or cluttered environments where reverberation can obscure the primary signal. Advanced receivers attempt to filter multipath through pulse coding and timing discrimination, but signal ambiguity remains a critical issue for reliable range estimation (Kinsey, 2006) (Caiti, 2022).

Ambient noise is another source of signal degradation. Vessel propellers, marine fauna (e.g., cetaceans), industrial equipment, and environmental factors (e.g., storms) contribute significant acoustic background noise. This interference can reduce signal-to-noise ratio (SNR), making transponder replies harder to detect or distinguish. Wideband signals and directional receivers help, but sensitivity to noise remains a concern in dynamic operational environments (Bibuli, 2012) (Saeedi, 2021).

Sound speed variation introduces another class of error. The travel time of acoustic pulses depends on the local sound velocity, which is affected by temperature, salinity, and pressure. In regions with strong thermoclines or haloclines, such as coastal or arctic zones, the actual sound path may curve substantially—violating the straight-line assumption used in many TOF calculations. Without correction (e.g., via sound velocity profilers or CTD casts), these ray-bending effects can bias range estimates and reduce positional accuracy (Kinsey, 2006) (Jalal, 2021).

System performance is also bounded by range–resolution trade-offs. High-frequency systems (e.g., >300 kHz) yield better resolution but suffer from strong attenuation, limiting effective range to a few hundred meters. Conversely, low-frequency systems (~10–20 kHz) provide multi-kilometre coverage but with degraded bearing resolution and increased susceptibility to multi-path effects. Even top-tier USBL systems experience range-dependent error scaling: slant-range accuracy may degrade from decimetre level at 100 m to metres at several kilometres (Chutia S., 2017).

The infrastructure and deployment burden can be substantial, particularly for LBL. Installing and surveying multiple seabed transponders—often via ROVs or divers—requires specialised support vessels and calm sea conditions. These constraints limit applicability in remote, high-current, or under-ice regions. While USBL and SBL require less infrastructure, vessel-mounted systems demand precise calibration of sensor positions and orientation, and they are sensitive to hull flexure and multipath from the vessel itself (Caiti, 2022) (Jalal, 2021).

Update latency is intrinsic to the acoustic medium: with sound travelling at ~1500 m/s, a 5 km round-trip introduces ≈3.3 s delay, not including processing. Thus, updates are typically limited to ~0.5–1 Hz. This imposes tight integration demands on the vehicle’s INS and DVL; without robust dead reckoning, the vehicle’s navigation solution can drift significantly between updates (Kinsey, 2006) (Saeedi, 2021).

Single-beacon systems are particularly ill-conditioned: range-only measurements define an annulus of possible positions, and without manoeuvres or additional data, horizontal uncertainty can grow unbounded. Effective use requires good initial estimates and synchronisation with other modalities (Melo, 2017).

Finally, cost and size remain limiting factors. Industrial-grade USBL and LBL systems have significant cost, with high-end configurations requiring large transducers, pressure housings, and deck units. These make them unsuitable for micro-AUVs or low-cost deployments, although miniaturised alternatives are emerging.

6.11.7. EMERGING SYSTEMS

Acoustic positioning continues to underpin reliable PNT solutions for underwater vehicles. USBL remains the standard for tracking small- to medium-scale AUVs and ROVs, while LBL systems maintain dominance for high-precision deepwater operations (Kinsey, 2006) (Caiti, 2022). Recent developments have introduced miniaturised USBL units and acoustic modems with ranging, extending PNT access to smaller platforms and lower-budget missions (Saeedi, 2021).

Current trends reflect a shift towards more scalable, distributed, and low-SWaP architectures aimed at autonomy and flexible deployment. This includes approaches such as the use of encoded emission beacons in Acoustic Local Positioning Systems (ALPS), which enable multi-user support and higher resilience to interference through signal strategies such as direct-sequence spread spectrum and frequency-hopping (Ureña, 2018).

Another line of innovation focuses on swarm localisation approaches, whereby multiple underwater nodes collaborate to estimate their positions through mutual ranging and asynchronous multilateration (Jiang, 2024). These techniques reduce the reliance on fixed infrastructure, offering adaptability, fault tolerance, and scalable accuracy. Architectures under this model are particularly relevant for cooperative AUV operations and wide-area monitoring.

Mobile acoustic references, such as GNSS-enabled drifting buoys, are also being developed. These floating units eliminate the need for seabed installations and allow underwater vehicles to compute their position using hyperbolic multilateration of timestamped acoustic pings (Otero, 2023). This reduces logistical constraints while maintaining support for multiple clients and flexible positioning geometries and may be integrable with existing or future floating infrastructure.

Described in the localisation section of this report, acoustic navigation also benefits from the significant developments in SLAM methods, including deep learning and AI.

Collectively, these trends mark a transition from monolithic and infrastructure-heavy systems toward flexible, low-power, and multi-agent solutions that support autonomy and large-scale marine sensing.

6.12. CELESTIAL NAVIGATION TECHNIQUES

Celestial navigation, sometimes called astronavigation, is the practice of determining one's position and orientation using observations of stars, the Sun, Moon, and planets. Before satellite navigation, it was the foundation for navigation at sea and in the air and remains valuable today for resilience in GNSS-denied or spoofed environments. Modern developments include both manual techniques and automated optical sensor systems, with star trackers and celestial cameras for real-time, automated solutions that image the sky, identify bodies against catalogues, and solve for the platform's attitude and, when geometry and timing permit, its position (Slocum, 1985) (Gooley, 2025).

6.12.1. PNT OUTPUTS

In a Local PNT system-of-systems, celestial sensing contributes absolute references that bound inertial drift and improve integrity when external signals are unreliable (Marin, 2020). This provides the following forms of PNT data:

- Absolute Attitude / Heading: Star-field matching yields a three-axis attitude solution referenced to the celestial frame, giving true heading and roll/pitch. Terrestrial systems typically deliver sub-degree attitude; spacecraft-grade trackers reach arcsecond-class. Update is exposure-limited (seconds-scale under good skies) (Finney, 2023) (InsideGNSS, 2022) (Marin, 2020).
- Absolute Position: With precise time and sufficient sky, multi-body observations (stars/Sun/Moon/planets) produce latitude/longitude fixes. Where geometry is limited, outputs degrade gracefully to lines of position (LOPs) or partial constraints (e.g., latitude from Polaris, noon sight latitude). Altitude is not directly measured; a horizon/vertical reference is assumed or must be provided by other sensors (Slocum, 1985) (Wingard, 2025) (Thomson, 2024) (Wojtyczka, 2025) (Marin, 2020).
- Constraints to bound INS drift: Even when a full position fix is unavailable (cloud, daylight, occlusion), celestial navigation provides high-integrity attitude/heading and/or LOPs that constrain an INS solution, reducing drift and improving integrity during GNSS outages (Marin, 2020).
- Time cross-check: Given known position (or solved jointly), celestial observations can estimate clock bias/UTC to coarse precision (seconds-level order in practice). In most implementations, accurate time is

an input rather than a primary output; but this may be used as an integrity cross-check (Kaplan, 1999).

- Velocity estimates: Celestial techniques do not measure ground-referenced velocity, but can provide attitude rate (from successive attitude solutions), which indirectly stabilises INS velocity estimates (Marin, 2020).
- Integrity data: Outputs include match residuals, star-count/geometry metrics, estimated covariance, and validity flags (e.g., sky fraction, saturation/blur detection). These enable weighting in the PNT filter and integrity monitoring (Wakita, 2024) (Jadhav, 2025) (Ning, 2009).

6.12.2. PERFORMANCE TIERS

6.12.2.1. MANUAL CELESTIAL NAVIGATION

Traditional celestial navigation is based on measuring angles between celestial bodies and the visible horizon, typically using a sextant. The navigator records the observed altitude of a body (such as the Sun or Polaris) and the exact time, referencing published tables (almanacs) to calculate the geographic position (GP) of the celestial body at that time. After "sight reduction," a line of position (LOP) is plotted on a chart. Intersecting multiple LOPs gives a position fix (Slocum, 1985).

Common methods include:

- Using Polaris for Latitude: Polaris sits close to the true north celestial pole; its altitude above the horizon directly indicates latitude in the northern hemisphere (Wingard, 2025) (Thomson, 2024)
- Noon Sight Navigation: Observing the Sun's highest point at local noon gives latitude directly; longitude is calculated by time difference from Greenwich (Wojtyczka, 2025).
- Using Multiple Stars: Sights from three to five stars provide intersecting LOPs, giving precise fixes; plotting these forms the "cocked hat" triangle indicating position accuracy (Wingard, 2025).

For latitude, navigators in the northern hemisphere use Polaris (the North Star) as its altitude equals the observer's latitude. For longitude, precise timing of observations (such as the Sun's noon altitude) is used in combination with published tables or nautical almanacs. Navigators plot these angular measurements against celestial coordinates, performing "sight reduction" to calculate the GP of each observed body. Plotting LOPs from several bodies, ideally three or more, enables accurate position fixing at sea or in the air. The intersection of these LOPs yields the navigator's position; plotting forms a "cocked hat" triangle, with accuracy indicated by its size (Wingard, 2025) (Wojtyczka, 2025) (Thomson, 2024).

In practice, performance is driven by sextant error, horizon definition, refraction and timing. A widely used rule is 1 arcminute ≈ 1 nautical mile; competent practice under good skies typically achieves few-NM fixes. Availability requires a clear horizon and sufficient sky, and cadence is minutes-scale (Slocum, 1985).

Performance summary:

- Outputs: LOPs; latitude (Polaris/noon sight); multi-star fixes ("cocked hat").
- Accuracy: Few-NM typical under good conditions.
- Cadence & availability: Minutes-scale; needs clear horizon/sky.

6.12.2.2. AUTOMATIC CELESTIAL NAVIGATION

Modern systems use star trackers and optical sensors, employing wide-field Charge Coupled Device (CCD)/ Complementary Metal Oxide Semiconductor (CMOS) cameras to capture images of the night sky. Onboard processors perform automatic "pattern recognition" by referencing star catalogues, deriving attitude and position through real-time astrometric calculations. These sensors are integrated with inertial navigation (INS) usually via Kalman filtering, allowing navigation solutions that are highly resilient to GNSS denial or jamming (Marin, 2020).

Advanced systems use multispectral imaging (including Short Wave Infrared (SWIR)) to enable day and night operation, and adaptive filtering to compensate for adverse weather or partial sky visibility. Automated systems utilise shortwave infrared (SWIR) sensors for day/night operation, these multispectral methods help mitigate weather effects and enable solutions under partial cloud cover or light pollution (Swank, 2022) (USA Patent No. US20210033400A1, 2021).

Marine and airborne systems employ gyro-stabilised mounts, providing continuous navigation under motion, and are increasingly miniaturized for UAV and autonomous platforms. Automated celestial navigation achieves sub-degree attitude accuracy and positional fixes of tens of meters under optimal conditions (Finney, 2023) (InsideGNSS, 2022).

Spacecraft-grade trackers set the accuracy ceiling for celestial navigation, delivering arcsecond attitude at high update rates using high-quality optics and curated catalogues; however, they are primarily attitude sensors with position only in specialised mission geometries (Finney, 2023) (Ning, 2009).

Outputs are fused with INS, typically via Kalman filtering, to suppress drift, interpolate fixes under sky obstruction, and provide continuous navigation resilience, especially in dynamic marine or airborne environments. This and supporting adaptive algorithms ensure near-instant updates after exposure and during platform motion (Panov, 2022).

Performance summary:

- Terrestrial star trackers
  - Output: Three-axis attitude/true heading plus opportunistic absolute position and high-integrity constraints (e.g., LOPs) to bound INS drift.
  - Accuracy: Sub-degree attitude/heading; position fixes at tens of metres under ideal conditions.
  - Latency/update: Seconds-scale convergence after exposure; cadence set by exposure, star count and processing.
- Spacecraft-grade star trackers
  - Output: High-precision three-axis attitude; position only solved in specialised geometries.
  - Accuracy: Arcsecond attitude. (Finney, 2023; Ning, 2009)
  - Latency/update: High-rate, exposure-limited updates suitable for tight control loops.

6.12.3. SWAP AND INTEGRATION

Terrestrial star-camera payloads target compact, low-power operation suitable for small platforms for the imager and onboard processing. Day-capable and more robust systems (e.g., with SWIR optics, aggressive baffling, or environmental hardening) increase size and power modestly. Gyro-stabilised mounts materially add mass and power but are often necessary on maritime & air platforms to avoid motion blur and keep adequate star counts in-frame (Finney, 2023) (University of South Australia, 2024) (Panov, 2022) (USA Patent No. US20210033400A1, 2021) (Swank, 2022).

Data processing from the star tracker following a standard pipeline: star detection and centroiding, pattern/graph matching against an onboard catalogue, and attitude/position estimation. This is typically part of the star tracker system, and the outputs from this are fused with the platform's navigation solver, exploiting the high-integrity attitude and opportunistic position/LOP updates to bound drift during GNSS outages. Explicit integrity monitoring metadata is also brought into this fusion, to enable direct weighting of the star tracker's outputs. Star catalogues, curated for brightness/colour indices, must also be periodically refreshed (Marin, 2020) (Jadhav, 2025) (Ning, 2009) (Wakita, 2024).

Accurate time-stamping is essential for ephemeris queries, and if GNSS-derived time is unavailable a disciplined local clock/source of time on-platform is required (Kaplan, 1999) (Ning, 2009).

For physical integration, alignment (boresight) between the camera and the platform reference frame must be calibrated and monitored. Marine/air platforms benefit from stabilised gimbals, however land systems may accept fixed mounts if exposure times and vehicle dynamics permit. Thermal management, de-fog/de-ice, and obscurant minimisation (salt spray, dust) are practical enablers of availability and may be specific to platform integration/intended environment (Panov, 2022) (Sodern Group, 2025).

Typical interfaces are Ethernet or serial for measurement and control, with PPS/trigger lines for timing. Primary data outputs are attitude (quaternion/Euler) with covariance, quality flags, and, if solvable, position/LOP updates plus observability metrics.

6.12.4. KEY PROVIDERS

Space-heritage star-tracker OEMs: Sodern (Auriga/Hydra), Jena-Optronik (ASTRO product family) and Leonardo (A-STR / AA-STR and variants) supply the mainstream space market and constellation programmes.

Small-sat specialists: Rocket Lab (Sinclair Interplanetary) and Blue Canyon Technologies (NST) provide low-SWaP trackers widely used on CubeSat/microsat missions, with integrated catalogues and "lost-in-space" capability.

Terrestrial & defence: Honeywell markets CNAV (passive, GPS-free navigation using star tracking and resident space object observations) for air/land/sea platforms, Kearfott publicly presents celestial-aided PNT concepts and open-architecture approaches aimed at GPS-denied scenarios, and Sodern has developed ASTRADIA for daytime terrestrial star tracking.

6.12.5. APPLICATIONS AND BENEFITS

Land, air and sea: GNSS/RF independent attitude & true-heading reference, with opportunistic absolute position fixes, when sky conditions allow. This can be used to provide holdover, integrity, and bound drift. Better maintained estimates during periods of GNSS disruption also aid faster reconvergence when signal returns.

Space: Star trackers are the primary source of high-precision attitude on orbit; while Local PNT focuses on terrestrial systems, space-heritage performance (arcsecond-class) is the benchmark informing what is feasible as terrestrial optics, sensors and processing improve.

6.12.6. CHALLENGES AND LIMITATIONS

Sky access & obscuration: Cloud, fog, precipitation, aerosols, canopy/urban canyons and platform self-occlusion reduce star count and can preclude a solution entirely. Daylight adds sky radiance; twilight and light pollution can depress usable stars (Sodern Group, 2025) (Swank, 2022).

Day/night complexity: Day-capable operation demands SWIR/multispectral optics, stringent baffling and short exposures. These increase SWaP and cost, and still deliver lower availability than clear night skies (Swank, 2022).

Motion blur & stabilisation: Ship/airframe dynamics smear star images at navigation-rate exposures. Gyro-stabilised mounts or very fast sensors reduce blur but add mass, power and integration complexity (Panov, 2022).

Atmospheric effects: Refraction (especially at low elevation angles), scintillation and extinction can bias measurements unless modelled or filtered. Residuals rise with haze and humidity (Wakita, 2024).

Catalogue, timing & alignment integrity: Solutions depend on accurate ephemerides/time stamps, curated star catalogues, and stable boresight calibration. Time or catalogue errors, optical misalignment and thermal drift manifest as attitude/position biases (Kaplan, 1999) (Ning, 2009).

Throughput & duty cycle: Although convergence can be seconds, practical update rate is governed by exposure windows, sky fraction and platform operations; availability is intermittent compared with inertial sensors (University of South Australia, 2024).

False matches & glare: Bright sources (Moon, planets, aircraft lighting) and stray light increase the risk of misidentification; rejection logic is required to handle this but is not infallible.

Environmental hardening: Optics are vulnerable to salt spray, dust, icing/condensation and thermal cycling; mitigation (heaters, de-fog, coatings) adds integration burden and potential points of failure, although robust high-grade units are well.

6.12.7. EMERGING SYSTEMS

Day-capable celestial: SWIR/multispectral optics, tighter baffling, short exposures and radiometric methods are pushing daytime and twilight operation to fieldable systems. These also improve availability under partial cloud/light pollution, but come with modest SWaP increases (USA Patent No. US20210033400A1, 2021) (Swank, 2022) (Sodern Group, 2025) (Nguyen, 2025).

Algorithmic advances: ML-assisted star identification (including subgraph/pattern matching), robust centroiding and false-match rejection can shorten convergence times and improve performance with incomplete skies. Factor-graph and advanced Kalman variants tighten INS fusion and expose richer integrity metrics for principled weighting (Jadhav, 2025) (Ning, 2009) (Wakita, 2024) (University of South Australia, 2024).

Low-SWaP terrestrial trackers: Research prototypes demonstrate sub-kilogram, <5 W payloads with on-board processing for UAVs and autonomous platforms (Nguyen, 2025) (University of South Australia, 2024) (Wakita, 2024).

Stabilisation-light approaches: Faster sensors, exposure control, electronic de-blur and estimator designs that tolerate interleaved "good" frames are aiming to reduce or remove the need for large gimbals on maritime/air platforms (Panov, 2022).

New contexts: Experimental work in the areas of space exploration including on planetary rovers, landers, and interplanetary spacecraft, includes integrating celestial sensing with planetary horizon detection for absolute and relative navigation (Gui, 2024) (Ning, 2009).

6.13. CLOCKS AND OSCILLATORS IN LOCAL PNT SYSTEMS

Clocks and oscillators provide the stable frequency and time references that underpin all local positioning, navigation, and timing (PNT) systems. These timing devices range from quartz oscillators to high-stability atomic clocks and are essential for synchronising systems, maintaining time during GNSS outages and enabling precise navigation. Oscillator stability is characterised over different timescales: short-term noise is measured via Allan deviation, while long-term drift reflects factors like aging and temperature dependence (Vectron International, 2025).

Quartz oscillators (traditional quartz oscillators or XOs and temperature compensated crystal oscillators or TCXOs) are compact and low-power but have limited stability. In contrast, oven-controlled crystal oscillators (OCXOs) and atomic standards, such as rubidium or caesium clocks, offer much better holdover performance and lower frequency drift, at the cost of increased size, power, and complexity (Haji, 2024) (Lam, 2008) (Vectron International, 2025). Chip-scale atomic clocks (CSACs) represent a newer class, combining low SWaP with moderate atomic performance (Microchip Technology Inc, 2023). Quantum clocks (optical and microwave) are a maturing area both providing new medium SWaP systems with performance several orders of magnitude better than existing traditional clocks of similar size, as well as advancing the state-of-the-art capabilities of holdover atomic clocks.

Accurate time is essential for inertial navigation systems (INS), where clocks are used to timestamp accelerometer data for fusion. Any error in the timebase leads to cumulative integration errors in position estimates over time (Advanced Navigation, 2023). Similar time precision is required in multi-sensor navigation platforms, where clocks align data from different sensor subsystems, such as IMUs, cameras, RF receivers, or LiDAR, into a coherent reference frame (GPS World, 2023).

Critically, clocks maintain accurate and synchronised time during GNSS outages, providing local timing holdover. Loss of time has far-ranging impacts on system or platform capability, affecting navigation data, but also communications within and outside the platform. Of the three elements of PNT, time is the most fundamental to a platform and is relied on extensively. Holdover provided by clocks is entirely dependent on their grade but may range from minutes and hours to 10+ days (Curry C. , 2010).

Beyond navigation, clocks are foundational to telecom and timing infrastructure. They synchronise 5G networks, enable precise radar and time-of-flight ranging, and support accurate timestamping in data centres and financial systems (GPS World, 2023) (Haji, 2024). Holdover capabilities are particularly critical in telecom base stations and GNSS-disciplined networks where signal outages must not cause service degradation (Rakon Ltd, 2023).

6.13.1. OUTPUTS PROVIDED

Clocks and oscillators in local PNT systems provide two essential outputs: a highly stable frequency reference (typically 10 MHz) and a 1 pulse per second (1 PPS), which can be synchronised to the time-of-day. These outputs enable system-wide coordination, timestamping, and deterministic execution across navigation, communications, and sensing domains (Vectron International, 2025) (Microchip Technology Inc, 2023).

In GNSS-denied scenarios, the oscillator assumes the role of a flywheel, maintaining precise time during holdover. High-performance oscillators—such as OCXOs and CSACs—can limit accumulated time error to microseconds over hours or days, depending on their drift profile. For example, in 5G telecom applications, base stations rely on rubidium or disciplined OCXO modules to maintain sub-microsecond timing over 24-hour outages, ensuring continuity of service when GNSS is unavailable (Rakon Ltd, 2023) (Haji, 2024).

The outputs are used in several ways:

- Frequency reference (10 MHz) is used to clock high-speed data converters (ADCs/DACs), RF systems, and signal processors. This ensures consistent sampling rates and stable carrier generation.
- Time pulse (1 PPS) provides absolute timing marks for synchronising datasets and events across systems, including sensor fusion modules, inertial subsystems, and time-transfer protocols (GPS World, 2023).
- Digital interfaces (e.g., RS-232, I²C, USB) enable remote configuration, status monitoring, and GNSS disciplining (e.g., steering to an external 1 PPS input), making the clock a fully integrated time server component in larger architectures (Microchip Technology Inc, 2023).

In navigation systems, these timing outputs synchronise inertial data with other sensors. For instance, a 1 PPS signal might align timestamps between an IMU and a GNSS receiver, while a 10 MHz clock stabilises data sampling from optical or radar systems. In radar-guided weapon systems, accurate timing ensures deterministic pulse transmission and reception, reducing uncertainty in time-of-flight measurements (Haji, 2024).

Clocks and oscillators are core to the function and resilience of local PNT systems. Their role is not merely to generate a signal, but to maintain an independent and precise timebase under challenging conditions—linking motion, enabling signal coherence, and maintaining system integrity when external timing references are lost.

6.13.2. SWAP AND INTEGRATION

Clocks and oscillators used in local PNT systems vary dramatically in Size, Weight, and Power (SWaP), depending on their underlying technology and intended use. At the low end, quartz oscillators and temperature-compensated variants (XO and TCXO) are compact, milliwatt-class devices, often just a few millimetres in size and weighing under a gram. These are widely integrated into consumer and embedded systems, where basic timing suffices.

Oven-Controlled Crystal Oscillators (OCXOs) represent the next tier, offering improved stability at the cost of greater SWaP. Typically housed in metal cans of approximately 25 × 25 × 15 mm, OCXOs weigh around 50–100 g and require 1–5 W of power to maintain a constant internal temperature. Warm-up times are on the order of several minutes, during which the oscillator stabilises to its rated accuracy (Vectron International, 2025).

Rubidium atomic clocks exist in both bench-top and compact embedded formats. Traditional rackmounted rubidium standards can weigh 10–15 kg and consume 10–20 W or more, making them suitable for base stations and reference labs. More modern embedded rubidium clocks, such as those produced by Microchip and Safran, offer module sizes around 144 cm³ with power consumption closer to 3–5 W (Haji, 2024).

Chip-Scale Atomic Clocks (CSACs) offer a significant reduction in SWaP while preserving much of the timing performance required for resilient PNT. Typical modules are about 1.6" × 1.4" × 0.45", with volumes under 20 cm³ and weights under 100 g. Power consumption is generally below 0.3 W, with fast start-up and warm-up times. These features make CSACs attractive for battery-powered and space-constrained platforms such as UAVs, dismounted systems, and compact GNSS holdover modules (Microchip Technology Inc, 2023) (Travagnin, 2022).

At the high end of the SWaP spectrum are hydrogen masers and caesium beam or fountain clocks. Laboratory-grade masers typically occupy a full rack (19") and weigh upwards of 50 kg, consuming 100–300 W of power, while caesium fountains require vacuum systems, laser optics, and optical tables—easily reaching hundreds of kilograms. These systems remain confined to fixed infrastructure or metrology labs (Haji, 2024) (Bandi, 2023). Portable optical clocks are beginning to bridge this gap, with current deployable systems that are rack-mountable with a 3-4U volume.

Integration with navigation systems typically involves standardised electrical interfaces. Most timing modules output a 10 MHz sinewave or TTL-level frequency signal, alongside a 1 Pulse-Per-Second (1 PPS) signal aligned to absolute time. These are used to clock processors, synchronise sensor logging, and provide time-stamping for data fusion. Serial interfaces such as RS-232, USB, or I^2C are often available for configuration and status monitoring. Higher-end oscillators may accept external references, such as GNSS 1 PPS, to enable disciplining and continuous calibration (Microchip Technology Inc, 2023) (Vectron International, 2025).

Overall, the SWaP and integration characteristics of clocks span a wide design space—from ultra-low-power chip-scale units, on the one hand, to high-performance but power-intensive atomic references, on the other. A detailed discussion on the variances can be found in (Curry C. , 2010).

6.13.3. PERFORMANCE TIERS

Clocks and oscillators used in local PNT systems span several performance tiers, differentiated by their frequency stability, noise characteristics, drift rates, warm-up behaviour, and power requirements. These characteristics determine their suitability for holdover, sensor fusion, time-transfer, and navigation applications.

6.13.3.1. QUARTZ OSCILLATORS (XO, TCXO)

- Stability and Noise: Quartz oscillators are the entry tier for timing applications. Basic crystal (XO) units offer frequency stability in the range of ±(10–50) ppm (1–5×10-5), with low short-term jitter but significant temperature-dependent drift (Lam, 2008). Temperature-compensated versions (TCXO) improve stability ~±0.1–0.5 ppm (1×10-7–5×10-7). Short-term Allan deviation, (1 s), is typically ~10-9–10-10 for good TCXO.
- Drift and Holdover: Long-term aging is typically ~1–10 ppm/year (1×10-6–1×10-55/year), rendering them unsuitable for precision holdover applications beyond a few seconds or minutes (Lam, 2008).
- Warm-Up and Power: XOs and TCXOs require no warm-up and consume <10-50 mW, making them ideal for embedded and battery-operated devices.

6.13.3.2. OVEN-CONTROLLED CRYSTAL OSCILLATORS (OCXO)

- Stability and Noise: OCXOs achieve fractional frequency stability of σ_γ(1–10 s) ~10-11–10-9 depending on grade by maintaining the crystal at a fixed temperature (Rakon Ltd, 2023) (Vectron International, 2025). Noise performance is much improved, with phase noise for a 10 MHz carrier typically −120 to −140 dBc/Hz at 10 Hz offset, improving to ~−150 dBc/Hz by 1 kHz.
- Drift and Holdover: OCXOs exhibit aging on the order of ~10-11–10-10/day (~0.01–0.1 ppb/day), and can sustain ~1–10 µs/24 h predictive holdover when disciplined prior to GNSS outage, or tens-to-hundreds µs/24 h for free-running error (Rakon Ltd, 2023).
- Warm-Up and Power: Warm-up time is several minutes; power draw ranges from 1–5 W.
- Most used in telecom (Stratum-3E clocks), GNSS-disciplined oscillators, and as the local reference in time servers.

6.13.3.3. RUBIDIUM OSCILLATORS

- Stability and Noise: Rubidium vapor-cell standards offer Allan deviations of σ_γ(1 s) ~ 10^{-11}, with aging of ~(0.5–2)×10^{-11}/month (~0.005–0.02 ppb/month) (Haji, 2024) (Jaduszliwer, 2021). These outperform quartz-based solutions by orders of magnitude.
- Drift and Holdover: Typically drift is sub-µs/day, providing 24–72 hour holdover at sub-to-low µs error levels without correction, although in stable environments (GPS World, 2023).
- Warm-Up and Power: Require 5–15-minute warm-up; draw 5–15 W. Modules vary in form factor but are typically >1 litre (Safran, 2023) (Microchip, 2025).

6.13.3.4. CHIP-SCALE ATOMIC CLOCKS (CSAC)

- Stability and Noise: CSACs bridge the gap between crystal and full-sized atomic clocks. Devices like the Microchip SA65 achieve a short term stability of σ_γ(1 s) ~3.5 × 10^{-10} and aging of ~9 × 10^{-10} (0.9 ppb/month) (GPS World, 2023).
- Drift and Holdover: This supports ~1–10 µs/24 drift if uncompensated, enabling short-duration GNSS holdover in mobile platforms (Haji, 2024), however CSACs are highly temperature dependent and this figure may be considerably worse in non-benign thermal conditions.
- Warm-Up and Power: Fast start-up (~30-120 s), extremely low power (0.12–0.3 W), and compact volumes (~17cm^3) (Microchip Technology Inc, 2023).
- Typically used embedded in man-portable radios, GNSS-denied UAVs, assured-PNT modules, and low-SWaP sensor fusion systems

6.13.3.5. CAESIUM BEAM STANDARDS

- Stability and Noise: Caesium beam clocks offer superior stability to rubidium clocks, with short-term stabilities of $\sigma_y(1\ s)$ ~(5×10^{-12}–1×10^{-11}), and aging of $<1\times10^{-14}$/day (0.01 ppt/day) (Jaduszliwer, 2021).
- Drift and Holdover: Excellent holdover is achievable (e.g. <200 ns/day), making them suitable as national primary references (Bandi, 2023).
- Warm-Up and Power: High power (~100 W); large rackmount form factors (>20 kg); require temperature-controlled environments.
- Applications: Serve as SI-traceable time standards in metrology labs, GNSS control segments, and telecom networks.

6.13.3.6. HYDROGEN MASERS

- Stability and Noise: Offer exceptional short- to mid-term stability: $\sigma_y(1000\ s)$ ~1×10^{-15} (Bandi, 2023). Phase noise is extremely low, making them valuable in frequency comparisons and scientific networks.
- Drift and Holdover: Drift typically $<1\times10^{-15}$/day (0.001 ppt/day); providing sub-ns holdover for weeks-to-months in controlled lab environments (Haji, 2024).
- Warm-Up and Power: High overheads (100–300 W), mass >50 kg, and require hydrogen reservoir replenishment.
- Used in timing labs (e.g., NPL, PTB), deep space networks, very long baseline interferometry (VLBI) radio telescopes, and GNSS master stations.

6.13.3.7. QUANTUM CLOCKS

- Stability and Noise: Optical lattice clocks (e.g., Sr, Yb) demonstrate short-term stability as low as $\sigma_y(1\text{–}10\ s)$ ~1×10^{-18}, outperforming all microwave standards. Performance for compatible fieldable variants is typically 3-5 orders of magnitude lower ~10^{-13}–10^{-15} for similar $\sigma_y(\tau)$, competing with caesium standards and hydrogen masers (Boldbaatar, 2023) (Roslund, 2024).
- Drift and Holdover: Fieldable clock prototypes have achieved <100 ps/day (~1×10^{-15} fractional) drift, positioning them as potential replacements for hydrogen maser clocks at lower SWaP and significantly improved thermal performance, removing the need for temperature controlled environments (Gellesch, 2020).
- Warm-Up and Power: Current laboratory systems are non-portable, requiring laser cooling, optical tables, and ~1 kW; volume typically tens of litres (Roslund, 2024). Fieldable optical clocks are 3-4U rack mounted systems, weighing <50kg and consuming <100W power.
- Quantum clocks are the highest performing systems, and the highest of these are lab-bound and still under development for space-qualified PNT systems. Portable standards, and entangled time-transfer research deployable mid-performance systems, have applications for holdover in data centres, telecommunications infrastructure, and defence platforms (Boldbaatar, 2023) (Inflegtion, 2025).

6.13.4. KEY MANUFACTURERS AND RESEARCH GROUPS

Local PNT systems depend on a specialised global supply chain of oscillator and atomic clock vendors. Whereas quartz and OCXO devices are broadly manufactured, high-stability atomic references (rubidium, caesium, hydrogen masers, CSACs) are produced by a small set of industrial and national actors. The UK maintains active capability in next-generation quantum and optical clock development.

Global Commercial Suppliers

- Microchip Technology Inc. (USA): One of the world's largest providers of precision timing, Microchip (via its Microsemi division) produces a full range of devices, including OCXOs, rubidium standards, CSACs, and caesium beam references. It also manufactures hydrogen masers for national labs and space clocks for GNSS platforms.
- Safran (France): Safran offers a wide range of timing products across performance tiers, including space-qualified rubidium clocks, commercial atomic references, and hydrogen masers.
- Oscilloquartz SA (Switzerland): Specialises in telecommunications and networked timing. They offer high-end (D)OCXOs, rubidium modules, caesium clocks, PTP-based time servers for holdover, and GNSS-holdover in telecom networks.
- Stanford Research Systems (SRS) (USA): Manufactures laboratory-grade frequency references, including low-phase-noise OCXOs, rubidium frequency standards, and general-purpose timebases, primarily for academic and metrology settings
- Rakon (New Zealand): Global supplier of quartz, TCXO, VCXO/VCSO, and OCXO components; provides frequency products for space, defence, and telecoms

UK Companies

- Teledyne e2v (UK): Offers rubidium oscillator modules, high-reliability quartz timing units, and frequency generation electronics for space and defence applications; supplies subsystems into ESA and UK defence programmes

- AccuBeat (UK/Israel): Designs and manufactures OCXO, rubidium, and GNSS-disciplined oscillators (GPSDOs) for military and telecom holdover
- Infleqtion (UK/USA): Developing deployable quantum clocks, including the Tiqker platform, a compact rubidium-based device targeting ~5 × 10^{-15} stability
- CPI-TMD (formerly TMD) (UK): Developing a quantum calcium ion frequency standard (CIFS)—a compact optical atomic clock based on a single trapped ion—targeting 1 × 10^{-16} stability and a rugged portable cold-atom microwave clock targeting 1 × 10^{-14} (gClock)
- Aquark Technologies (UK): Developing a portable cold-atom quantum clock (AQlock) for timing and synchronisation, based on a novel miniaturised cold-atom engine with inherent environmental ruggedisation

Public Research and Metrology Institutes (Non-exhaustive list)

- National Physical Laboratory (NPL, UK): The UK's national timing authority. NPL develops optical lattice clocks (e.g., Sr, Yb) and caesium fountains (e.g., NPL-CsF2). It leads the UK National Timing Centre programme and is centrally involved in the UK NQTP and ESA contracts. As of 2025, it was developing nine next-generation holdover atomic clock technologies, adding to its offering of NPLTime services (Haji, 2024) (Boldbaatar, 2023).
- Physikalisch-Technische Bundesanstalt (PTB, Germany): Operates hydrogen masers, caesium fountains, and transportable optical clocks for international timekeeping; plays a key role in UTC definition and clock intercomparison.
- National Institute of Standards and Technology (NIST, USA): Pioneer in time and frequency research and primary standard development; developed the NIST-F2 fountain and DSAC (Deep Space Atomic Clock) for NASA; provides calibration standards and time transfer services
- European Space Agency (ESA): Funds frequency and timing systems development, including space-qualified designs for next-generation systems, in partnership with national labs and commercial developers provides engineering tools and test-bed capabilities through its Navigation Laboratory

6.13.5. APPLICATIONS AND BENEFITS

Precision timing devices underpin the continuity, accuracy, and coordination of local PNT systems, particularly when external synchronisation (e.g., GNSS) is unavailable or degraded. Their applications span defence, navigation, telecommunications, and distributed infrastructure.

- Holdover in GNSS-Denied Environments: A central application is holdover—maintaining accurate timing when GNSS signals are unavailable. High-performance oscillators enable systems to maintain sub-microsecond accuracy for extended periods. For instance, chip-scale atomic clocks (CSACs) like the Microchip SA65 can maintain drift below 100 ns/day under stable conditions (Microchip Technology Inc, 2023). In telecom, OCXOs and CSACs maintain sub-µs synchronisation over 24 h holdover in 5G base stations (Rakon Ltd, 2023). Defence applications include resilient PNT modules, where clocks carry time across GNSS outages in jamming-prone environments (GPS World, 2023). These systems may need holdover for several to tens of days.
- Inertial Navigation and Sensor Fusion: Timing devices are essential to dead reckoning, where inertial navigation systems (INS) integrate accelerations over time. A precise timebase ensures integration accuracy and reduces drift. For example, inaccuracies in oscillator frequency can accumulate into significant position errors within minutes in GNSS-denied navigation (Advanced Navigation, 2023). In sensor fusion, accurate clocks enable time-alignment across data streams (e.g., camera, IMU, radar), which is crucial in autonomous vehicles and robotics. A 1 PPS signal and 10 MHz reference are typically used to synchronise timestamping and clock internal processing (Haji, 2024).
- RF Navigation and Time-of-Flight Ranging: Radio-based navigation systems (e.g., UWB, coherent radar, and bistatic systems) require high-quality timing to determine time-of-flight or phase differences. Sub-nanosecond accuracy may be required for meter-level position resolution. Oscillators such as OCXOs or rubidium clocks provide the needed low-jitter reference for pulse generation, phase-locked loops, and high-resolution ranging (Haji, 2024).
- Telecommunications and Network Synchronisation: Modern telecom networks rely on precision time protocol (PTP) and IEEE-1588v2 synchronisation. Without accurate local timing, packet loss, jitter, and sync failure occur. Atomic clocks provide disciplined timing for switches and base stations during GNSS loss, avoiding service degradation. This is especially important in edge computing and 5G+ fronthaul systems with strict phase and frequency tolerance (Rakon Ltd, 2023) (GPS World, 2023).

- Financial Systems and Data Centres: High-frequency trading and distributed ledger technologies require timestamping events to microsecond or sub-microsecond precision. Local atomic clocks support compliance with regulations (e.g., MiFID II) and ensure traceable, secure transaction histories. Timing servers often integrate OCXOs or CSACs, with GNSS disciplining for long-term accuracy (Haji, 2024).
- Scientific and Critical Infrastructure Timing: In laboratories and metrology, rubidium, caesium, and hydrogen maser clocks serve as timebase references for measurement and calibration. They are also deployed in timing hubs (e.g., UK's National Timing Centre) as part of resilient national infrastructure. In power grids and transport, timing signals support network synchronisation and fault detection (Haji, 2024).
- Emerging and Strategic Applications: Future space-based and inter-platform synchronisation may use optical or quantum clocks enabling tighter time transfer, resilient inter-satellite navigation, and cislunar PNT architectures.

6.13.6. CHALLENGES AND LIMITATIONS

Despite their critical role, clocks and oscillators used in local PNT systems present several technical, operational, and economic challenges. These limitations are tier-dependent, with distinct constraints emerging as performance improves.

- Environmental Sensitivity: Oscillator performance is highly susceptible to temperature. Quartz oscillators exhibit frequency variation with thermal drift on the order of 10†–10†/°C, while even oven-controlled OCXOs—designed to stabilise internal temperature—can drift under rapid ambient changes. Warm-up time is a related constraint: OCXOs may require several minutes to reach thermal equilibrium within ±100 ppb, making them unsuitable for systems requiring immediate startup. Higher grade clocks typically incorporate greater levels of environmental shielding to mitigate these issues; but, fundamentally, this must be solved through appropriate ruggedisation (Haji, 2024) (Vectron International, 2025).
- Power Consumption: Power draw increases with stability. While TCXOs consume milliwatts, OCXOs often require 1–5 W, and rubidium standards up to 10 W or more. Hydrogen masers and caesium fountains can exceed 100+ W, which limits use to fixed infrastructure or large platforms. CSACs bridge the power-performance gap, offering ~10^{-11} stability at <0.3 W but still fall short of rubidium performance for extended holdover (Microchip Technology Inc, 2023) (Haji, 2024) (Bandi, 2023).
- SWaP Constraints: Size and weight vary drastically across clock types. Crystal oscillators and CSACs are chip-scale and weigh <10 g, while rack-mounted caesium or maser standards weigh tens of kilograms. This restricts high-stability clocks to platforms where space and weight are not constrained, such as ground stations, research labs, or naval vessels (Haji, 2024).
- Vibration and Shock: Vibration affects oscillator frequency stability, particularly in mobile or airborne systems. Crystal oscillators may experience frequency modulation under dynamic acceleration (g-sensitivity), while atomic clocks require ruggedisation to maintain vacuum and thermal isolation (Vectron International, 2025).
- Cost and Availability: Price increases sharply with performance. Commercial TCXOs cost a few pounds, while OCXOs range from £100–£1,000. Rubidium modules typically cost several thousand pounds, and masers or caesium fountains can exceed £100,000. Early quantum optical clocks are in a similar £100,000+ price range. At the very top end, clocks can cost millions of pounds.
- Drift Over Extended Holdover: Even the best oscillators accumulate error over long GNSS outages. For instance, a CSAC with drift of <0.9 ppb/month corresponds to ~100 ns/day. Rubidium standards may extend holdover to several days, and Caesium standards, quantum clocks, and masers may extend beyond this. This consequently limits standalone operation in long-duration missions when SWaP-C is constrained or for very long missions (spanning months) (Microchip Technology Inc, 2023) (Jaduszliwer, 2021) (Haji, 2024).
- Maintenance and Calibration: High-end clocks require periodic recalibration and, in the case of hydrogen masers, hydrogen replenishment. Long-life operation may also require regular environmental conditioning and shielding from EMI (electromagnetic interference). Without this, clocks degrade or shift, undermining their utility for precision PNT. Ultimately, specific skills are required for deploying and maintaining high-end time and frequency systems (Bandi, 2023).

6.13.7. EMERGING SYSTEMS

The frontier of clock development for Positioning, Navigation, and Timing (PNT) is rapidly advancing, driven by increasing demands for precision, resilience, and compactness in defence, space, and CNI. At the forefront are quantum (optical and microwave) clocks, which are redefining the limits of timing performance (Boldbaatar, 2023) (Haji, 2024) (Roslund, 2024).

These systems have value in the context of metrology labs and national resilience. They guide the way for future ultra-high-performance systems for strategic purposes and the space segment, and their miniaturisation is actively researched. The translation of the best laboratory clocks into more practical and commercial devices is a well-established trend in the sector. This is seen directly in the emerging rack-mountable quantum clock products, offering portability and ruggedisation whilst exceeding the performance of alternatives in their SWaP bracket (Haji, 2024).

Alongside optical systems, chip-scale atomic clocks (CSACs) continue to evolve, improving performance while maintaining ultra-low Size, Weight, and Power (SWaP). For instance, Microchip's latest LN-CSAC delivers sub-10^{-11} Allan deviation at 1 s with holdover drift below 100 ns per day, all within a 0.3 W, 20 cm^3 package. The position of CSACs as critical components in embedded PNT modules, unmanned systems, autonomous platforms, and other SWaP constrained contexts will only increase, and this will remain an area of significant development and investment (Martinez, 2023) (Microchip Technology Inc, 2023) (Travagnin, 2022).

In the space domain, future missions are prompting the evolution of onboard timing. Programmes such as NASA's Deep Space Atomic Clock (DSAC) are testing compact, ultra-stable clocks to improve deep-space navigation, autonomous spacecraft timing, and inter-satellite synchronisation (Jaduszliwer, 2021).

Looking further ahead, there is considerable interest in deploying optical clocks in orbit, both for stability and for optical time transfer (Boldbaatar, 2023). Complementing advances in clock hardware, new approaches to time transfer are being explored, including quantum time transfer, discussed below.

7. NETWORK TIME TRANSFER TECHNOLOGIES

Precise time transfer and synchronisation are critical enablers of modern technological systems, underpinning almost all the applications noted in Section 1.4.2. (Key Applications and Beneficiaries). Accurate and stable time transfer ensures coordinated operations across distributed networks, minimises latency, and enhances system reliability and security.

This section covers technologies used in modern networks to transfer time. Time transfer is also able to be achieved using terrestrial RF technologies, as noted appropriately in Section 5 (Existing Terrestrial RF Systems).

As networks increasingly rely on real-time data processing and high-speed communications, technologies like Network Time Protocol (NTP), Precision Time Protocol (PTP), and White Rabbit have become essential for achieving sub-microsecond network synchronisation, each offering unique capabilities to meet diverse operational demands.

7.1. OVERVIEW

Time synchronisation ensures that distributed systems share a common temporal reference, enabling coordinated operations, data consistency, and reliable performance across applications. Precise time transfer is vital for telecommunications (e.g., 5G networks requiring synchronised base stations), financial systems (e.g., high-frequency trading with microsecond accuracy), and scientific experiments (e.g., particle physics requiring sub-nanosecond precision) (Mills D. L., 2010) (IEEE, 2019). GNSS and smart grids also depend on accurate timing to function effectively. Challenges include network latency and symmetry/asymmetry, clock drift, jitter, and environmental factors like temperature, which can degrade synchronisation accuracy (Lombardi, 2002).

7.2. NETWORK TIME PROTOCOL (NTP)

The Network Time Protocol (NTP), developed by David L. Mills in 1985, is a widely adopted protocol for synchronising clocks over packet-switched networks like the internet (Mills D. L., 2010). It remains a standard for general-purpose timekeeping in distributed systems.

NTP operates in a client-server model (Figure 44), where clients query time from servers synchronised to high-precision sources, such as GNSS or atomic clocks. It uses a hierarchical structure (tree-like structure) of strata, with Stratum 0 as reference clocks (e.g., GPS receivers) and Stratum 1 servers directly connected to them. NTP exchanges timestamps to estimate network delays and adjust local clocks, using algorithms like the Marzullo intersection to mitigate errors (Mills D. , 1995). It is based on UDP (User Datagram Protocol), which uses port 123.

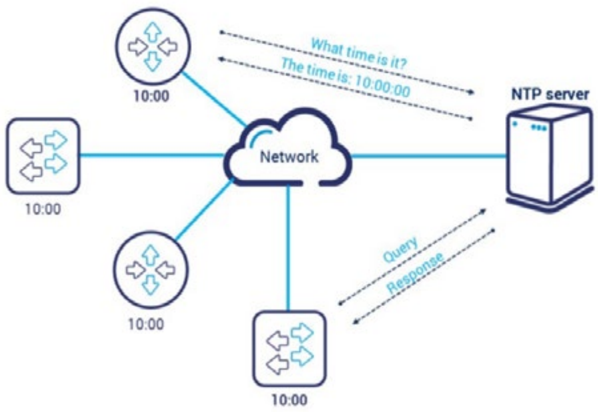


Figure 45: Simple NTP configuration (Tonmind, 2022)

NTP achieves millisecond-level accuracy, typically 1–50 ms (Mills D. L., 2010), depending on network conditions. Its precision is limited by network asymmetry, jitter, and server load, making it unsuitable for sub-microsecond applications. Security vulnerabilities, such as spoofing attacks, also pose risks (Malhotra, 2016).

NTP is most commonly used in internet servers, enterprise networks, and IoT devices for tasks like log timestamping, email synchronisation, and database consistency. NTP's advantages include its simplicity, widespread adoption, and low-cost software implementation. However, its limited precision and susceptibility to network variability restrict its use in high-precision environments.

7.2.1. NETWORK TIME SECURITY

Network Time Security (NTS) is a protocol which has been developed for securing communications between NTP clients and servers. NTS adds authentication and encryption layers to NTP exchanges, thus protecting them from attacks. The first proposals for a specification of the NTS protocol date back to 2015 (Sibold, 2015).

NTS corrects NTP shortcomings in terms of security by providing an authentication and encryption mechanism for NTP packets. This mechanism ensures that time synchronisation data between the client and the server is both authentic and reliable. NTS uses a modern cryptographic method to authenticate the source of NTP messages. This enables checking the legitimacy of servers providing the reference time in a network.

NTS encrypts the message flow using a variant of the AES (Advanced Encryption Standard) algorithm. This encryption guarantees the confidentiality of exchanges between clients and the time server. A replay attack against NTP consists of intercepting a message sent by a server and replaying it to the client (also known as 'man-in-the-middle'). The format of NTS packets enables the client to identify the replay.

NTS has been developed as an extension to NTP, which means that it complements the existing protocol without requiring major changes to the existing infrastructure. Servers and clients that support the NTS protocol can still communicate with NTP devices that do not support it. In that case, connections to these devices will not benefit from the security enhancements provided by NTS. A detailed description of NTS can be found in (NetNod, 2020).

7.3. PRECISION TIME PROTOCOL (IEEE -1588)

The Precision Time Protocol (PTP), standardised as IEEE 1588, was introduced in 2002 to provide sub-microsecond synchronisation for local networks (IEEE, 2019). It is designed for applications requiring higher precision than NTP.

PTP employs a master-slave architecture, with a grandmaster clock (synchronised to GPS or atomic clocks) distributing time to slave devices. It uses timestamped messages to measure propagation delays (Eidson, 2006). Hardware timestamping in network devices, supported by transparent or boundary clocks, enhances accuracy by reducing jitter. PTP profiles, such as the telecom profile (ITU-T G.8275.1), tailor the protocol to specific industries (ITU-T, 2014). Power (IEEE, 2017) and Audio Video Bridging over Ethernet (AVB) (IEEE, 2020) are additional profiles.

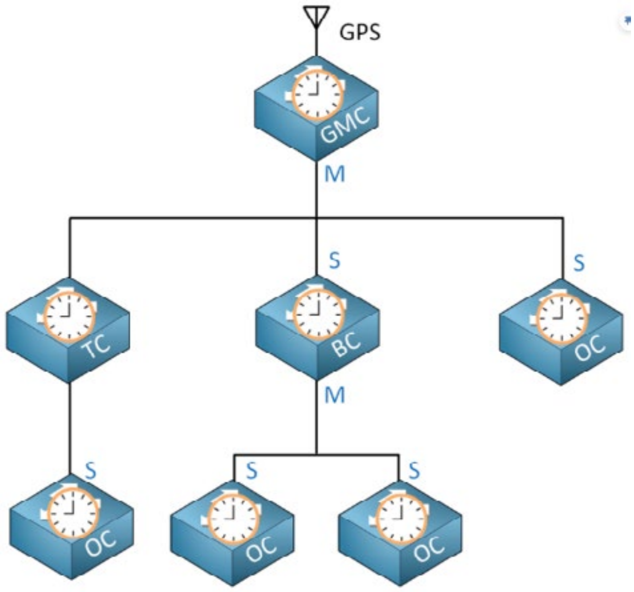


Figure 46: PTP Clock types (Network Lessons, 2025)

There are four types of PTP clocks employed in a network: a Grandmaster Clock, a Transparent Clock, a Boundary Clock and an Ordinary Clock (IEEE, 2019) (Network Lessons, 2025).

- Grandmaster - Primary source of time in PTP and is the timing reference. This clock is connected to a reliable time source, such as GPS or an atomic clock. All other clocks synchronise directly or indirectly with it.
- Transparent - Introduced in PTPv2; their goal is to forward PTP messages. They cannot be a source clock like a grandmaster or boundary clock.
- Boundary - The boundary clock runs PTP on two or more interfaces. It can synchronise one network segment with another. The upstream interface that connects to the grandmaster clock has the slave role. The downstream interface that connects to other clocks has the master role.
- Ordinary - The ordinary clock runs PTP on only one of its interfaces. This interface can have the slave or master role. This is usually an end device that needs its time synchronised.

PTP achieves sub-microsecond to nanosecond precision (100 ns–1 μs), depending on network configuration and hardware. Its limitations include the need for IEEE 1588-compliant hardware, increasing costs, and complex configuration for large networks (IEEE, 2019) (Eidson, 2006).

PTP is critical in telecommunications (e.g., 5G synchronisation), industrial automation (e.g., motion control), and power grids (e.g., synchrophasors for grid stability). Its implementation requires network infrastructure supporting IEEE 1588, careful topology design to minimise asymmetric delays, and vendor interoperability testing. Scalability in large networks has been a challenge in the past (Correll, 2002), although many scalability issues have been overcome (Obleukhov, 2022).

7.4. WHITE RABBIT

White Rabbit (WR), developed at CERN in the early 2000s, is a high-precision time synchronisation technology designed for scientific applications. It is in use by several metrology institutes globally. It extends PTP and integrates Synchronous Ethernet to achieve sub-nanosecond accuracy to synchronise both time and frequency. It uses high-precision clocks and fibre-optic links, performing continuous delay measurements to account for environmental factors like temperature-induced fibre delays (Lipinski, 2011) (Serrano, 2013).

WR achieves synchronisation accuracy below 1 nanosecond, critical for applications where timing errors can compromise results. This precision supports complex, distributed systems requiring extreme synchronisation such as high-energy physics (e.g., CERN's Large Hadron Collider), radio astronomy (e.g., Square Kilometre Array), and quantum networks. It is also starting to be used at the heart of next-generation telecom, data centre, financial, and energy systems (Derviškadić, 2019) (Moreira, 2009) (Lipinski, 2011) (Jiménez-López, 2019).

Unlike NTP's millisecond accuracy or PTP's sub-microsecond precision, WR's sub-nanosecond performance is significant but requires specialised hardware and controlled environments, increasing complexity and cost. A simple rule of thumb can be set out as:

- NTP: General-purpose applications like server synchronisation and IoT
- PTP: Telecommunications, industrial automation, and power grids
- White Rabbit: Scientific research and emerging high-precision fields

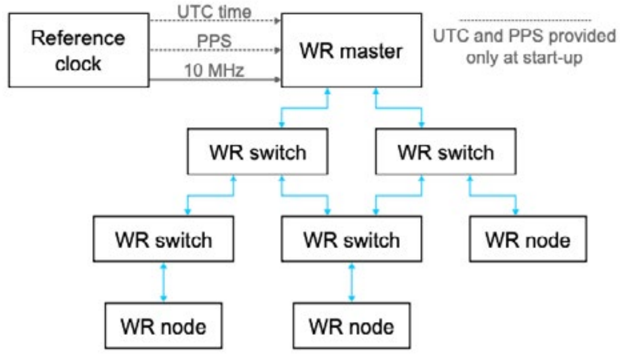


Figure 47: White Rabbit Architecture (Derviškadić, 2019)

Figure 46 shows the layout of a typical WR network, composed of nodes and switches and interconnected by fibre links. It behaves as a standard Ethernet switched network. This means that there is no hierarchy: any node can talk to any other node in the network; however, for time synchronisation, a hierarchy exists from top (grandmaster) down to switches and nodes. The WR switch is similar to a standard Ethernet switch but can precisely distribute the clock over the network.

The main limitation of WR is that the operating environment is not fitted with fibre-optic cables, which is economically difficult to achieve, and this would hinder any associated business case for implementation. Copper (1000BaseT) can be also used in small portions of the network with less-stringent timing requirements (Guita, 2025) (Derviškadić, 2019).

7.5. QUANTUM TIME TRANSFER

Quantum time transfer is an emerging technology that uses quantum mechanics to achieve ultra-precise synchronisation of clocks across distant locations. By utilising quantum entanglement—where particles share special correlations regardless of distance—quantum time transfer enables the distribution of time signals with unprecedented accuracy, potentially surpassing traditional methods like GPS-based synchronisation.

This technology has applications in secure communications, global navigation, and fundamental physics experiments, such as testing relativity. For instance, research has demonstrated the feasibility of using entangled photons to synchronise clocks with picosecond-level precision over long distances (Hou, 2019). However, challenges like maintaining entanglement over noisy channels and scaling infrastructure remain. Importantly, quantum time transfer protocols enable a layering of quantum key distribution security principles to ensure security across the time distribution network guaranteed by the laws of physics (Lamas-Linares, 2018).

ESA is investing in this technology to understand its potential (European Space Agency, 2025).

8. PNT SITUATIONAL AWARENESS

PNT Situational Awareness (SA) systems are critical for ensuring robust, resilient, and accurate PNT services across military, civilian, and commercial applications. These systems are designed to monitor, assess, and mitigate threats to PNT capabilities, particularly those reliant on GNSS, which have weak signal reception power. Threats such as jamming, spoofing, and environmental interference can degrade PNT, as well as space-based and terrestrial-based performance, impacting domains like aviation, maritime navigation, autonomous vehicles, and military operations.

Figure 48: Mock up of a PNT SA capability (Source: X.com)

8.1. DEFINITION AND IMPORTANCE OF PNT SITUATIONAL AWARENESS

PNT SA refers to the ability to perceive, comprehend, and predict the status of PNT systems within a given environment, including the detection and characterisation of threats or anomalies that could compromise performance. A mock up is shown in Figure 47.

This aligns with Endsley's three-level model of situational awareness: perception (Level 1), comprehension (Level 2), and projection (Level 3) (Endsley, 1995). PNT SA involves:

- Perception: Detecting signals, interference, or anomalies in GNSS or alternative PNT sources
- Comprehension: Analysing the nature, source, and impact of these anomalies (e.g., intentional jamming or natural ionospheric effects)
- Projection: Predicting future PNT system states and recommending mitigation strategies
- PNT SA is critical because GNSS signals are inherently weak (approximately -160 dBW at the receiver) and vulnerable to disruption. For instance, personal privacy devices (PPDs) used for jamming can disrupt GNSS signals over wide areas, affecting critical infrastructure like air traffic control or power grids. In military contexts, SA is vital for maintaining operational effectiveness in contested environments where adversaries employ electronic warfare tactics (Jada, et al., 2021).

8.2. ARCHITECTURE OF PNT SITUATIONAL AWARENESS SYSTEMS

PNT SA systems integrate hardware, software, and analytical frameworks to provide real-time monitoring and decision support. Their architecture typically includes the elements that follow.

8.2.1. SIGNAL ACQUISITION AND SENSING

- GNSS Receivers: Multi-frequency, multi-constellation receivers (e.g., GPS L1/L2/L5, Galileo E1/E5) collect raw signals for analysis. Advanced receivers incorporate anti-jamming features like Controlled Reception Pattern Antennas (CRPAs).
- Alternative Sensors: INS, atomic clocks, and vision-based navigation systems can provide complementary PNT data when GNSS is unavailable.
- RF Sensors: Spectrum analysers and direction-finding equipment detect interference sources, such as jammers or spoofers (Munir, Aved, & Blasch, 2022).

8.2.2. DATA PROCESSING AND ANALYSIS

- Signal Processing: Algorithms analyse carrier-to-noise ratio (C/N0), pseudorange errors, and signal phase to detect anomalies. For example, simultaneous drops in C/N0 across all satellites in view indicate jamming (Jada, et al., 2021).
- Machine Learning (ML): Convolutional neural networks (CNNs) and recurrent neural networks (RNNs) classify interference patterns or predict signal degradation (Munir, Aved, & Blasch, 2022).
- Digital Twins: Virtual models of PNT systems simulate real-time conditions, enabling predictive analysis of threats.

8.2.3. DECISION SUPPORT AND VISUALISATION

- Human-Machine Interfaces (HMIs): Dashboards display real-time PNT status, threat locations, and mitigation options. Augmented reality (AR) systems, like the U.S. Army's Integrated Visual Augmentation System (IVAS), enhance operator SA (Qian-ran Hu, 2023).
- Automated Decision-Making: Artificial intelligence (AI) systems recommend actions, such as switching to alternative PNT sources or adjusting receiver settings (Munir, Aved, & Blasch, 2022).

8.2.4. COMMUNICATION NETWORKS

- Networked SA: Distributed networks of GNSS receivers share data to localise interference sources. For example, continuously operating reference stations (CORS) detect jamming events near motorways or points of interest.
- Cyber-Physical Integration: PNT SA systems integrate with cybersecurity frameworks to counter spoofing attacks that manipulate GNSS data (Zhang, Feng, Liu, & Zhao, 2023).

8.3. KEY TECHNOLOGIES IN PNT SITUATIONAL AWARENESS

Recent research highlights several technologies driving advancements in PNT SA:

8.3.1. GNSS JAMMING AND SPOOFING DETECTION

- Jamming Detection: (Jada, et al., 2021) developed algorithms to detect GNSS jamming by analysing C/N0 drops across satellite signals. Their methods, tested on CORS data, identified tens to hundreds of jamming events monthly near highways, primarily caused by PPDs. These algorithms use statistical models to differentiate jamming from natural signal variations.
- Spoofing Detection: Techniques like signal authentication (e.g., Galileo's Open Service Navigation Message Authentication) and receiver autonomous integrity monitoring (RAIM)(see below) identify spoofed signals by comparing expected and received signal characteristics.
- Signal Processing-Based Detection: Signal processing techniques analyse GNSS signal characteristics to identify anomalies indicative of jamming or spoofing. These methods leverage metrics such as carrier-to-noise ratio (C/N0), pseudorange errors, and signal power levels.
  - Automatic Gain Control (AGC) Monitoring: Jamming often increases the RF noise floor, causing the receiver's AGC to adjust its gain to maintain signal amplitude. A sudden drop in AGC gain can indicate jamming, according to (Jada, et al., 2021) which demonstrated AGC-based detection using Continuously Operating Reference Stations (CORS) data, identifying jamming events caused by personal privacy devices (PPDs) with high accuracy.
  - C/N0 Analysis: A simultaneous drop in C/N0 across multiple satellites suggests jamming, while an unusually high C/N0 may indicate spoofing, as counterfeit signals often have higher power. (Borhani-Darian, Li, Peng, & Pau, 2020) used C/N0 thresholds combined with deep neural networks (DNNs) to achieve spoofing detection with low false-alarm rates.

- Cross-Ambiguity Function (CAF) Analysis: The CAF, computed during signal acquisition, maps delay and Doppler shifts to detect authentic satellite signals. Spoofing introduces additional peaks in the CAF, which can be identified using statistical hypothesis testing. A 2024 study proposed a CAF-based deep learning classifier that detects spoofing with superior performance at moderate-to-high signal-to-noise ratios (SNRs) (Borhani-Darian, Li, Peng, & Pau, 2020).
- RAIM algorithms compare pseudorange measurements from multiple satellites to detect inconsistencies. RAIM+ variants enhance spoofing detection by validating range data against expected satellite geometry. They can successfully identify non-authentic signals even from advanced signal generators (Lopez & Simsky, 2021).

Signal processing methods struggle with low-power or synchronised spoofing attacks, where counterfeit signals closely mimic authentic ones. Multipath and unintentional interference can also trigger false positives, necessitating robust differentiation algorithms.

- Machine Learning and Deep Learning Approaches: Machine learning (ML) and deep learning (DL) have revolutionised GNSS interference detection by modelling complex signal patterns and adapting to dynamic environments. These methods excel in distinguishing subtle differences between authentic and malicious signals.
  - Convolutional Neural Networks (CNNs): CNNs analyse time-frequency representations of GNSS signals (e.g., spectrograms) to classify jamming or spoofing. (Ghanbarzade & Soleimani, 2025) achieved 99% accuracy in jamming detection using CNNs on real-world datasets, improving performance by 5% over prior methods.
  - Deep Neural Networks (DNNs): DNNs process raw I/Q (in-phase and quadrature) samples or post-correlation metrics to detect spoofing. (Borhani-Darian, Li, Peng, & Pau, 2020) trained DNNs on cross-ambiguity function delay/Doppler maps, achieving high detection probabilities for per-satellite spoofing attacks.
  - Generative Adversarial Networks (GANs): GANs model the confrontation between authentic and spoofed signals, improving detection in scenarios with high signal synchronisation. A 2023 IEEE study demonstrated a GAN-based anti-spoofing method with 98% detection probability when the pseudocode phase difference exceeds 0.5 chips (Li, Zhu, Ouyang, Li, & Fu, 2021).
  - Clustering Algorithms: Combined with DL, clustering estimates the number and parameters of spoofing signals (Borhani-Darian, Li, Peng, & Pau, 2020).
  - Advantages: ML/DL methods adapt to evolving threats and handle complex interference scenarios, including combinations of jamming, spoofing, and multipath. Datasets like TEXBAT (University of Texas, 2025) and OAKBAT (Albright, 2025) provide standardised spoofing scenarios for training and validation.
  - Limitations: These methods require large, diverse datasets to avoid overfitting. Real-time implementation is computationally intensive, and low-cost receivers may lack the processing power for on-board ML (Radoš, Brkić, & Begušić, 2024).
- Antenna-Based Detection: Antenna technologies exploit spatial and polarisation properties to detect and mitigate interference, offering robust solutions for high-stakes applications.
  - Controlled Reception Pattern Antennas (CRPAs): CRPAs use multiple antenna elements to create nulls in the reception pattern, suppressing jamming signals from specific directions. NovAtel's GAJT antenna, for example, mitigates in-band interference effectively, even under high-power jamming (Hexagon, 2013). (Zhang, Cui, Xu, & & Lu, 2019) proposed a two-stage interference suppression scheme using CRPA arrays, achieving significant jamming and spoofing mitigation.

- Dual-Polarised Antennas: These antennas exploit differences in polarisation between authentic GNSS signals (right-hand circularly polarised) and spoofed signals, which may have inconsistent polarisation. Research by (Psiaki, 2016) demonstrated spoofing detection using dual-polarised antennas, with ongoing studies exploring their integration into commercial receivers.
- Space-Time Adaptive Processing (STAP): STAP combines spatial and temporal filtering to mitigate jamming in dynamic environments, modern STAP based implementations cover L1, L2, L5 and other GNSS bands.

- Signal Authentication and Cryptographic Methods: Cryptographic techniques authenticate GNSS signals to prevent spoofing, ensuring only legitimate signals are processed.
  - Open Service Navigation Message Authentication (OSNMA): Galileo's OSNMA provides cryptographic authentication of navigation messages, enabling receivers to verify signal integrity.
  - Chimera Authentication: The US GPS Chimera service, expected to be broadcast from the Navigation Technology Satellite-3 (NTS-3) in 2025 (Air Force Research Lab (AFRL), n.d.), embeds authentication codes in the signal structure.
  - Maximum Likelihood Estimation (MLE): MLE-based methods estimate signal parameters to distinguish authentic signals from spoofed ones. (Wang, Li, & Lu, 2017) developed an MLE approach for spoofing detection, achieving high accuracy in low-SNR environments.
- Multi-Frequency, Multi-Constellation Analysis: Modern receivers leverage signals across multiple GNSS bands (e.g., GPS L1/L2/L5, Galileo E1/E5) to detect interference.
- Crowdsourced Detection: Distributed networks of low-cost receivers, such as smartphones, can detect localised jamming or spoofing events.
- Quantum Sensors: Quantum-based magnetometers and atomic clocks offer potential for interference-resistant PNT, indirectly supporting SA by reducing reliance on GNSS. While still experimental, these technologies are being explored for future integration (Lei, et al., 2024).

8.3.2. ALTERNATIVE PNT SOURCES

As noted within this report, there are many sources of PNT that can be used as part of a PNT systems-of-systems to support PNT SA.

8.4. CHALLENGES IN PNT SITUATIONAL AWARENESS

Despite advancements, PNT SA systems face significant challenges, outlined below.

8.4.1. QUANTIFICATION AND MEASUREMENT

- Measuring SA is complex due to its cognitive and system-level components. The Situational Awareness Global Assessment Technique (SAGAT) uses random queries to assess operator knowledge but is less effective for automated systems (Hunter, Porter, & Williams, 2020).
- Quantifying the impact of interference on PNT performance requires robust metrics, such as error rates in position estimates or timing accuracy.

8.4.2. ENVIRONMENTAL AND OPERATIONAL VARIABILITY

- Ionospheric scintillation, multipath effects, and urban canyons degrade GNSS signals, complicating SA. Models must account for these variations to avoid false positives in threat detection.
- High-dynamic environments (e.g., air combat or autonomous vehicle navigation) demand real-time SA with low latency, straining computational resources.

8.4.3. SCALABILITY AND COST

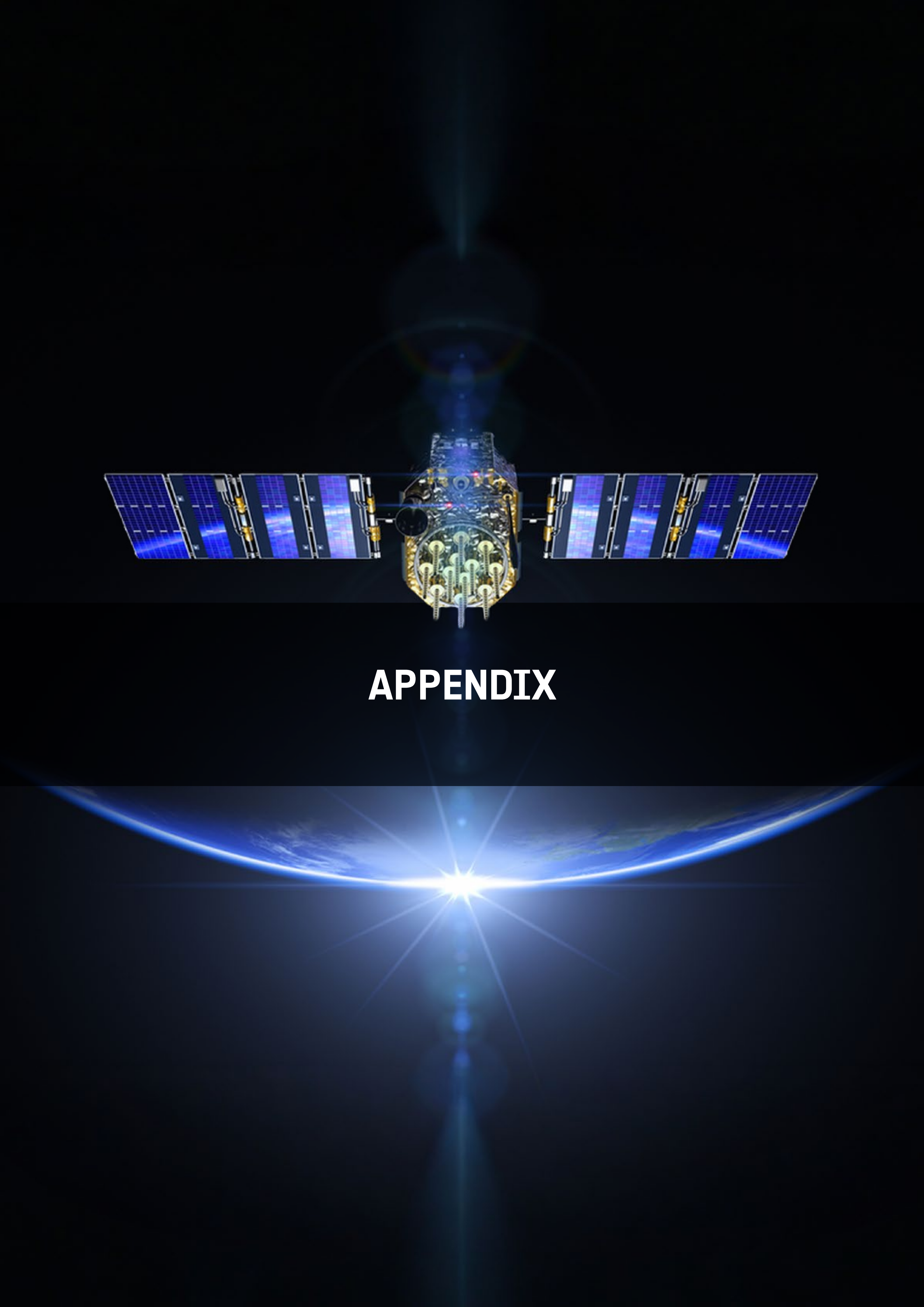
Deploying PNT SA systems over large networks, such as national CORS grids, requires significant infrastructure investment. Cost-effective solutions are needed for civilian applications. Balancing resilience with affordability is a key challenge for widespread adoption of PNT SA in commercial sectors like autonomous vehicles.

8.5. COMMERCIALLY DEPLOYABLE PNT SA SYSTEMS

This section lists (at Figure 48) several of the marketed PNT SA systems which could be deployed in the UK. It is likely that some research and development will be required for any system deployed. This non-exhaustive list shows that there are many capabilities that could be deployed to initiate PNT SA functions. This does not include the UK Government's activity using the Ordnance Survey's CORS network.

System	Company	Country	Link
GAARDIAN	Chronos	UK	https://gps-world.biz/research/
SENTINEL	Chronos	UK	https://gps-world.biz/research/
COLOSSUS	GMV/ESA	UK	https://www.unoosa.org/documents/pdf/icg/IDM/IDM7/IDM7_2018_02.pdf
Strike-3	GMV/EU	EU	https://ieeexplore.ieee.org/document/8874709
Signal Sentry	L3-Harris	USA	https://www.gpsworld.com/sentry-stands-on-jammer-alert/
GENS	CGI	UK	https://navisp.esa.int/uploads/files/project_documents/Final%20presentation%20EL3%20014.pdf?v=474235
Hawkeye-360	Hawkeye	USA	https://www.he360.com/hawkeye-360-signal-detection-reveals-gps-interference/
Marinai	MarinAI	UK	https://marinai.space/
GSS200D Detector	Spirent	UK	https://www.spirent.com/newsroom/press-releases/09-13-16_gss200d-gnss-multi-frequency-interference-detection-analysis-solution
GNSS Interference Detection and Analysis System (GIDAS)	OHB/ESA	DE	https://navisp.esa.int/project/details/13/show#:~:text=The%20GNSS%20Interference%20Detection%20and,means%20of%20jamming%20and%20spoofing.
GPSPatron	GPSPatron	PO	https://gpspatron.com/
GIMAD	Indra	ES	https://www.mdpi.com/2673-4591/54/1/25
AIM+	Septentrio/Hexagon	BE	https://www.ion.org/gnss/upload/files/2157_Septentrio_GNSS_Interference_A5_LR.pdf
SRX-10i	GMV	ES	https://www.gmv.com/sites/default/files/content/file/2020/06/11/1/srx-10i_brochure.pdf
Griffin	GPSATSYS	Aus	https://gpsatsys.com.au/griffin/
Forsberg	Teleplan Forsberg	UK	https://forsbergpnt.com/index.php/applications/security/
GANDALF-4	NATO Communications and Information Agency	NATO	https://insidegnss.com/nato-tests-gandalf-4-sensor-to-counter-gnss-signal-threats-and-improve-situational-awareness/
NAVSentry	Dimator	AT	https://www.dimetor.com/

Figure 49: PNT SA (non-Exhaustive) capture of commercial, or near commercial capabilities



APPENDIX

APPENDIX A BIBLIOGRAPHY

3GPP. (2020, July). NG-RAN; Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN. *3GPP TS 38.305 V16.0.0 (2020-07)* . 3GPP.

3GPP. (2024). 3GPP TS 38.104 (Release 16/17). https://www.3gpp.org/ftp/Specs/archive/38_series/38.104/.

3GPP. (2025). *RAN Release 19 Status and a Look Beyond*. Retrieved from https://www.3gpp.org/technologies/ran-rel-19

Abdulrahman, A., AbdulMalik, A.-S., Mansour, A., Ahmad, A. S., Al-Hadhrami, S., & Al-Hadhrami. (n.d.). Ultra Wide-band Indoor Positioning Technologies: Analysis and Recent Advances. *Sensors,, 19*(5), p. 1215.

Abu-Alrub, N., & Rawashdeh, N. (2023). Radar odometry for autonomous ground vehicles: A survey of methods and datasets. *IEEE Transactions on Intelligent Vehicles, 9*(3), 4275--4291. doi:10.1109/TIV.2023.3340513

ADS Advance. (2024). *Viasat Proves UK SBAS Accuracy.* Retrieved April 2025, from https://www.adsadvance.co.uk/viasat-proves-uk-sbas-accuracy.html

Advanced Navigation . (2025). *Non Directional Beacon (NDB)*. Retrieved from Advanced Navigation Glossary Terms: https://www.advancednavigation.com/glossary/ndb/

Advanced Navigation. (2022). *The Future of Inertial Navigation is Classical-Quantum Sensor Fusion.* Retrieved from Advanced Navigation: https://www.advancednavigation.com/articles/the-future-of-inertial-navigation/

Advanced Navigation. (2023). *An Introduction to Dead Reckoning - Advanced Navigation Technical Article.* Retrieved from Advanced Navigation: https://www.advancednavigation.com/tech-articles/an-introduction-to-dead-reckoning/

Advanced Navigation. (2025). *MEMS IMU.* Retrieved from Advanced Navigation: https://www.advancednavigation.com/products/motus

Advances in Bistatic Radar. (2007). SciTech Publishing.

Air Force Research Lab (AFRL). (n.d.). *Navigation Technology Satellite – 3 (NTS-3).* Retrieved 2025, from AF Research: https://afresearchlab.com/technology/nts-3

Albright, A. P. (2025). *A tool for furthering GNSS security research: The Oak Ridge spoofing and interference test battery (OAKBAT).* Retrieved from https://www.osti.gov/servlets/purl/1836467

Alhashimi, A., Adolfsson, D., Andreasson, H., Lilienthal, A., & Magnusson, M. (2024). BFAR: improving radar odometry estimation using a bounded false alarm rate detector. *Autonomous Robots, 48*(8), 29. doi:10.1007/s10514-024-10176-2

American Meteorological Society. (2017). *The Radio Frequency Spectrum and Weather, Water, and Climate: Uses and Challenges.* Retrieved 2025, from Ametsoc.org: https://www.ametsoc.org/ams/policy/policy-memos/the-radio-frequency-spectrum-and-weather-water-and-climate-uses-and-challenges/

AMS OSRAM. (2025). *AS5048a High Resolution Position Sensor*. Retrieved from AMS OSRAM: https://ams-osram.com/products/sensor-solutions/position-sensors/ams-as5048a-high-resolution-position-sensor

Amsler, S., & Shea, S. (2021, 3). *RFID (radio frequency identification).* (TechTarget) Retrieved 4 28, 2025, from https://www.techtarget.com/iotagenda/definition/RFID-radio-frequency-identification

AOSense. (n.d.). *Gravity Measurement.* Retrieved from AOSense: https://aosense.com/research-and-development/geodetic-and-geophysical-sensors/

Apple. (2021, 2 18). *Ultra wide band secuirty in iOS.* (Apple) Retrieved 4 24, 2025, from https://support.apple.com/en-jo/guide/security/sec1e6108efd/web

AV Web. (2019, 06 2). *DME Basics*. Retrieved 4 17, 2025, from https://www.avweb.com/avionics/dme-basics/

AVNET ABACUS. (2020). *Pressure sensors: The design engineer's guide.*

Bandi, T. N. (2023). A Comprehensive Overview of Atomic Clocks and their Applications. *BEMS Reports, 9*(1), 1-10.

Barbour, N. (2011). *Inertial Navigation Sensors (NATO STO SET-116 TR).* Cambridge, MA: NATO.

Barnes, D., Gadd, M., Murcutt, P., Newman, P., & Posner, I. (2020). The Oxford Radar RobotCar Dataset: A Radar Extension to the Oxford RobotCar Dataset. *2020 IEEE International Conference on Robotics and Automation (ICRA),* (pp. 6433--6438). doi:10.1109/ICRA40945.2020.9196884

Bar-Shalom, Y., Li, X.-R., & Kirubarajan, T. (2001). *Estimation with Applications to Tracking and Navigation.* John Wiley \& Sons.

Bartington. (2025). *MAG-03 Three-Axis Fluxgate Magnetometer -- Datasheet & Application Notes.* Retrieved from https://www.bartington.com/product/mag-03-three-axis-fluxgate-magnetometer/

Barzanjeh, S., Pirandola, S., Vitali, D., & Fink, J. (2020). Microwave quantum illumination. *Science Advances, 6*(19), eabb0451. doi:10.1126/sciadv.abb0451

Basheer, A.-T., Thorsten, H., Ahmed, A., & Ayoub, A.-H. (2024). A review of visual SLAM for robotics: evolution, properties, and future applications. *Robot AI, 11.*

Beyeler, A., Zufferey, J.-C., & Floreano, D. (2009). Vision-based control of near-obstacle flight. *Autonomous Robots, 27*(3), 201-219.

Bibuli, M. C. (2012). Guidance of Unmanned Surface Vehicles: Experiments in Vehicle Following. *IEEE Robotics & Automation Magazine, 19*(3), pp. 92–102.

Bluetooth. (2022). Bluetooth location services.

Bluetooth. (2023). *Bluetooth Core Specification version 5.4.*

Boșneagu, R., & Lupu, S. (2014). Modern Hyperbolic Navigation Systems, Present and future. *Constanta Maritime university Annals.*

Bolanakis, D. E. (2017). MEMS barometers and barometric altimeters in industrial, medical, aerospace, and consumer applications. *IEEE Instrumentation & Measurement Magazine*, 20(6), 30-55.

Boldbaatar, E. G. (2023). Evaluating Optical Clock Performance for GNSS Positioning. *Sensors, 23*(13), 5998.

Boldmethod. (2024). *How does an Altimeter work*. Retrieved from Boldmethod: https://www.boldmethod.com/learn-to-fly/systems/how-does-an-aircraft-altimeter-work-in-flight/

Borhani-Darian, P., Li, H., Peng, W., & Pau, C. (2020). Deep neural network approach to detect GNSS spoofing attacks. *ION GNSS+ 2020,* (pp. 3241 - 3252).

Bosch Sensortec. (n.d.). *Pressure sensor BMP388*. Retrieved from https://www.bosch-sensortec.com/products/environmental-sensors/pressure-sensors/bmp388/

Bronk, K., Koncicki, P., Lipka, A., Niski, R., & Wereszko, B. (2021). Concept, signal design, and measurement studies of the R-mode Baltic system. *Navigation: Journal of the institute of navigation , 68*(3), 465-483.

Brown, A., Nguyen, D., & Huerta, S. (2024). Leveraging commercial SATCOM services as Signals of Opportunity to provide PNT as a Service (PNTaaS). *2024 National Defense Industrial Association's (NDIA) Emerging Technologies for Defense Conference and Exhibition.*

Burger, W. (2006). Space-Time Adaptive Processing: Fundamentals. *Advanced Radar Signal and Data Processing,* 6-1 - 6-14.

CACI international. (2025). *Resilient Positioning, Navigation, and Timing (PNT)*. Retrieved from CICI Ever Vigilant: https://www.caci.com/PNT

Cadena, C., Carlone, L., Carrillo, H., Latif, Y., Scaramuzza, D., Neira, J., & Leonard, J. J. (2016). Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age. *IEEE Transactions on Robotics, 32*(6), 1309-1332.

Caiti, A. C. (2022). Simulation-Based Design and Validation of Navigation, Guidance and Control Algorithms for Underwater Gliders. *Sensors, 22*(2), 499.

Calian. (2025). *GNSS Constellations, Radio Frequencies and Signals*. Retrieved 2025, from https://www.calian.com/advanced-technologies/gnss/information-support/gnss-constellations-radio-frequencies-and-signals/

Callea Design. (2024, 9 5). *DCF77: HOW THE RADIO-CONTROLLED TIME SYNCHRONISATION SYSTEM WORKS IN EUROPE*. Retrieved 4 23, 2025, from https://www.calleadesign.co.uk/magazine/post/dcf77-guide-to-the-radio-time-synchronisation-system-for-europe.html

Campos, C. E. (2021). ORB-SLAM3: An Accurate Open-Source Library for Visual, Visual-Inertial and Multimap SLAM. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 43*(11), 4106-4121.

Carranza, A. (2020). *Cold Atom Interferometry for Inertial Navigation Sensors.* Retrieved from JRC Science for Policy Report: https://publications.jrc.ec.europa.eu/repository/handle/JRC122785

Chen, C.-H., Chen, P.-W., Chen, P.-J., & Liu, T.-H. (2021). Indoor Positioning Using Magnetic Fingerprint Map Captured by Magnetic Sensor Array. *Sensors, 21*(17), 5707. doi:10.3390/s21175707

Cheng, X., Hu, Y., & Varga, L. (2022). 5G network deployment and the associated energy consumption in the UK: A complex systems' exploration. *Technological forecasting and social change*.

China National Space Administration. (n.d.). *China National Space Administration*. Retrieved April 2025, from https://www.cnsa.gov.cn/english/

China Satellite Navigation Office. (2018). *BeiDou Navigation Satellite System Open Service Performance Standard (Version 2.0)* . Retrieved April 2025, from http://www.beidou.gov.cn/xt/gfxz/201812/P020181227529449178798.pdf

China Satellite Navigation Office. (2019). *The Application Service Architecture of BeiDou Navigation Satellite System (Version 1.0)*. Retrieved April 2025, from http://www.beidou.gov.cn/xt/gfxz/201912/P020191227337275341705.pdf

China Satellite Navigation Office. (2020). *BeiDou Navigation Satellite System Signal in Space. Interface Control Document (Version 1.0)* . Retrieved April 2025, from http://en.beidou.gov.cn/SYSTEMS/Officialdocument/202008/P020231201543618407017.pdf

China Satellite Navigation Office. (2021, September). Beidou Satellite Navigation System Development. *15th Meeting of the International Committee on Global Navigation Satellite Systems*. Retrieved April 2025, from https://www.unoosa.org/documents/pdf/icg/2021/ICG15/03.pdf

Christina Pinell, F. S. (2023). Receiver architectures for positioning with low earth orbit satellite signals: a survey. *Journal of Advanced Signal Processing, 60*.

Chutia S., N. M. (2017). A Review of Underwater Robotics, Navigation, Sensing Techniques and Applications. *Air 17*. New Delhi, India.

Clear Flight. (n.d.). *The VOR Explained*. Retrieved 04 17, 2025, from https://clearflight.co.uk/index.php/2023/12/24/the-vor-explained/

CMI Distribution . (n.d.). *Future-Ready Solutions: The Scalability and Future-Proofing of RFID Tags in Modern Businesses*. Retrieved 4 28, 2025, from https://www.cmilabsplc.com/future-ready-solutions-the-scalability-and-future-proofing-of-rfid-tags-in-modern-businesses/

Colone, F., Cristallini, D., Lombardo, P., & Grüneberg, K. R. (2014). A Tutorial on Passive Radar. *IEEE Aerospace and Electronic Systems Magazine, 29*(9), 39--57. doi:10.1109/MAES.2014.130050

Coluccia, A., Ricciato, F., & Ricci, G. (2014, Feb). Positioning Based on Signals of Opportunity. *IEEE Communications Letters, 18*(2), 356-359.

Correll, K. B. (2002). Design considerations for software-only implementations of the IEEE 1588 Precision Time Protocol. *Conference on IEEE 1588*, (pp. 1-10).

CRFS. (2025). *CRFS*. Retrieved from Crfs.com: https://www.crfs.com/

CRFS. (2025). *Guide to RF GeoLocation*. Retrieved from crfs.com: https://www.crfs.com/guide-to-rf-geolocation

Critchley-Marrows, J. (2024). A VDE-SAT Delivered R-Mode for Maritime Navigation, steps towards a LEO- PNT. Proceedings of Civil GPS Service Interface Committee. Baltimore, Maryland, USA.

Crossley, D. H. (2013). The measurement of surface gravity. *Reports on Progress in physics*, 76(4), 046101.

Curry, C. (2010). *Dependency of Communications Systems on PNT Technology*. Chronos Technology Ltd.

Curry, C. (2014). *Delivering a National Timescale using eLoran*. Chronos Technology.

Dai, Z., Wolf, A., Ley, P.-P., Glück, T., Sundermeier, M. C., & Lachmayer, R. (2022). Requirements for Automotive LiDAR Systems. *Sensors, 22*(19), 7532.

DatacenterDynamics. (2023). *OneWeb Launches GPS Alternative*. Retrieved April 2025, from https://www.datacenterdynamics.com/en/news/oneweb-launches-gps-alternative-for-greater-satellite-internet-stability/

DDK Positioning. (2025). *DDK Positioning*. Retrieved from https://www.ddkpositioning.com/

Delta-G. (n.d.). *Delta-G*. Retrieved from Delta-G: https://www.delta-g.co.uk/

Department for Science, Innovation, and Technology. (2023, 10 18). *Critical services to be better protected from satellite data disruptions through new Position, Navigation and Timing framework*. (UK Parliament) Retrieved 4 25, 2025, from https://www.gov.uk/government/news/critical-services-to-be-better-protected-from-satellite-data-disruptions-through-new-position-navigation-and-timing-framework

Department of Transportation. (n.d). Low frequenct advanced terrestrial PNT system.

Derviškadić, A. W. (2019). The White Rabbit Time Synchronization Protocol for Synchrophasor Networks. *IEEE Transactions on Smart Grid*.

Dgtl Infra. (2024, 1 14). *Cell tower range: How far do they reach?* . Retrieved 4 22, 2025, from https://dgtlinfra.com/cell-tower-range-how-far-reach/

Dimetor. (2025). *Dimetor.* Retrieved from Dimetor.com: https://www.dimetor.com/

DJI. (2023). *DJI UK.* Retrieved from DJI: https://www.dji.com/uk

Durrant-Whyte, H., & Bailey, T. (2006). Simultaneous localization and mapping: part I. *IEEE Robotics & Automation Magazine, 13*(2).

E. Grayver, R. N. (2024). Position and Navigation Using Starlink. *IEEE Aerospace Conference.* Big Sky, MT, USA.

Eidson, J. C. (2006). *Measurement, control, and communication using IEEE 1588.* Springer.

El-Sheimy, N. Y. (2020). Inertial sensors technologies for navigation applications: state of the art and future trends. *Satellite Navigation Navig, 1*(2).

EMCORE. (2021). *Quartz MEMS Tactical Grade Inertial Sensors.* Retrieved 2025, from GPS World: https://www.gpsworld.com/emcore-quartz-mems-tactical-grade-inertial-sensors

(latest ed.). *EN 301 091-1: Short Range Radar (76--77 GHz) --- Harmonised Standard.* ETSI. Retrieved from https://www.etsi.org/

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors, 37*(1), 32-64.

EUROCAE. (2019). *ED-114B - MOPS For Global Navigation Satellite Ground Based Augmentation System Ground Equipment To Support Precision Approach and Landing.*

Eurocontrol. (2025, 1 17). *CNS Evolution Plan 2024.* Retrieved from https://www.eurocontrol.int/publication/cns-evolution-plan-2024

European Agency for Space Programmes. (2024). *GNSS and EO Market Report Issue 2.* European Union.

European Commission. (2023). *Assessing alternative positioning, navigation, and timing technologies for potential deployment in the EU.* JRC Science for policy report.

European GNSS Service Centre. (2025). *Galileo System.* EU GNSS Service Centre.

European Space Agency . (2024, 6 4). *Advanced VDES-R User Technologies for Alternative PNT.* Retrieved 4 23, 2025, from https://navisp.esa.int/news/article/Advanced%20VDES-R%20User%20Technologies%20for%20Alternative%20PNT

European Space Agency. (2011). *GLONASS Architecture.* Retrieved 2025, from https://gssc.esa.int/navipedia/index.php/GLONASS_Architecture

European Space Agency. (2011). *GLONASS Performance.* (European Space Agency) Retrieved 2025, from https://gssc.esa.int/navipedia/index.php?title=GLONASS_Performances

European Space Agency. (2011). *Precise Point Positioning.* Retrieved April 2025, from https://gssc.esa.int/navipedia/index.php/Precise_Point_Positioning

European Space Agency. (2021). *UTD - UK Time Distribution* . Retrieved from European Space Agency NAVISP: https://navisp.esa.int/project/details/169/show

European Space Agency. (2024, 2 28). *057 - Development of advanced VDES-R user technologies for alternative PNT.* Retrieved 4 23, 2025, from https://navisp.esa.int/project/details/193/show

European Space Agency. (2024). *A concept for precise Time Transfer via Viasat's Global Xpress (GX) satellites in GEO, ultimately independent of any GNSS, has been developed and referred to as Global Xpress Time Transfer. The concept uses enhanced orbit determination data and will make* . Retrieved April 2025, from https://navisp.esa.int/project/details/349/show

European Space Agency. (2025). *QUANTUM TIME TRANSFER.* Retrieved from ESA: https://navisp.esa.int/project/details/317/show

European Union Agency for Space Programmes (EUSPA). (2023). *GALILEO Open Service Interface Control Document (OS SIS ICD).* EUSPA.

EUSPA. (2022). *Galileo High Accuracy Service Signal in Space interface Control Document.* Retrieved 2025, from https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_HAS_SIS_ICD_v1.0.pdf

EUSPA. (2024, Sep). *Galileo Open Service Navigation Message Authentication Interface Control Document.* Retrieved April 2025, from https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_OSNMA_IDD_ICD_v1.1.pdf

EUSPA. (2024, Dec). *Galileo Open Service Performance Report Dec 2024.* Retrieved April 2025, from https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo-OS-Quarterly-Performance_Report-Q4-2024.pdf

EUSPA. (2025). *Industry Sectors: Agriculture.* (EU) Retrieved from https://www.euspa.europa.eu/industry-sectors/agriculture

EUSPA. (n.d.). *Galileo Open Service, Service Definition Document.* Retrieved April 2025, from https://www.gsc-europa.eu/sites/default/files/Galileo_OS_SDD_V1.0_final.pdf

EutelSat OneWeb. (2021, June). *Written Evidence Submitted by OneWeb (SPA0008).* Retrieved April 2025, from https://committees.parliament.uk/writtenevidence/37124/pdf/

EutelSat OneWeb. (2025). *EutelSat OneWeb: Our network.* Retrieved 2025, from https://oneweb.net/our-network/experience-oneweb

Everitt, M., Bjergstrom, K., & Duffus, S. (2024). *Quantum Mechanics.* Chichester: Wiley.

EvoLogics. (2025). *USBL Positioning System.* Retrieved from EvoLogics: https://www.evologics.com/usbl

Exail. (2023). *MARINS Series Inertial Navigation Systems.* Retrieved from Exail: https://www.exail.com/media-file/7650/exail-datasheetmarins-series.pdf

Exail. (2025). *GAPS USBL Series.* Retrieved from Exail: https://www.exail.com/product-range/ultra-short-baseline-usbl-solutions

Exail. (n.d.). *Quantum Gravimeters.* Retrieved from Exail: https://www.exail.com/product/quantum-gravimeters

FAA. (2022, 3 29). *Instrument Procedures Handbook (IPH).* Retrieved from United States Department of Transport: https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/instrument_procedures_handbook

FAA. (2025, 2 20). *FAA Aeronautical Information Manual (AIM), Chapter 1-1-7.* Retrieved from Aeronautical Information Manual : https://www.faa.gov/Air_Traffic/publications/atpubs/aim_html/chap1_section_1.html# $paragraph1-1-7

FAA. (2025). *FAA AIM (Aeronautical Information Manual), 1-1-3.* Retrieved from Aeronautical Information Manual : https://www.faa.gov/Air_Traffic/publications/atpubs/aim_html/chap1_section_1.html# $paragraph1-1-2

FAA. (2025). *FAA AIM 1-1-9 – Instrument Landing System (ILS).* Retrieved from Aeronautical Information Manual: https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap1_section_1.html# $paragraph1-1-9

Faragher, R. &. (2015). Location Fingerprinting With Bluetooth Low Energy Beacons. *IEEE Journal on Selected Areas in Communications, 33*(11), 2418-2428.

Farragher, R. (2020). *The Pros Cons and Predictions for a OneWeb UK GNSS.* (Forbes) Retrieved April 2025, from https://www.forbes.com/sites/ramseyfaragher/2020/07/11/the-pros-cons-and-predictions-for-a-oneweb-uk-gnss/

FDA. (2018, 9 17). *Radio Frequency Identification (RFID).* Retrieved 4 28, 2025, from https://www.fda.gov/radiation-emitting-products/electromagnetic-compatibility-emc/radio-frequency-identification-rfid

Feasycom. (2024, 5 11). *What you need to know about UWB positioning technology with 10cm accuracy.* Retrieved from LinkedIn: https://www.linkedin.com/pulse/exploring-uwb-positioning-technology-principles-advantages-limitations-r9iac/

Federal Adviation Administration. (2025). *Navigation Aids.* Retrieved 4 17, 2025, from https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap1_section_1.html

Federal Aviation Administration. (2024, 3 18). *GBN - Distance Measuring Equipment (DME).* Retrieved 4 17, 2025, from https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gbng/lpdme

Federal Aviation Administration, Department of Transportation. (n.d.). *Appendix E to Part 43, Title 14.* Retrieved from https://www.ecfr.gov/current/title-14/appendix-Appendix%20E%20to%20Part%2043

Feiyu Mao, Y. L. (2024). Evaluation of timing and time transfer with PPP using Galileo High Accuracy Service. *Measurement, 226.* Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0263224124000368

FirstNet Authority. (2024). *September 3GPP Plenary: Release 19 track includes ISAC channel modeling study.* Retrieved from https://firstnet.gov/newsroom/blog/september-3gpp-plenary-6g-officially-begins-release-19-track

Fischer, J., & Courtois, J.-Y. (2018). *A holistic approach to trusted, resilient PNT: GNSS, STL, and eLoran.* Orolia.

Flechtner, F. R. (2021). Satellite gravimetry: a review of its realization. *Surveys in Geophysics*, 42(5), 1029-1074.

Fortescue, P., Swinerd, G., & Stark, J. (2011). *Spacecraft Systems Engineering 4th Ed.* Chichester: Wiley.

Fraunhofer Institute for Integrated Circuits IIS. (n.d.). *Galileo PRS Receivers.* (Fraunhofer Institute for Integrated Circuits IIS) Retrieved April 2025, from https://www.iis.fraunhofer.de/en/ff/lv/lok/gnss/galileoprs.html

Frontier SI. (2024). *State of the Market Report - Low Earth Orbit PNT.* Frontier SI.

Gallego, G., Delbrück, T., Orchard, G., Bartolozzi, C., Taba, B., Censi, A., & Scaramuzza, D. (2022). Event-Based Vision: A Survey. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 44*(1), 154-180.

Galleon. (2003). *Time synchronisation using atomic clocks.* Retrieved from Questions: https://www.galleon.eu.com/faq.html?utm_source=chatgpt.com

Galleon. (2025). *Choosing GPS or MSF as a timing reference for NTP servers.* Retrieved from https://www.galsys.co.uk/time-reference/gps-and-ntp/gps-or-msf-for-timing-reference.html?utm_source=chatgpt.com

Gallo, E. &. (2023). Long-Distance GNSS-Denied Visual Inertial Navigation for Autonomous Fixed-Wing Unmanned Air Vehicles: SO(3) Manifold Filter Based on Virtual Vision Sensor. Aerospace. *Aerospace, 10*(8), 708.

Garmin. (2017). LIDAR-Lite v3: Operation Manual and Technical Specifications. *Technical datasheet for 40m ranging sensor.* Garmin International.

Gellesch, M. J. (2020). Transportable optical atomic clocks for use in out-of-the-lab environments. *Advanced Optical Technologies, 9*(5), 313–325.

Gemsys. (2025). *GSM-19 Overhauser Magnetometer -- Specifications.* Retrieved from https://www.gemsys.ca/products/gsm-19-overhauser-magnetometer/

GEOExPro. (2022, July 19). *Gradiometry - The new standard.* Retrieved from GeoExPro: https://geoexpro.com/gradiometry-the-new-standard/

Ghanbarzade, A., & Soleimani, H. (2025). GNSS/GPS Spoofing and Jamming Identification Using Machine Learning and Deep Learning. *ARXIV.* Cornell University.

GLA. (2006). *The case for eLoran: Research and radionavigation General Lighthouse Authorities for the UK and Ireland.* Research and Radionavigation GLA.

GLA Research and Development. (2023). Spectrum access for Enhanced Long-Range Navigation. Essex.

Glennie, C., & Lichti, D. D. (2010). Static calibration and analysis of the Velodyne HDL-64E S2 for high accuracy mobile scanning. *Remote Sensing, 2*(6), 1610–1624.

Global Security.Org. (n.d.). *Space: GLONASS.* Retrieved 2025, from https://www.globalsecurity.org/space/world/russia/glonass.htm

Globalstar Inc. (2025). *Our Technology.* Retrieved from Globalstar: https://www.globalstar.com/en-gb/about/our-technology

GlobeAir. (2025). *VOR (VHF Omnidirectional Range).* Retrieved 04 17, 2025, from https://www.globeair.com/g/vor-vhf-omnidirectional-range

GMV. (n.d.). *Presence2 - PRS Receiver.* Retrieved April 2025, from https://www.gmv.com/en-pl/node/8136/printable/print

GNS Wireless. (2025). *What is 802.11az: Next Generation Positioning (NGP).* Retrieved 4 23, 2025, from https://www.gnswireless.com/blog/what-is-802-11az/

Gonzales-Garrido, A., Querol, J., & Chatzinotas, S. (2023). 5G Positioning Reference Signal Configuration for terrestrial/non-terrestrial network scenario. *IEEE.*

Government Office for Science. (2018). *Satellite Derived Position and Time: A Study of Critical Dependencies.* London: UK Government.

GPS World. (2018, 3 18). *PNT Roundup: Positioning integral to system design of 5G cellular networks.* (GPS World) Retrieved 4 22, 2025, from https://www.gpsworld.com/pnt-roundup-positioning-integral-to-system-design-of-5g-cellular-networks/

GPS World. (2020). *BeiDou a threat to the West, but perhaps not individuals.* (North Coast Media) Retrieved April 2025, from https://www.gpsworld.com/beidou-a-threat-to-the-west-but-perhaps-not-individuals/

GPS World. (2023, April). *Safran Provides GNSS Simulation for Xona Space Systems.* (North Coast Media) Retrieved April 2025, from https://www.gpsworld.com/safran-provides-gnss-simulation-solutions-for-xona-space-systems-leo-constellation/

GPS World. (2023). Tiny Clock Meets Big Challenges. *GPS World*, pp. https://www.gpsworld.com/tiny-clock-meets-big-challenges/.

Graham, L., Boddice, D., Palin, M., Zhang, Q., Breeze, J., & others. (2025). On the road with a diamond magnetometer: Opportunities for geomagnetic surveying with robust quantum sensors. *Diamond and Related Materials, 146*, 109502. doi:10.1016/j.diamond.2025.109502

Grant, A., & Goward, D. (2022, 4 11). *10 answers about eLoran.* (GPS World) Retrieved 4 25, 2025, from https://www.gpsworld.com/10-answers-about-eloran/

Greaves, M. (2018, 9 27). *OS Net - Preparations for Future GNSS.* (GIM International) Retrieved 4 28, 2025, from https://www.gim-international.com/content/article/os-net-preparations-for-future-gnss

Grewal, M., Andrews, A., & Bartone, C. (2013). *Global Navigation Satellite Systems, Inertial Navigation, and Integration* (3 ed.). John Wiley \& Sons.

Griffiths, H., Baker, C., Baubert, J., Kitchen, N., & Treagust, M. (1999). Television-Based Bistatic Radar. *IEE Proceedings - Radar, Sonar and Navigation, 146*(3), 155--161. doi:10.1049/ip-rsn:19990249

Groves, P. (2018). *Principles of GNSS, Inertial, and multisensor Integrated Navigation Systems.* London: Artech House.

Guangteng Fan, X. C. (2024). Toward Massive Satellite Signals of Opportunity Positioning: Challenges, Methods, and Experiments. *Space: Science & Technology, 4*, 191.

Guita, V. (2025). *Copper SPF Modules*. Retrieved from GitLab: https://gitlab.com/ohwr/project/white-rabbit/-/wikis/CopperSFP

Gutierrez, P. (2023, 9 11). *Brussels View: Bringing New A-PNT Opportunities to Life*. Retrieved from Inside GNSS: https://insidegnss.com/brussels-view-bringing-new-a-pnt-opportunities-to-life/

Gutierrez, P. (2025, 4 24). *ESA-backed VAUTAP Advances VDES R-Mode for maritime PNT*. Retrieved from Inside GNSS: https://insidegnss.com/esa-backed-vautap-advances-vdes-r-mode-for-maritime-pnt/?utm_source=chatgpt.com

Hager, P. K. (2025). Barometer-Driven Height Estimation for Indoor Positioning Including Elevator and Escalator Detection Mechanisms. *IEEE/ION Position, Location and Navigation Symposium (PLANS)* (pp. 1280-1288). IEEE.

Haimovich, A., Eldar, Y., & Bliss, D. (2008). {MIMO} Radar with Colocated Antennas. *IEEE Signal Processing Magazine, 25*(1), 116--129. doi:10.1109/MSP.2007.905288

Haji, M. H. (2024). *Holdover Atomic Clock Landscape Review. NPL Report TQE 32.* Teddington: National Physical Laboratory.

Han, J. Z. (2024). The effect of satellite code bias on GPS PPP time transfer. . *Journal of Spatial Science, 70*(1), 29-44.

Hansard, M., Lee, S., Choi, O., & Horaud, R. (2013). Time-of-flight cameras: principles, methods and applications. *Springer Briefs in Computer Science*, 95-102.

Harris, M. (2022, October). *Starlink signals can be reverse-engineered to work like GPS—whether SpaceX likes it or not.* (Technology Review) Retrieved April 2025, from https://www.technologyreview.com/2022/10/21/1062001/spacex-starlink-signals-reverse-engineered-gps/

Hasch, B., Topak, E., Schnabel, R., Zwick, T., Weigel, R., & Waldschmidt, C. (2012). Millimeter-Wave Technology for Automotive Radar Sensors in the 77 GHz Band. *IEEE Transactions on Microwave Theory and Techniques, 60*(3), 845--860. doi:10.1109/TMTT.2011.2178427

Hasler Rail. (2025). *Speed sensing and Odometry*. Retrieved from Hasler Rail: https://www.haslerrail.com/products-solutions/obe/speed-sensing-and-odometry/

He, J. N. (2025). Survey on positioning technology based on signal of opportunity from low earth orbit. *Frontiers in Physics, 13.*

Heliwg, A., Offermans, G., Stout, C., & Schue, C. (2011). eLoran System Definition and Signal. UrsaNav: International Loran Association .

Hendricks, J. (2018). Quantum for pressure. *Nature Physics*, 100.

Hesai, B. (2021, Jan). *A Sense of Responsibility: Lidar Sensor Makers Build on NVIDIA DRIVE.* Retrieved May 2025, from NVIDIA Blogs: https://blogs.nvidia.com/blog/lidar-sensor-nvidia-drive/

Hexagon. (2013). *Understanding-the-difference-between-anti-spoofing-and-anti-jamming.* Retrieved from Novatel : https://novatel.com/tech-talk/velocity-magazine/velocity-2013/understanding-the-difference-between-anti-spoofing-and-anti-jamming

Hexagon and Leica Geosystems. (2025). *HxGN SmartNet - Satellite Positioning Service.* Retrieved from https://leica-geosystems.com/en-gb/services-and-support/hxgn-smartnet-satellite-positioning-service

HM Government. (2023). *UK National Risk Register.* London: UK Government.

Hoffman-Wellenhof, B. L. (2001). *GPS Theory and Practice.* New York: Springer.

Homeland Security. (2024, 1 8). *Radio Frequency Identification (RFID): What is it?* Retrieved 4 28, 2025, from https://www.dhs.gov/archive/radio-frequency-identification-rfid-what-it

Honcharenko, W. (2019). Sub-6 GHz mMIMO Base stations meet 5G's size and weight challenges. *Microwave Journal* .

Honeywell. (2014). *Honeywell Precision Barometer HPB.* Honeywell.

Honeywell. (2023). *HG9900 Inertial Navigation System.* Retrieved from Honeywell Aerospace: https://aerospace.honeywell.com/us/en/products-and-services/products/navigation-and-sensors/inertial-measurement-units/hg9900-inertial-measurement-unit

Honeywell. (2025). *Honeywell Radar Velocity System.* Retrieved from Honeywell: https://aerospace.honeywell.com/us/en/products-and-services/products/navigation-and-sensors/navigation-systems/honeywell-radar-velocity-system

Hou, F. Q. (2019). *Physical Review A, 100,* 023849.

Huang, Z., Ye, G., Yang, P., & Yu, W. (2025). Application of multi-sensor fusion localization algorithm based on recurrent neural networks. *Scientific Reports, 15.*

Hunter, J., Porter, M., & Williams, B. (2020, Feb). owards a theoretical framework for situational awareness in paramedicine. *Safety Science, 122.*

ICAO. (2003). ICAO study into the spectral requirements for MLS. *Regional Prepatory group meeting for world radio communication conference 2003.*

ICAO. (2004). *Manual on the simultaneous operations of parallel or near-parallel instrument runways (SOIR). First Edition.* ICAO.

ICAO. (2009). *Aeronautical communications panel (ACP): Progress on MLS at Heathrow.* Montreal: ICAO.

ICAO. (2018). *Manual on Testing of Radio Navigation Aids - Volume I - Testing of Ground-based Radio Navigation Systems (Doc 8071-Vol 1).*

ICAO. (2021). *Handbook on radio frequency spectrum requirements for civil aviation - Doc 9718, Volume I.*

ICAO. (2023). Aeronautical Telecommunications. Annex 10, Volume 1. Radio Navigation Aids. 7th edition. .

IEC. (2002). *IEC 60945:2002: Maritime navigation and radiocommunication equipment and systems – General requirements – Methods of testing and required test results.* International Electrotechnical Commission (IEC). Retrieved from https://webstore.iec.ch/en/publication/3959

IEC. (2024). *IEC 61162-450: Maritime navigation and radiocommunication equipment and systems – Digital interfaces – Part 450: Multiple talkers and multiple listeners – Ethernet interconnection.* International Electrotechnical Commission (IEC). Retrieved from https://webstore.iec.ch/publication/69032

IEEE. (2017). *IEEE C37.328 PTP Power Profile.* Retrieved from IEEE: https://standards.ieee.org/ieee/C37.238/6650/

IEEE. (2019). *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems (IEEE Std 1588-2019).* IEEE.

IEEE. (2019). *IEEE Std 1588-2019: IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems.* IEEE. doi:10.1109/IEEESTD.2020.9120376

IEEE. (2020). IEEE 802.15.4z-2020 Standard. *Low Rate Wireless Networks: Enhanced Ultra Wideband (UWB) Physical Layers.*

IEEE. (2020). *IEEE 802.1AS-2020 Standard for Local and Metropolitan Area Networks--Timing and Synchronization for Time-Sensitive Applications* . Retrieved from IEEE: https://standards.ieee.org/ieee/802.1AS/7121/

IEEE. (2020). *IEEE Std 802.1AS-2020: Timing and Synchronization for Time-Sensitive Applications.* IEEE. doi:10.1109/IEEESTD.2020.9129087

IEEE. (2023). IEEE Standard for Information Technology–Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks–Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amend. *IEEE Std 802.11az-2022* .

(2025). *IEEE.* IEEE 802.11 Working Group. Retrieved from https://www.ieee802.org/11/Reports/tgbf_update.htm

IEEE Standards Association. (2023). *Newly Released IEEE 802.11az Standard Improving Wi-Fi Location Accuracy is Set to Unleash a New Wave of Innovation.* (IEEE SA) Retrieved 4 23, 2025, from https://standards.ieee.org/beyond-standards/newly-released-ieee-802-11az-standard-improving-wi-fi-location-accuracy-is-set-to-unleash-a-new-wave-of-innovation/

IGRF-14. (2024). *International Geomagnetic Reference Field (IGRF-14).* Retrieved from https://www.ncei.noaa.gov/products/international-geomagnetic-reference-field

iMAR Navigation & Control. (n.d.). *iCORUS.* Retrieved from iMAR Navigation & Control: https://www.imar-navigation.de/en/products/by-product-names/category/icorus-inat-airborne-gravimetry

IMO. (2004). *Resolution MSC.192(79): Revised Performance Standards for Radar Equipment.* International Maritime Organization (IMO). Retrieved from https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.192(79).pdf

Infineon. (2020). *DPS310 Digital XENSIVTM Barometric Pressure Sensor for Portable Devices.* Retrieved from https://www.infineon.com/dgdl/Infineon-DPS310-DataSheet-v01_02-EN.pdf?fileId=5546d462576f34750157750826c42242

Infleqtion. (2025). *Tiqker.* Retrieved from Infleqtion: https://infleqtion.com/tiqker/

Infleqtion. (n.d.). *Quantum Sensing: Precision for National Security and Critical Infrastructure.* Retrieved from Infleqtion: https://infleqtion.com/quantum-sensing/

Inside GNSS. (2024, 8 8). *Protecting the Skies: GNSS-Less Aircraft Navigation with Cellular Signals of Opportunity.* Retrieved from Inside GNSS: https://insidegnss.com/protecting-the-skies-gnss-less-aircraft-navigation-with-cellular-signals-of-opportunity/

Inside GNSS. (2025, 2 27). *NextNav Successfully Demonstrates Positioning Reference Signal-Based PNT Technology.* Retrieved from Inside GNSS: https://insidegnss.com/nextnav-successfully-demonstrates-positioning-reference-signal-based-pnt-technology/?utm_source=chatgpt.com

InsideGNSS. (2019). *Iridium Next LEO Satellites as an Alternative PNT in GNSS Denied Environments.* (GNSS Media and Research) Retrieved April 2025, from https://insidegnss.com/iridium-next-leo-satellites-as-an-alternative-pnt-in-gnss-denied-environments-part-1/

InsideGNSS. (2020, August). *Now Operational, BeiDou Could Conceal Cybersecurity Threat.* (GNSS Research and Media LLC) Retrieved April 2025, from https://insidegnss.com/now-operational-beidou-could-conceal-cybersecurity-threat/

InsideGNSS. (2024, Aug). *Protecting the Skies: GNSS-Less Aircraft Navigation with Cellular Signals of Opportunity.* Retrieved May 2025, from InsideGNSS.com: https://insidegnss.com/protecting-the-skies-gnss-less-aircraft-navigation-with-cellular-signals-of-opportunity/#:~:text=The%20flights%20spanned%20different%20altitudes,-main%20conclusions%20from%20SNIFFER%20are:&text=Cellular%20signals%20are%20surprisingly

Institute for Communications and Navigation. (2018). Research on A-PNT in Europe. *iCNS Conference.* Redondo Beach.

International Civil Aviation Authority. (2023). Annex 10 - Aeronautical Telecommunications. *Annex 10 - Aeronautical Telecommuncations Volumes 1 - 6.* ICAO.

International Defence Security and Technology. (2023, March). *China's Beidou Navigation Satellite System (BDS) provides global coverage with millimeter level accuracy.* Retrieved April 2025, from https://idstch.com/space/chinas-beidou-navigation-satellite-system-bds-provides-global-coverage-with-millimeter-level-accuracy/

Interreg. (2021). *R-Mode Baltic.* Retrieved 4 23, 2025, from https://interreg-baltic.eu/project/r-mode-baltic/#:~:text=R%2DMode%20Baltic%20testbed,wide%20accepted%20terrestrial%20navigation%20system.

Iridium. (2024, December). *Iridium STL Factsheet.* (Iridium) Retrieved April 2025, from https://www.iridium.com/resources/resource-download/?resource-id=403955

Iridium. (2024). *Reliable and Secure PNT.* (Iridium) Retrieved April 2025, from https://satelles.com/technology/reliable-and-secure-pnt-stl/

ISO. (2018). *ISO 26262:2018: Road vehicles – Functional safety.* International Organization for Standardization (ISO). Retrieved from https://www.iso.org/standard/68383.html

ITU-R. (2005). *Recommendation ITU-R P.838-3: Specific attenuation model for rain for use in prediction methods.* ITU-R. Retrieved from https://www.itu.int/rec/R-REC-P.838-3-200503-I/en

ITU-R. (2019). *Recommendation ITU-R P.676-12: Attenuation by atmospheric gases and related effects.* ITU-R. Retrieved from https://www.itu.int/rec/R-REC-P.676-12-201908-I/en

ITU-R. (2019). *Recommendation ITU-R P.840-9: Attenuation due to clouds and fog.* ITU-R. Retrieved from https://www.itu.int/rec/R-REC-P.840-9-201908-I/en

ITU-T. (2014). *Precision time protocol telecom profile for phase/time synchronization with full timing support from the network (ITU-T G.8275.1). .* International Telecommunication Union .

Jada, S. P. (2021). Evaluation of PNT situational awareness algorithms and methods. *Proceedings of the 34th International Technical Meeting of the Satellite Division of ION.*

Jada, S., Psiaki, M., Landerkin, S., Langel, S., Scholz, A., & Joerger, M. (2021). Evaluation of PNT situational awareness algorithms and methods. *Proceedings of the 34th International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS+* (pp. 816-833). Institute of Navigation.

Jaduszliwer, B. C. (2021). Past, present and future of atomic clocks for GNSS. *GPS Solutions, 25*(27).

Jalal, F. &. (2021). Underwater Navigation, Localization and Path Planning for Autonomous Vehicles: A Review. *International Bhurban Conference on Applied Sciences and Technology (IBCAST).*

Jarraya, I., Al-Batati, A., Bilal Kadri, M., Abdelkader, M., Ammar, A., Boulila, W., & Koubaa, A. (2025). GNSS-Denied UAV Navigation: Sensor Fusion & Complexity. *Satellite Navigation, 6*(9).

Jiang, Y. R. (2024). Low-Cost Underwater Swarm Acoustic Localization: A Review,. *IEEE Access, 12.*

Jiménez-López, M. T.-G.-R.-Á. (2019). A Fully Programmable White-Rabbit Node for the SKA Telescope PPS Distribution System. *IEEE Transactions on Instrumentation and Measurement, 68*(2).

Johnson, A. (2022). Terrain-relative navigation on Mars 2020 Perseverance rover. *Science Robotics, 7*(64).

Jones, M. (2018, 2 22). *Signals of opportunity - Holy grail or a waste of time?* Retrieved from GPS World: https://www.gpsworld.com/signals-of-opportunity-holy-grail-or-a-waste-of-time/

Joseph P Kennedy, J. C. (2022). US Patent US-11280911-B2. Retrieved from US PTO: https://ppubs.uspto.gov/api/pdf/downloadPdf/11280911?requestToken=eyJzdWIiOiI5NTZiNTMwNi0xMWYwLTQyNTUtYjBiYS02ZDU1ZWVhYWEwOGQiLCJ2ZXIiOiI2NjAxY2VhMS04MjU2LTQ3N2ItOWY5MC0xOTEzYWY5YjgxNDMiLCJleHAiOjB9

Justia. (2019). *Justia Patent Search.* Retrieved from Justia: https://patents.justia.com/patent/11280911

Kaplan, E., & Hegaty, C. (2017). *Understanding GPS/GNSS: Principles and Applications, 3rd ed.* Boston: Artech House.

Karutin, S. (n.d.). *GLONASS: The decade of transition to CDMA signals .* (North Coast media) Retrieved March 03, 2025, from https://www.gpsworld.com/glonass-the-decade-of-transition-to-cdma-signals

Katz, P. (2016). *Blocked Pitot Tubes.* Retrieved from Plane and Pilot: https://www.planeandpilotmag.com/article/blocked-pitot-tubes/

Keep Longwave. (2024, 3 26). *Longwave closure may be postponed until at least 2025.* Retrieved 4 25, 2025, from https://keeplongwave.co.uk/2024/03/26/longwave-closure-may-be-postponed-until-at-least-2025/

Keselman, L. W.-J. (2017). Intel RealSense Stereoscopic Depth Cameras. *IEEE Conference on Computer Vision and Pattern Recognition Workshops (CVPRW),* (pp. 1267-1276).

Khalil, J. (2024, Feb). *Geely Expands Satellite Network for Autonomous Vehicles.* (North Coast Media) Retrieved April 2025, from https://www.gpsworld.com/geely-expands-satellite-network-for-autonomous-vehicles/

Kinsey, J. C. (2006). A Survey of Underwater Vehicle Navigation: Recent Advances and New Challenges. *IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC).* Lisbon.

Kiong, T., Salem, S., Paw, J., Sankar, & Darzi. (2014). Minimum variance distortionless response beamformer with enhanced nulling level control via dynamic mutated artificial immune system. *Scientific World Journal,* 164053.

Kloss, C., Finlay, C., Olsen, N., T{\o}ffner-Clausen, L., Gillet, N., & Grayver, A. (2025). *CHAOS-8: Time-dependent near-Earth geomagnetic field (1999--2025).* doi:10.5281/zenodo.15806240

Kongsberg Maritime. (2025). *Acoustic Positioning Systems*. Retrieved from Longsberg Maritime: https://www.kongsberg.com/discovery/navigation-positioning/hipap/

Korolov. (2020). *GLONASS Open Service Performance Standard Ed 2.2.*

Lachapelle, G. (2018). *Advanced GNSS Theory and Applications.* Artech house.

Lam, C. S. (2008). A Review of the Recent Development of MEMS and Crystal Oscillators. *IEEE International Ultrasonics Symposium Proceedings*, (pp. 694–704.).

Lamas-Linares, A. &. (2018). Secure quantum clock synchronization. *Advances in Photonics of Quantum Computing, Memory, and Communication XI*, Vol. 10547, pp. 59-66.

Landing Systems. (2025). *Microwave Landing System*. Retrieved 04 22, 2025, from https://landingsystem.com/mls/

Laverty, J. (1999). Retrieved from Time and Frequency Dissemination in the UK: https://eprintspublications.npl.co.uk/1894/1/bemc99-16.pdf

Lazaro, F., Raulefs, R., Bartz, H., & Jerkovits, T. (2021). VDES R-Mode: Vilnerability analysis and mitigation concepts. *International Journal of Satellite Communications and Networking*, 178-194.

Ledergerber, A. &. (2018). Ultra-Wideband Range Measurement Model with Gaussian Processes. *IEEE Robotics and Automation Letters, 3*(4), 3167-3174.

Lee, T.-N., & Canciani, A. (2020). Aerial Simultaneous Localisation and Mapping Using Earth's Magnetic Anomaly. *NAVIGATION, 67*(1), 95--116. doi:10.1002/navi.352

Lefevre, H. C. (2014). *The Fiber-Optic Gyroscope.* Boston: Artech House.

Lei, W., Lei, C., Baiyu, L., Zhe, L., Zongnan, L., & Zukun, L. (2024). Development status and challenges of anti-spoofing technology of GNSS/INS integrated navigation. *Frontiers in Physics, 12.*

Leonardo. (2021, January). *Galileo PRS - The diamond in the crown.* Retrieved April 2025, from https://www.leonardo.com/en/news-and-stories-detail/-/detail/prs-galileo-the-diamond-in-the-crown-1

Leonardo. (2023). *Electro-Optical Systems.* Retrieved from https://uk.leonardo.com/en/electronics/electro-optical-systems

LeonardoDRS. (2025). *Assured PNT*. Retrieved from Assured PNT: https://www.leonardodrs.com/what-we-do/products-and-services/a-pnt/

Li, J., Zhu, X., Ouyang, M., Li, W., & Fu, Z. C. (2021). GNSS Spoofing Jamming Detection Based on Generative Adversarial Network," in IEEE Sensors Journal. *IEEE Sensors, 21*(20), 22823-22832.

Li, Y. H. (2020). Research on the eLoran Differential Timing Method. *Sensors, 20*(22), 6518.

Liebe, C. C. (2016). Star trackers for spacecraft navigation. *Journal of Guidance, Control and Dynamics, 39*(11), 2582–2592.

Lin, C. E. (2008). Electronic barometric altimeter in real time correction. *IEEE/AIAA 27th Digital Avionics Systems Conference* (pp. 6-A). IEEE.

LinkQuest Inc. (2025). *LinkQuest.* Retrieved from https://www.link-quest.com

Lipinski, M. &. (2011). White rabbit: a PTP application for robust sub-nanosecond synchronization. *2011 International IEEE Symposium on Precision Clock Synchronization for Measurement Control and Communication (ISPCS)* (pp. 25-30). IEEE.

Liu, F., Cui, Y., Masouros, C., Xu, J., Han, T., Eldar, Y., & Buzzi, S. (2022). Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond. *IEEE Journal on Selected Areas in Communications, 40*(6), 1728--1767. doi:10.1109/JSAC.2022.3156632

Lo, S. J. (2009). Defining Primary, Secondary and Additional Secondary Factors for RTCM Minimum Performance Specifications. *38th Annual Technical Symposium of the International Loran Association (ILA38).* Portland, ME.

Locata. (2022). *Locata technology demonstration for the european commission: technical report v1.5.* Locata.

Locata. (2025). *About Locata*. Retrieved 4 24, 2025, from https://www.locata.com/aboutlocata

Locata. (2025). *New EU report validates Locata's new 'Alternative to GPS' Technology.* (Locata) Retrieved 4 24, 2025, from https://www.locata.com/

Lockheed Martin Corporation. (2013). *Lockheed Martin Gravity Systems.* Retrieved from Lockheed Martin Gravity Systems: https://www.lockheedmartin.com/content/dam/lockheed-martin/rms/documents/gravity-gradiometry/LM-Gravity-Systems-brochure.pdf

Lombardi, M. A. (2002). Fundamentals of time and frequency. In *Handbook of measurement in science and engineering* (pp. 1-28). NIST.

Lopez, G., & Simsky, M. (2021, March). *What is GNSS Spoofing?* Retrieved May 2025, from GIM International: https://www.gim-international.com/content/article/what-is-gnss-spoofing

Luccio, M. (2020, 7 23). *GPS World*. Retrieved from New Players offering GNSS correction services: https://www.gpsworld.com/new-players-offering-gnss-correction-services/

Luccio, M. (2021, 11 3). *eLoran: Part of the solution to GNSS vulnerability*. Retrieved from Inside GNSS: https://www.gpsworld.com/eloran-part-of-the-solution-to-gnss-vulnerability/?utm_source=chatgpt.com

Luccio, M. (2023, 7 5). *PNT by other means: Locata*. (GPS World) Retrieved 4 24, 2025, from https://www.gpsworld.com/pnt-by-other-means-locata/#:~:text=One%20of%20the%20few%20things,to%20navigate%20on%20transoceanic%20flights.

Luminar Technologies. (2023). Luminar Iris LiDAR Specifications. *Luminar Product Sheet.*

Macario Barros, A., Michel, M., Moline, Y., Corre, G., & Carrel, F. (2022). A Comprehensive Survey of Visual SLAM Algorithms. *Robotics, 11*(1), 24.

Mai, C. P. (2018). Vision-based localisation for underwater inspection and navigation. *IEEE Journal of Oceanic Engineering, 43*(4), 944-957.

Maimone, M. C. (2007). Two years of visual odometry on the Mars Exploration Rovers. *Journal of Field Robotics, 24*(3), 169-186.

Makokha, R. (2021). *The Future of Radio Advertising: Opportunities and Challenges for Brands*. Retrieved May 2025, from Bunny Studio: https://bunnystudio.com/blog/the-future-of-radio-advertising-opportunities-and-challenges-for-brands/

Maksymiuk, R., Kania, D., Samczynski, P., Malanowski, M., Kitlinski, P., & others. (2024). 5G-based passive radar on a moving platform---Detection and classification. *IET Radar, Sonar \& Navigation, 18*(12), 2414--2426. doi:10.1049/rsn2.13113

Malhotra, A. C. (2016). Attacking the Network Time Protocol. *Proceedings of the 23rd USENIX Security Symposium*, (pp. 971–986).

Maloney, D. (2020, Feb). *How does Starlink Work Anyway?* (Hackaday) Retrieved April 2025, from https://hackaday.com/2020/02/20/how-does-starlink-work-anyway/

Marquand, Y. L. (2024, Aug). *Signals of Opportunity could provide alternative to GPS*. Retrieved May 2025, from https://www.revolution.aero/deep_dive/signals-of-opportunity-could-provide-alternative-to-gps/

Martinez, G. D. (2023). A chip-scale atomic beam clock. *Nature Communications, 14*, 3501.

Mb 21. (2023, 2 15). *The transmission gallery: Droitwich*. Retrieved 4 25, 2025, from https://tx.mb21.co.uk/gallery/gallerypage.php?txid=1454&pageid=2072

Melo, J. M. (2017). Survey on Advances on Terrain-Based Navigation for AUVs. *Ocean Engineering, 139*, 250-264.

Meyer, B., Saltus, R., & Chulliat, A. (2017). Derivation and Error Analysis of the Earth Magnetic Anomaly Grid at 2-arc-minute Resolution (EMAG2v3). *Geochemistry, Geophysics, Geosystems, 18*, 4522--4537. doi:10.1002/2017GC007280

Meyer, D. a. (2014). Nuclear magnetic resonance gyro for inertial navigation. *Gyroscopy and Navigation, 5*(2), 75-82.

Microchip. (2020, 7 23). Location! Location! Location! An examination of ultra precise positioning. A 5G PNT Implementation for smart cities.

Microchip. (2025). *XPRO Rhubudium Oscillator*. Retrieved from Microchip: https://www.microchip.com/en-us/product/xpro

Microchip Technology Inc. (2023). *Microchip launches next-generation of low-noise chip-scale atomic clock*. Retrieved from Microchip Press Release: https://www.microchip.com/en-us/about/news-releases/products/microchip-launches-next-generation-of-low-noise-chip-scale-atomic-clock

Micro-g LaCoste. (n.d.). Retrieved from https://microglacoste.com/

Miller, B., Miller, A., Popov, k., & Stepanyan, K. (2019). UAV Landing Based on the Optical Flow Videonavigation. *Sensors (Basel), 18*(19), 1351.

Miller, N. S., Koza, J. T., Morgan, S. C., Martin, S. M., Neish, A., & Grayson, R. (2023). SNAP: A Xona Space Systems and GPS Software-Defined Receiver. *IEEE/ION Position, Location and Navigation Symposium (PLANS)*. Monterey, CA.

Mills, D. (1995). Improved algorithms for synchronizing computer network clocks. *IEEE/ACM Transactions on Networking, 3*(3), 245-254.

Mills, D. L. (2010). *Network Time Protocol Version 4: Protocol and algorithms specification (RFC 5905)*. Internet Engineering Task Force.

Misra, P., & Enge, P. (2004). *Global Positioning System Signals, Measurement and Performance*. Ganga-Jamuna Press.

Mohammad Neinavaie, J. K. (2021). Exploiting Starlink Signals for Navigation: First results. *Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021)*. St Louis.

Montillete, J.-P. (2008). Precise Positioning in Urban Canyons: Applied to the Localisation of Buried Assets. UK: University of Nottingham.

Moreira, P. &. (2009). White rabbit: Sub-nanosecond timing distribution over ethernet. *International Symposium on Precision Clock Synchronization for Measurement, Control and Communication, 2009. ISPCS 2009.* , (pp. 1-5).

Mourikis, A. I. (2007). A Multi-State Constraint Kalman Filter for Vision-aided Inertial Navigation. *Proceedings of ICRA*.

Mrozowski, M., Lupinski, T., Karwat, P., Gruszecki, P., Grygorcewicz, G., Damski, A., . . . others. (2024). A Distributed Network of Optically Pumped Magnetometers for Magnetic Navigation in Marine, Air and Land Environments. *Scientific Reports, 14*(1), 16207. doi:10.1038/s41598-024-76739-0

Munguia R, T. J. (2021). A Hybrid Visual-Based SLAM Architecture: Local Filter-Based SLAM with KeyFrame-Based Global Mapping. *Sensors (Basel), 29*(22), 210.

Munir, A., Aved, A., & Blasch, E. (2022). Situational Awareness: Techniques, Challenges, and Prospects. *AI, 3*, 55-77.

Mur-Artal, R., Montiel, J., & Tardon, J. (2015). ORB-SLAM: A versatile and accuracte monocular SLAM system. *IEEE Transactions on Robotics, 31*(5), 1147-1163.

Mur-Atal, R., & Tardos, J. (2017). ORB-SLAM2: An open Source SLAM system for Monocular, Stereo and RGB-D Cameras. *IEEE Transactions on Robotics, 33*(5), 1255-1262.

Nabil Jardak, R. A. (2023). Practical Use of Starlink Downlink Tones for Positioning. *Sensors (Basel), 23*(6).

NASA Goddard Spaceflight Center. (2020). *Art of the Leverage*. Retrieved from Cutting Edge: https://issuu.com/nasagsfc/docs/fall_2020_final_web_version/s/11672594

NASA Marine. (2025). *Electromagnetic Log 2*. Retrieved from NASA Marine: https://www.nasamarine.com/product/electromagnetic-log/

National Oceanic and Atmospheric Administration. (2025). *What is Lidar*. Retrieved from National Ocean Service: https://oceanservice.noaa.gov/facts/lidar.html

NAVAC. (2024). *PNT Vision 2035 - White Paper.*

Navigraph. (2024). *VOR Navigation*. Retrieved 04 17, 2025, from Navigraph: https://navigraph.com/blog/vor-navigation

Navrátil, V., Karásek, R., & Vejražka, F. (2016). Position estimate using radio signals from terrestrial sources. *2016 IEEE/ION Position, Location and Navigation Symposium - PLANS 2016*. Institute of Navigation.

Navstar GPS Joint Program Office. (2020). *GPS Space Segment*. (U.S. Air Force) Retrieved 2025, from https://www.gps.gov/systems/gps/space/

Navtech Radar. (2025). *CTS/HP series FMCW scanning radars*. Retrieved from https://navtechradar.com/

NavVis. (2025). *NavVis VLX's SLAM*. Retrieved from NavVis: https://vlx2.docs.navvis.com/further-information/navvis-vlxs-slam/#:~:text=The%20mobile%20mapping%20system%20measures,it%27s%20important%20to%20close%20loops

NetNod. (2020). *NTS Whitepaper*. Retrieved from Netnod.se: https://www.netnod.se/sites/default/files/2021-01/Netnod_NTS_Whitepaper_2020.pdf

Network Lessons. (2025). *An Introduction to PTP*. Retrieved from Newtowrk Lessons: https://networklessons.com/ip-services/introduction-to-precision-time-protocol-ptp

New Space Economy. (n.d.). *Global Navigation Satellite Systems (GNSS): A Comparative Overview of Satellite Constellations*. (New Space Economy) Retrieved 2025, from https://newspaceeconomy.ca/2024/09/09/global-navigation-satellite-systems-gnss-a-comparative-overview-of-satellite-constellations/#google_vignette

NextNav. (2024, 4 16). Enabling next-generation terrestrial positioning, navigation, and timing and 5G: A plan for the lower 900 MHZ band (902-928 MHz).

Nextnav. (2025). *Accurate, floor-level vertical location*. (Nextnav) Retrieved 4 24, 2025, from https://nextnav.com/pinnacle/

Nextnav. (2025). *Accurate, Secure, Resilient 3D PNT Solutions*. (Nextnav) Retrieved 4 24, 2025, from https://nextnav.com/terrapoint/

NextNav. (2025). Next generation gps. next nav.

Nextnav. (2025). *Pinnacle coverage map*. Retrieved 4 24, 2025, from https://nextnav.com/pinnacle-coverage-map/

NextNav. (2025). *Terrestrial 3D PNT*. Retrieved 4 24, 2025, from https://nextnav.com/

Niyonsaba, J., & Vivek, S. (2019). Comparative Study of ILS and MLS Systems and. *International Journal of Scientific Research & Engineering Trends, 5*(6), 2240-2250.

NLA International. (2025). *Project SPARK: SPACE BASED AUGMENTATION SYSTEMS REPORT*. NLAI.

NLAI. (2020). *Maritime Resilience and integrity of Navigation (MarRINav)*. NLA International.

NOAA. (2025). *Planetary K-index (Kp)*. Retrieved from https://www.swpc.noaa.gov/products/planetary-k-index

Nolan, R. E. (2014). *Aviation Radio Navigation* . Dordrecht: Springer.

Northrop Grumman. (2025). *LN-200 Inertial Measurement Unit*. Retrieved from Northrop Grumman: https://www.northropgrumman.com/what-we-do/ln-200s-inertial-measurement-unit

Novatel. (2025). *PPP Corrections: Novetel Correct*. (Hexagon) Retrieved April 2025, from https://www.navtechgps.com/novatel_correct_with_ppp/

NPL. (2025). *Time and Frequency: MSF radio time signal*. Retrieved 4 23, 2025, from https://www.npl.co.uk/msf-signal

NXP Semiconductors. (2025). *TEF810x/TEF82xx automotive radar transceiver family*. Retrieved from https://www.nxp.com/

Obleukhov, O. B. (2022). *PTP at Meta*. Retrieved from Engineering.fb.com: https://engineering.fb.com/2022/11/21/production-engineering/precision-time-protocol-at-meta/

O'Connor, M. (2025, March/April). IRIDIUM STL: PROTECTING PNT AS PART OF A LAYERED APPROACH. *GPS World*, pp. 32-36.

Ofcom. (2005). *Ultra wideband*. Ofcom.

Ofcom. (2024, 1 5). *eLoran (Enhanced Long Range Navigation)*. Retrieved 4 25, 2025, from https://www.ofcom.org.uk/spectrum/radio-equipment/enhanced-long-range-navigation

Ogunsina, M. &. (2024). Advanced Sensor Fusion and Localization Techniques for Autonomous Systems: A Review and New Approaches. *International Journal of Frontline Research in Science and Technology, 2*(1), 51-60.

OpenLR. (2025). *What is OpenLR*. Retrieved from OpenLR: https://www.openlr.org/location-referencing/

Ordnance Survey. (2021, 7 8). *An introduction to OS Net*. Retrieved 4 28, 2025, from https://www.ordnancesurvey.co.uk/insights/os-net-case-study

Ordnance Survey. (2025). *OS Net: Frequenty Asked Questions*. Retrieved from Ordnance Survey: https://www.ordnancesurvey.co.uk/geodesy-positioning/os-net/faq

Ostroumov, I. K. (2022). Estimation of Geodetic Altitude from Barometric One with Actual Meteorological Aerodrome Report Data. *12th International Conference on Advanced Computer Information Technologies (ACIT)* (pp. 375-378). IEEE.

Otero, P. H.-R.-N.-Á. (2023). Underwater Positioning System Based on Drifting Buoys and Acoustic Modems. *Journal of Marine Science and Engineering, 11*(4), 682.

Ouyang, G., Zeng, W., Xie, Z., Wang, Z., Li, X., Pan, Y., . . . Sun, X. (2023). Magnetic-Field-Based Indoor Positioning Using Temporal Convolutional Networks. *Sensors, 23*(3), 1514. doi:10.3390/s23031514

Oxbotica. (2023). *Oxbotica.* Retrieved from https://www.oxbotica.com/

Parkinson, B., & Spilker, J. (1996). *Global Positioning System: Theory and Applications, vol. 1.* Washington DC: AIAA.

Parsons. (2025). *Assured Positioning System (APS)*. Retrieved from Parsons Corporation: https://www.parsons.com/products/aps/

Parsons. (2025). *Space and geospatial.* Retrieved May 2025, from Parsons: https://www.parsons.com/space/

Parsons Corporation. (2025). *Parsons Acquisitions*. Retrieved from Parsons Corporation: https://www.parsons.com/acquisitions/

Patole, S., Torlak, M., Wang, D., & Ali, M. (2017). Automotive Radars: A Review of Signal Processing Techniques. *IEEE Signal Processing Magazine, 34*(2), 22--35. doi:10.1109/MSP.2016.2628914

Pau, G. &. (2021). Ultra-Wideband (UWB) for Indoor Positioning: A Review. *IEEE Sensors Journal, 21*(14), 15423-15436.

Pau, G., Arena, F., Engida Gebremariam, Y., & You, I. (2021). Bluetooth 5.1: An Analysis of Direction Finding Capability for High-precision location services. *Sensors.*

Paull, L. S. (2014). AUV Navigation and Localization: A Review. *IEEE Journal of Oceanic Engineering, 39*(1), 131-149.

Pavan, G., & Galati, G. (2024). Range Limitations in Microwave Quantum Radar. *Remote Sensing, 16*(14), 2543. doi:10.3390/rs16142543

Piester, D. &. (2011). Time and frequency broadcast with DCF77. *43rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting.* Long Beach, CA.

PNI Sensor. (2025). *RM3100 Magnetometer -- Datasheet/User Guide.* Retrieved from https://www.pnicorp.com/product/rm3100/

Pratt, T. B. (2002). *Satellite Communications, 2nd ed.* Hoboken, NJ, USA: Wiley.

Precise Point Positioning and Its Challenges, Aided-GNSS and Signal Tracking. (2007). (GNSS Research and Media) Retrieved April 2025, from https://insidegnss.com/precise-point-positioning-and-its-challenges-aided-gnss-and-signal-tracking/

Premium Positioning. (2025). *Premium Positioning.* Retrieved from Premium Positioning: https://www.premium-positioning.com/en/

Proctor, A. G. (2025). PhD Thesis: A structured method to acheive resilience and assurance in PNT systems. Unpublished.

Psiaki, M. &. (2016). Attackers can spoof navigation signals without our knowledge. Here's how to fight back GPS lies. *IEEE Spectrum, 53*, 26-53.

PTB - National Metrology Institute. (2025). *DCF77.* Retrieved 4 23, 2025, from https://www.ptb.de/cms/en/ptb/fachabteilungen/abt4/fb-44/ag-442/dissemination-of-legal-time/dcf77.html

Q-CTRL. (2025, 05). *Q-CTRL overcomes GPS denial with quantum sensing; achieves quantum advantage.* Retrieved from https://q-ctrl.com/blog/q-ctrl-overcomes-gps-denial-with-quantum-sensing-achieves-quantum-advantage

Q-CTRL. (n.d.). *Quantum Sensing.* Retrieved from Q-CTRL: https://q-ctrl.com/our-work/quantum-sensing

Qian-ran Hu, X.-y. S.-m.-y.-q. (2023). The personal protective equipment (PPE) based on individual combat: A systematic review and trend analysis. *Defence Technology, 28*, 195-221,.

Qin, T., Chen, T., Chen, Y., & Su, Q. (2020). AVP-SLAM: Semantic Visual Mapping and Localization for Autonomous Vehicles in the Parking Lot. *The IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2020.* Arxiv.

Qin, T., Li, P., & Shen, S. (2018). VINS-Mono: A robust and versatile monocular visual-inertial state estimator. *IEEE Transactions on Robotics, 34*(4), 1004-1020.

QuSpin. (2025). *QTFM / QTFM Gen-2 Total-Field Magnetometer -- Specifications.* Retrieved from https://quspin.com/product/qtfm/

Radoš, K., Brkić, M., & Begušić, D. (2024). Recent Advances on Jamming and Spoofing Detection in GNSS. *Sensors, 24*(13), 4210.

Raj, T., Hashim, F. H., Huddin, A. B., Ibrahim, M. F., & Hussain, A. (2020). A Survey on LiDAR Scanning Mechanisms. *Electronics, 9*(5), 741.

Rakon Ltd. (2023). *What is synchronisation holdover and why is it important in future-proofing telecom networks?* Retrieved from Rakon: https://www.rakon.com/learning-hub/blog-what-is-synchronisation-holdover-and-why-is-it-important-in-future-proofing-telecom-networks

Ran, Y., Xu, X., Tan, Z., & Luo, M. (2025). A Review of 2D Lidar SLAM Research. *Remote Sensing, 17*(7), 1214.

Rasshofer, R., Spies, M., & Spies, H. (2011). Influences of Weather Phenomena on Automotive Laser Radar Systems. *Advances in Radio Science, 9*, 49-60.

Reginald, N., Al-Buraiki, O., Choopojcharoen, T., Fidan, B., & Hashemi, E. (2025). Visual-Inertial-Wheel Odometry with Slip Compensation and Dynamic Feature Elimination. *Sensors (Basel), 25*(5), 1537.

Renaudin, V., Afzal, M., & Lachapelle, G. (2010). Complete Triaxis Magnetometer Calibration in the Magnetic Domain. *Journal of Sensors*, 967245. doi:10.1155/2010/967245

RethinkPNT. (2022). *PNT Resilience Definitions and PNT Threats.* Retrieved 2025, from https://rethinkpnt.com/20220623-pnt-terminology-definitions-v6/

Ribas, D. P. (2012). Underwater SLAM in Man-Made Structured Environments. *Journal of Field Robotics, 29*(9), 731–757.

Richards, M. (2014). *Fundamentals of Radar Signal Processing* (2 ed.). McGraw-Hill Education.

Rizos, C. Y. (2019, Apr). Background and Recent Advances in the Locata Terrestrial Positioning and Timing Technology. *Sensors (Basel), 19*(8), 1821.

Robert D. Christ., R. L. (2007). *The ROV Manual (Section 4.2.7 Advantages and Disadvantages of Positioning Systems).* Burlington, MA, USA: Elsevier.

Roberti, M. (2025). *How Accurate Can RFID Tracking Be?* (RFID Journal) Retrieved 4 28, 2025, from https://www.rfidjournal.com/ask-the-experts/how-accurate-can-rfid-tracking-be/

Roddy, D. (2006). *Satellite Communications, 4th ed.* New York, NY, USA: McGraw-Hill.

Rohde and Schwarz. (2023). Resilient positioning navigation and timing based on 5G broadcast.

Romijn, J. D. (2021). Multi-layer graphene pirani pressure sensors. *Nanotechnology*, 32(33), 335501.

Roslund, J. D. (2024). Optical clocks at sea. *Nature, 628*, 736–740.

Royo, S., & Ballesta-Garcia, M. (2019). An Overview of Lidar Imaging Systems for Autonomous Vehicles. *Applied Sciences, 9*(19), 4093.

RTCA. (1974). *DO-155: Minimum Performance Standards --- Airborne Low-Range Radar Altimeters.* RTCA, Inc.

RTCA. (2010). *DO-160G: Environmental Conditions and Test Procedures for Airborne Equipment.* RTCA, Inc.

SAE International. (2018). *Transmitted eLoran Signal Standard for Tri-State Pulse Position Modulation - SAE9990/1.* SAE International .

Saeedi, S. P. (2021). Localization for Autonomous Underwater Vehicles: Opportunities and Challenges. *Drones, 5*(3), 83.

Safran. (2023). *LPFRS Rhubidium Oscillator.* Retrieved from Safran Inc: https://safran-navigation-timing.com/wp-content/uploads/2023/07/SAFRAN_LPFRS_Datasheet_2-20-2023_US.pdf

Safran Electronics & Defense. (2025). *HRG Crystal – Game-Changing Technology.* Retrieved from Safran Electronics & Defense.: https://www.safran-electronics-defense.com/innovation/hrg-crystal

Saines, M. (2023, 8 2). *Nextnav tests 3D PNT service leveraging cellular infrastructure.* (GPS World) Retrieved 4 24, 2025, from https://www.gpsworld.com/nextnav-tests-3d-pnt-service-leveraging-cellular-infrastructure/

Saltus, R., Alken, P., Balmes, A., Boneh, N., Califf, S., Chulliat, A., . . . Nair, M. (2023). Magnetic Maps and Models for Alternative Navigation. *2023 IEEE/ION Position, Location and Navigation Symposium (PLANS)*, (pp. 805--813). doi:10.1109/PLANS53410.2023.10140025

Sang, C. L. (2021). Time Synchronization in UWB Networks. *IEEE Communications Magazine, 59*(6), pp. 84-90.

Satelles. (2025). *STL provides Global Coverage.* (Iridium) Retrieved April 2025, from https://satelles.com/technology/stl-provides-global-coverage-timing-synchronization/

Scaramuzza, D., & Zhang, Z. (2019). Visual-Inertial Odometry of Aerial Robots. *IEEE Robotics & Automation Magazine, 26*(3), pp. 69-83.

SCCS. (2025). *Leica SmartNet National GNSS Network Solution*. Retrieved from https://www.sccssurvey.co.uk/leica-smartnet.html

Schrock, G. (2021, 7 2). *Ultra-Wideband's Edge for Indoor Navigation and Positioning*. (Gogeomatics Canada) Retrieved 4 24, 2025, from https://gogeomatics.ca/ultra-wideband-pnt/

Scintrex. (n.d.). *Sintrex Gravity Products*. Retrieved from Scintrex: https://scintrexltd.com/product-category/gravity/

Segev, J. (2023, 8 22). *New Wi-Fi standard IEEE 802.11az aims to upgrade building design and user experience*. Retrieved from Buildings: https://www.buildings.com/smart-buildings/article/33017990/new-wi-fi-standard-ieee-80211az-aims-to-upgrade-building-design-and-user-experience

Sensonor. (2024). *SAR500 High Precision Gyroscope*. Retrieved from Sensonor: https://www.sensonor.com/products/sar500/

Serrano, J. C. (2013). The White Rabbit project. *Proceedings of the 2013 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication* (pp. 1-6). Oxford: IEEE.

Sharbel Kozhaya, J. S. (2024). Starlink for PNT: A Trick or a Treat? *Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2024)*. Baltimore, Maryland.

Sharbel Kozhaya, J. S. (2025). Unvieling Starlink for PNT. *Navigation, 72*(1).

Shashua, A., Levin, D., & Sinha, R. (2022). Vision-Based Autonomous Driving Systems: State of the Art and Future Directions. *IEEE Transactions on Intelligent Transportation Systems, 23*(2), 1234-1251.

Sibold, D. R. (2015). *Using the Network Time Security Specification to Secure the Network Time Protocol*. Internet Engineering Task Force (IETF).

Siebler, B., Lehner, A., Sand, S., & Hanebeck, U. (2023). Simultaneous Localization and Calibration (SLAC) Methods for a Train-Mounted Magnetometer. *NAVIGATION, 70*(1), navi.557. doi:10.33012/navi.557

Signal Identification Guide (SIGIDWIKI). (2025). *UK AM Data System*. Retrieved from SIGIDWIKI: https://www.sigidwiki.com/wiki/UK_AM_Data_System_(UK-AMDS)

Simple Flying. (2022, 10 9). *Instrument Landing Systems: Everything you need to know about ILS*. Retrieved 4 17, 2025, from https://simpleflying.com/instrument-landing-systems-complete-guide/

Skolnik, M. (2008). *Radar Handbook* (3 ed.). McGraw-Hill.

Skybrary. (2025). *Instrument Landing System (ILS)*. Retrieved 4 17, 2025, from https://skybrary.aero/articles/instrument-landing-system-ils

SLAMcore. (2023). *SLAMCore*. Retrieved from SLAMCore: https://www.slamcore.com/

Sobczak, Ł., Filus, K., & Domańska, J. (2022). Finding the best hardware configuration for 2D SLAM in indoor environments via simulation based on Google Cartographer. *Scientific Reports, 12*, 18815.

Sobreviela-Falces, G. (2022). A Navigation-Grade MEMS Vibrating Beam Accelerometer. *IEEE 35th International Conference on Micro Electro Mechanical Systems Conference (MEMS)*, (pp. 782-785). Tokyo, Japan.

Sonardyne. (2025). *Compatt-6 Plus*. Retrieved from Sonardyne: https://www.sonardyne.com/product/compatt-6-plus/

Sonardyne. (2025). *Micro Ranger 2 USBL*. Retrieved from Sonardyne: https://www.sonardyne.com/product/micro-ranger-2/

Sonardyne. (2025). *Mini Ranger 2 USBL*. Retrieved from Sonardyne: https://www.sonardyne.com/product/mini-ranger-2-usbl/

Sonardyne. (2025). *Ranger 2 USBL*. Retrieved from Sonardyne: https://www.sonardyne.com/product/ranger-2-usbl/

Sony Semiconductor Solutions. (2023). *STARVIS CMOS Image Sensors*. Retrieved from Sony Semiconductors: https://www.sony-semicon.com/en/products/IS/sensor1/products.html

Southern Avionics. (2025). *What is an NDB or Non-Directional Beacon?* Retrieved 4 22, 2025, from https://www.southernavionics.com/blog/bid/50999/what-is-an-ndb-or-non-directional-beacon

Space Agency of Russia. (2025). *GLONASS Constellation Status*. Retrieved 2025, from https://glonass-iac.ru/en/sostavOG/

Spachos, P. &. (2020). BLE Beacons for Indoor Positioning at an Interactive IoT-Based Smart Museum. *IEEE Systems Journal, 14*(3), 3483-3493.

Spilker, J., Axelrad, P., Parkinson, B. W., & Enge, P. (1996). *Global Positioning System: Theory and Applications Vol 1.* American Institute of Aeronautics and Astronautics.

Spirent Federal. (n.d.). *Safran provides GNSS simulation solutions for Xona Space Systems LEO constellation.* Retrieved April 2025, from https://spirentfederal.com/simxona/

Star:Oddi. (2025). *Salinity, Conductivity, Temperature and Depth Logger.* Retrieved from Star: Oddi Logging Life Science: https://www.star-oddi.com/products/data-loggers/salinity-logger-probe-CTD?

Starcomm Solutions. (n.d.). *OneWeb Services.* Retrieved April 2025, from https://starcommsolutions.com/one-web-services/

Starlink. (2025). *Starlink Technology.* (Starlink) Retrieved 2025, from https://www.starlink.com/gb/technology

Starlink. (n.d.). *Starlink Technology.* Retrieved April 2025, from https://www.starlink.com/technology

Starnav. (2024). *Positioning and Timing Receivers.* Retrieved from Starnav.io: https://starnav.io/technologies/

Stereolabs. (2023). *ZED X Stereo Camera – Product Specifications.* Retrieved from Stereolabs: https://www.stereolabs.com/zed-x/

Stimson, G., Griffiths, H., Baker, C., & Adamy, D. (2014). *Stimson's Introduction to Airborne Radar* (3 ed.). SciTech Publishing.

Stock, W., Schwarz, R. T., Hofmann, C. A., & Knopp, A. (2024). Survey on Opportunistic PNT With Signals From LEO Communication Satellites. *IEEE Communications Surveys & Tutorials, 27*(1).

Stone, M. (2021, 8 25). *Insights: What is ultra-wideband, and how does it work?* (Samsung) Retrieved 4 24, 2025, from https://insights.samsung.com/2021/08/25/what-is-ultra-wideband-and-how-does-it-work-3/

Straits Research. (2025). *Global Positioning Systems (GPS) Market Size, Demand and Forecast to 2030.* Straits Research.

Stray, B. L. (2022). Quantum sensing for gravity cartography. *Nature*, 602(7898), 590-594.

Strong., J. (1985). Microwave Landing System (MLS). *Proceedings of the 1985 National Technical Meeting of The Institute of Navigation*, 209-218.

Study Aircrafts. (2025). *Distance Measuring Equipment (DME).* Retrieved 4 17, 2025, from https://www.studyaircrafts.com/dme

Study Aircrafts. (2025, May). *VHF OmniDirectional Range (VOR).* Retrieved from Study Aircrafts: https://www.studyaircrafts.com/vor

Sturm, C., & Wiesbeck, W. (2011). Waveform Design and Signal Processing Aspects for Fusion of Wireless Communications and Radar Sensing. *Proceedings of the IEEE, 99*(7), 1236--1259. doi:10.1109/JPROC.2011.2131110

Tagliaferri, D., Manzoni, M., Mizmizi, M., Tebaldini, S., Monti-Guarnieri, A., Prati, C., & Spagnolini, U. (2024). Cooperative Coherent Multistatic Imaging and Phase Synchronization in Networked Sensing. *IEEE Journal on Selected Areas in Communications, 42*(10), 2905--2921. doi:10.1109/JSAC.2024.3414609

Teledyne FLIR. (2017). *Boson Thermal Camera Module Datasheet.* Retrieved from Teledyne FLIR: https://www.flir.co.uk/products/boson/

Teledyne Marine. (2025). *Acoustic Positioning Systems.* Retrieved from Teledyne Marine: https://www.teledynemarine.com/products/product-line/navigation-positioning/acoustic-positioning-systems

Tesla. (2023). *Tesla Autopilot.* Retrieved from Tesla: https://www.tesla.com/en_gb/autopilot

Teunissen, P., & Montenbruck, O. (2017). *Handbook of Global Navigation Satellite Systems.* Springer International.

Texas Instruments. (2021). *Fundamentals of millimeter-wave radar sensors.* Texas Instruments. Retrieved from https://www.ti.com/lit/an/swpd024/swpd024.pdf

Texas Instruments. (2025). *An Introduction to Automotive Lidar (Rev. D). TI White Paper* . Retrieved from https://www.ti.com/lit/slyy150

The White House. (2020). *Executive Order 13905: Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services.* Washington DC: White House.

Thommen Aircraft Equipment. (2025). *Digital Encoding Altimeter AD32 DEA80.* Retrieved 2025, from https://thommen.aero/wp-content/uploads/2017/02/AD32-DEA80_THOMMEN-DIGITAL-ENCODING-ALTIMETER.pdf

Timetools Limited. (2017). *Decoding the MSF.* Retrieved from https://timetoolsltd.com/atomic-clocks/decoding-the-msf-60-radio-time-signal/

Tippetts, B. L. (2016). Review of stereo vision algorithms and their suitability for resource-limited systems. *IEEE Access, 4*, 858-886.

Titterton, D. H. (2004). *Strapdown Inertial Navigation Technology (2nd ed.).* The Institution of Engineering and Technology.

Tonmind. (2022). *Network Time Protocol.* Retrieved from TONMIND TECHNOLOGY LIMITED: https://www.tonmind.com/blog/ntp-network-time-protocol_b29

Topcon Positioning. (2025). *GNSS Correction Services.* Retrieved from Topcon Positioning: https://www.topconpositioning.com/gb/en/solutions/technology/infrastructure-software-and-services/gnss-correction-services

Travagnin, M. (2022). *Next-generation Chip Scale Atomic Clocks EUR 31003 EN, .* Publications Office of the European Union.

Trimble. (2025). *Products and Services.* Retrieved from Trimble RTX: https://positioningservices.trimble.com/en/rtx

Tualcom . (2024). *Terrestrial navigation system* . Retrieved from Tualcom : https://www.tualcom.com/terrestrial-navigation-system/

Tualcom. (2023). TRNAV.

Tyler G. R. Reid, M. G. (2025). Xona PULSAR Compatibility with GNSS. *ION GNSS+.* Baltimore, Maryland.

U.S. Air Force. (2023, 05). *MagNav project successfully demonstrates real-time magnetic navigation.* Retrieved from https://www.af.mil/News/Article-Display/Article/3408951/magnav-project-successfully-demonstrates-real-time-magnetic-navigation/

U.S. Government Accountability Office. (2022). *GPS Modernization: Space Force Should Reassess Requirements for Next Generation Operational Control System. GAO-22-104611.* Retrieved 2025, from https://www.gao.gov/products/gao-22-104611

u-Blox. (2025). *Point perfect PPP/RTK Correction Services.* Retrieved from u-blox.com: https://www.u-blox.com/en/technologies/ppp-rtk-gnss-correction-services-pointperfect

UK Civil Aviation Authority. (2022). *DVOR / DME / NDB Rationalisation: Guidance for the use of RNAV Substitution.* Crawley: Civil Aviation Authority.

UK Space. (2019, Jan). *Global Xpress to be enhanced.* Retrieved April 2025, from https://www.ukspace.org/global-xpress-to-be-enhanced-with-arctic-capabilities/

University of Oxford. (2022). *Mapping the old with the new: handheld 3D scanning of Oxford's Sheldonian Theatre.* Retrieved from University of Oxford: https://www.ox.ac.uk/news/2022-12-12-mapping-old-new-handheld-3d-scanning-oxfords-sheldonian-theatre

University of Texas. (2025). *Texas Spoofing Test Battery (TEXBAT).* Retrieved from University of Texas at Austin Radionavigation Laboratory: https://radionavlab.ae.utexas.edu/texbat/

Ureña, J. H. (2018). Acoustic Local Positioning With Encoded Emission Beacons. *Proceedings of the IEEE, 106*(6), 1042–1058.

UrsaNav. (n.d). eLoran points of light. Massachusetts, USA.

US Department of Defence. (2017). *GPS PPS Performance Standard.* Retrieved 2025, from https://www.gps.gov/technical/ps/2007-PPS-performance-standard.pdf

US Department of Defense. (2020). *GPS SPS Performance Standard 5th Edition.* Retrieved 2025, from https://www.gps.gov/technical/ps/2020-SPS-performance-standard.pdf

US Department of Transportation. (2008). *GLOBAL POSITIONING SYSTEM WIDE AREA AUGMENTATION SYSTEM (WAAS) PERFORMANCE STANDARD* . US Government.

US Department of Transportation. (n.d., 3 2024). Complementary PNT Action Plan. Cambridge, MA.

US Government Navigation Center. (2025). *Current GPS Status.* Retrieved 2025, from https://www.navcen.uscg.gov/sites/default/files/pdf/gps/current.pdf

US Space Force. (2021). *GPS Control Segment.* Retrieved 2025, from https://www.gps.gov/systems/gps/control/

US Space Force. (2023). *Global Positioning System Fact Sheet.* (U.S. Space Force) Retrieved 2025, from https://www.spaceforce.mil/About-Us/Fact-Sheets/

US. Government. (2025). *Global Positioning System.* Retrieved 2025, from https://www.gps.gov/

Vasconcelos, J., Elkaim, G., Silvestre, C., Oliveira, P., & Cardeira, B. (2011). Geometric Approach to Strapdown Magnetometer Calibration in Sensor Frame. *IEEE Transactions on Aerospace and Electronic Systems, 47*(2), 1293--1306. doi:10.1109/TAES.2011.5751259

Vectron International. (2025). *Oscillator Short Term Stability and Allan Deviation Application Note.* Retrieved from https://ww1.microchip.com/downloads/aemDocuments/documents/VOP/ApplicationNotes/ApplicationNotes/Oscillator+Short+Term+Stability+and+Al

Velodyne Lidar. (2020). Alpha Prime Lidar Sensor Data Sheet (128-beam, 245m range LIDAR specifications). *Velodyne Product Specifications (Rev.1).* Velodyne.

Viasat. (2024). *Global Xpress Time Transfer - Precision Time Transfer from GEO.* (Viasat) Retrieved April 2025, from https://navisp.esa.int/project/details/349/show

Viasat. (n.d.). *Assured PNT Capabilities.* (Viasat) Retrieved April 2025, from https://www.viasat.com/perspectives/government/2023/viasat-showcases-multi-orbit-and-assured-pnt-capabilities/

Viasat. (n.d.). *Satellite-based augmentation services (SBAS) and positioning, navigation, and timing (PNT).* (Viasat) Retrieved April 2025, from https://www.viasat.com/government/missions/pnt/

Viasat. (n.d.). *Viasat - What we do.* (Viasat) Retrieved April 2025, from https://www.viasat.com/about/what-we-do/satellite-fleet/

Vicinity. (2024). *4g+5g integrated high power base station.* Retrieved from https://vicinitysys.com/product/4g5g-integrated-high-power-base-station/?utm_source=chatgpt.com

Viot, M., Bizalion, A., & Seegars, J. (2021, 6 14). *Exploring Ultra-Wideband Technology for Micro-Location-Based Services.* (Microwave Journal) Retrieved 4 24, 2025, from https://www.microwavejournal.com/articles/36143-exploring-ultra-wideband-technology-for-micro-location-based-services

Vovrosh, J. (2022, April 21). *Quantum gravity gradient sensor detects outdoor tunnel.* Retrieved from Laser Focus World: https://www.laserfocusworld.com/test-measurement/article/14270785/quantum-gravity-gradient-sensor-detects-outdoor-tunnel

Wang, B. (2020, Sep). *SpaceX Starlink Can Provide Super GPS With a Software Modification.* Retrieved April 2025, from https://www.nextbigfuture.com/2020/09/spacex-starlink-can-be-tweaked-to-provide-super-gps.html

Wang, F., Li, H., & Lu, M. (2017). GNSS Spoofing Detection and Mitigation Based on Maximum Likelihood Estimation. *Sensors, 17*(7), 1532.

Wang, j., & Olsen, E. (2016). Apriltag2: Efficient and robust fiducal detection. *IEEE?RSJ inernational Conference on Intelligent Robots and Systems (IROS),* (pp. 4193-4198).

Wang., S. Z. (2021). Characterising BDS signal-in-space performance from integrity perspective [online]. Available at: [Accessed 10/03/25]. *Navigation, 68*(1). Retrieved from https://navi.ion.org/content/68/1/157

Ward, K., Watts, S., & Tough, R. (2006). *Sea Clutter: Scattering, the {K} Distribution and Radar Performance* (2 ed.). London: The Institution of Engineering and Technology (IET).

Wartsila. (2025). *Speed Logs.* Retrieved from WÄRTSILÄ Encyclopedia of Marine and Energy Technology: https://www.wartsila.com/encyclopedia/term/speed-logs#:~:text=,to%20the%20master%20electronic%20unit

Winter, A., Morrison, A., & Sokolova, N. (2023). Analysis of 5G and LTE Signals for Opportunistic Navigation and Time Holdover. *Sensors (Basel), 24*(1), 213.

Wirsing, M., Dammann, A., & Raulefs, R. (2021). VDES R-Mode performance analysis and experimental results. *International journal of satellite communications and networking,* 158-177.

WMM2025. (2024). *World Magnetic Model 2025 (WMM2025).* doi:10.25921/aqfd-sd83

WMMHR2025. (2024). *World Magnetic Model High Resolution 2025 (WMMHR2025).* doi:10.25921/qb1c-vn52

Woodman, O. (2007). *An Introduction to inertial navigation.* Cambridge: University of Cambridge.

Wray, L. C. (2023). *The Global Positioning System (GPS) Resiliency through Redundancy.* Retrieved 2025, from https://www.gps.gov/cgsic/meetings/2023/wray.pdf

Wright, M. J., Anastassiou, L., Mishra, C., Davies, J. M., Phillips, A. M., Maskell, S., & Ralph, J. F. (2022). Cold atom inertial sensors for navigation applications. *Frontiers in Physics, 10,* 994459.

Xminnov. (2024, 6 21). *How much does RFID implementation cost?* Retrieved 4 28, 2025, from https://www.rfidtagworld.com/news/NFC-RFID-IOT-Knowledge_5867.html

Xona Space. (2025). *XONA IS BUILDING THE MOST ADVANCED SATELLITE NAVIGATION SYSTEM ON THE PLANET.* Retrieved April 2025, from https://www.xonaspace.com

Xucheng, M. (2023). Centispace LEO Augmentation Navigation System Status. . *Proceedings of the ICG Workshop on LEO PNT* . Vienna.

Y Combinator: Technology Review. (n.d.). *Starlink signals can be reverse-engineered to work like GPS.* Retrieved April 2025, from https://news.ycombinator.com/item?id=33287224

Yazdi, N., Ayazi, F., & Najafi, K. (1998). Micromachined Inertial Sensors. *Proceedings of the IEEE, 86*(8), 1640–1659.

Yoke T. Yoon, P. G.-A. (2024). Navigating a large satellite constellation in the new space era: An operational perspective. *Journal of Space Safety Engineering, 10*(4).

Yu, H., Zhao, Z., Liu, X., Chen, S., Du, J., & others. (2025). Experimental Demonstration of a Diamond Quantum Vector Magnetometer. *National Science Review, 12,* nwaf146. doi:10.1093/nsr/nwae478

Zafari, F. G. (2019). A Survey of Indoor Localization Systems and Technologies. *IEEE Communications Surveys & Tutorials, 21*(3), 2568-2599.

Zaher M. Kassas, S. K. (n.d.). *Navigation with Multi-Constellation LEO Satellite Signals of Opportunity: Starlink, OneWeb, Orbcomm, and Iridium.* Retrieved April 2025, from https://people.engineering.osu.edu/sites/default/files/2023-05/Kassas_Navigation_with_multi_constellation_LEO_satellite_signals_of_opportunity_Starlink_OneWeb_Orbcomm_and_Iridium.pdf

Zand, P. &. (2019). A high-accuracy phase-based ranging solution with Bluetooth Low Energy (BLE). *IEEE Wireless Communications and Networking Conference (WCNC).*

Zhang, J., Cui, X., Xu, H., & & Lu, M. (2019). A Two-Stage Interference Suppression Scheme Based on Antenna Array for GNSS Jamming and Spoofing. *Sensors, 19*(18), 3870.

Zhang, J., Feng, H., Liu, B., & Zhao, D. (2023). Survey of Technology in Network Security Situation Awareness. *Sensors, 23*(5).

Zhang, T. a. (2023). Mag-ODO: Motion speed estimation for indoor robots based on dual magnetometers. *Measurement, 222,* 113688.

Zhang, Y. S. (2025). Doppler positioning technology based on Globalstar opportunity signals[. *Journal of Beijing University of Aeronautics and Astronautics, 51*(2).

Zhao, X., Zhang, Z., & Zhuang, Q. (2025). Quantum illumination networks. *Communications Physics, 8*(1), Article 19. doi:10.1038/s42005-025-01968-8

APPENDIX B GLOSSARY

µGal	Micro-Gallon
2D	Two-Dimensional
3D	Three-Dimensional
3GPP	3rd Generation Partnership Project
5G LTE NR	5G Long Term Evolution New Radio
AC^{2}ES	Assured Command and Control Enablement System
ADAS	Advanced Driver Assistance Systems
ADCs	Air Data Computers
ADF	Automatic Direction Finder
ADS	Automatic Dependent Surveillance
AES	Advanced Encryption Standard
AFRL	Air Force Research Lab
AGC	Automatic Gain Control
AGV	Autonomous Ground Vehicle
AI	Artificial Intelligence
AIS	Automatic Identification System
ALPS	Acoustic Local Positioning Systems
AM	Amplitude Modulation
AMCS	Alternate Master Control Station
ANSP	Air Navigation Service Provider
AoA	Angle of Arrival
AoD	Angle of Departure
AP	Access Point
APNT	Assured PNT
A-PNT	Alternative PNT
APS	Assured Positioning System
AQG	Absolute Quantum Gravimeter
AQlock	Cold-Atom Quantum Clock
AR	Augmented Reality
ASECNA	Agency for Air Navigation Safety in Africa and Madagascar
ASF	Additional Secondary Factors
ATAK	Android Team Awareness Kit
ATM	Automated Teller Machine or Air Traffic Management
ATV	All-Terrain Vehicles
AUV	Autonomous Underwater Vehicle
BAE	British Aerospace
BBC	British Broadcasting Corporation
BCD	Binary Coded Decimal
BDS	BeiDou Navigation Satellite System
BIGF	British Isles Continuous GNSS Facility

BIM	Building Information Modelling
BLE	Bluetooth Low Energy
BST	British Summer Time
BVOR	Broadcast VHF Omni-directional Range
C/A	Coarse/Acquisition
C/N0	Carrier-to-Noise Density Ratio
CAF	Cross-Ambiguity Function
CAN	Controller Area Network
CAT	Category
CCF	Central Control Facility
CDMA	Code Division Multiple Access
CETC-29	The 29th Research Institute of China Electronic Technology Group Corporation
China SatNet	China Satellite Network Group Co. Ltd.
CIFS	Calcium Ion Frequency Standard
CLAS	Centimeter Level Augmentation Service
CNES	Centre National d'études Spatiales
CNNs	Convolutional Neural Networks
CNR	Carrier-to-Noise Ratio
CNS	Communications, navigation, surveillance
CNSA	China National Space Administration
COoPNAV	Collaborative Opportunistic Navigation
COpNav	Collaborative Opportunistic Navigation
CORS	Continuously Operating Reference Stations
CPF	Central Processing Facility
CRPA	Controlled Reception Pattern Antennas
CSAC	Chip-Scale Atomic Clocks
CVG	Coriolis Vibratory Gyroscopes
CVOR	Conventional VHF Omni-directional Range
D2D	Device-to-Device
dBm	Decibel Milliwatts
dBW	Decibel-Watt
DDUx	Data Distribution Unit – Expandable Technology
DFMC	Dual Frequency Multi Constellation
DGCA	Director General of Civil Aviation
DGNSS	Differential GNSS
DGPS	Differential GPS
DL	Deep Learning
DL-TDoA	Downlink Time Difference of Arrival
DME	Distance Measuring Equipment
DNNs	Deep Neural Networks
DOP	Dilution of Precision

DQG	Differential Quantum Gravimeter
DSAC	Deep Space Atomic Clock
DSP	Digital Signal Processor
DST	Daylight Saving Time
dTDOA	Differential Time Difference of Arrival
DTV	Digital Television
DVL	Doppler Velocity Log
DVOR	Directional VHF Omni-directional Range
EASA	European Union Aviation Safety Agency
EC	European Commission
E-CID	Enhanced Cell Identification
EDAS	EGNOS Data Access Service
EGNOS	European Geostationary Navigation Overlay Service
EIRP	Effective Isotropic Radiated Power
EKF	Extended Kalman Filters
EM	Electromagnetic
EMI	Electromagnetic Interference
EPOS	European Plate Observing System
ESA	European Space Agency
ESGs	Electrostatically Suspended Gyros
ESSP	European Satellite Services Provider
ETRS	European Terrestrial Reference System
ETSI	European Telecommunications Standards Institute
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EUSPA	European Union Agency for the Space Programme
eVTOL	electric Vertical Take-Off and Landing (eVTOL)
EWA	EGNOS Working Agreement
EWAN	ENOS Wide Area Network
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDA	Food and Drug Administration
FDMA	Frequency Division Multiple Access
FDOA	Frequency-Difference-of-Arrival
FIR	Flight Information Region
FM	Frequency Modulation
FMCW	Frequency-Modulated Continuous Wave
FOGs	Fibre-Optic Gyroscopes
FOV	Field of View
FPGA	Field-Programmable Gate Array
FTG	Full Tensor Gravity Gradiometer

FTM	Fine Timing Measurement
GAGAN	GPS Aided GEO Augmented Navigation
GAMES	GAGAN Message Service
GANs	Generative Adversarial Networks
GAS	Ground Augmentation System
GCC	Galileo Control Centres
GEO	Geostationary Orbit
GHz	Gigahertz
GIVEI	Grid Ionospheric Vertical Error Indicator
GLA	General Lighthouse Authority
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
GMS	Ground Mission Segment
gNB	Next generation NodeB
GNSS	Global Navigation Satellite System
GP	Geographic Position
GPS	Global Positioning System
GPSDO	GNSS-Disciplined Oscillators
GPU	Graphics Processing Unit
GS	Glideslope
GSMC	Global Short Message Communication
GSS	Galileo Sensor Stations
GTO	Geostationary Transfer Orbit
GX	Viasat's Global Xpress
HAS	High Accuracy Service
HD	High-Definition
HEA	Harbour Entrance Approach
HEO	Highly Elliptical Orbits
HF	High Frequency
HFT	High-Frequency Trading
HMI	Hazardous Misleading Information
HMIs	Human-Machine Interfaces
HPA	Honeywell's Precision Altimeter
HRG	Hemispherical Resonator Gyro
HRVS	Honeywell Radar Velocity System
Hz	Hertz
I/Q	In-Phase And Quadrature
I^2C	Inter-Integrated Circuit
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
ICG	International Committee on GNSS
IEEE	Institute of Electrical and Electronics Engineers

IGMA	International GNSS Monitoring and Assessment
IGSO	Inclined Geosynchronous Orbit
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IMU	Inertial Measurement Units
INRES	India Reference Station
INS	Inertial Navigation Systems
IoT	Internet of Things
IR	Infrared
IRNSS	Indian Regional Navigation Satellite System
ISAC	Integrated Sensing and Communication
ISMs	Integrity Support Messages
ISS	International Space Station
ITU	International Telecommunication Union
iUSBL	Inverted USBL
IVAS	Integrated Visual Augmentation System
JAXA	Japan Aerospace Exploration Agency
JCAB	Japan Civil Aviation Bureau
KASS	Korea Augmentation Satellite System
LBL	Long-Baseline
LDVs	Laser Doppler Velocimeters
LEO	Low Earth Orbit
LF	Low Frequency
LiDAR	Light Detection and Ranging
LOC	Localiser
LOP	Line Of Position
LOS	Line-Of-Sight
LPV	Localiser Performance with Vertical guidance
LTE	Long-Term Evolution
LVS	Laser Velocity Sensor
LWIR	Long-Wave Infrared
MADOCA-PPP	Multi-GNSS Advanced Orbit and Clock Augmentation – Precise Point Positioning
MASPS	Minimum Aviation System Performance Standards
MBS	Metropolitan Beacon System
MCC	Mission Control Centre
MCS	Master Control Station
MEMS	Micro-Electro-Mechanical Systems
MEO	Medium Earth Orbit
MF	Multifrequency
MIFR	Master International Frequency Register
MIMO	Multiple Inputs Multiple Outputs

ML	Machine Learning
MLE	Maximum Likelihood Estimation
MLIT	Japan's Ministry of Land, Infrastructure, Transport and Tourism
MLS	Microwave Landing System
MmWave	Millimetre Wave
MOPS	Minimum Operational Performance Standards
MS	Monitoring and Measuring Stations
MSAS	MTSAS Satellite Augmentation System
MTSAT	Multi-functional Transport Satellite
MW	Megawatts
n.d.	No Date Specified
NAS	National Air Space
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NaVIC	Navigation With Indian Constellation
NDB	Non-Directional Beacon
NERC	Natural Environment Research Council
NGP	Next Generation Positioning
NIST	National Institute of Standards and Technology
NLES	Navigation Land Earth Stations
NLOS	Non-Line-of-Sight
NPA	Non-Precision Approach
NPL	National Physical Laboratory
NR	New Radio
NSP	Navigation Systems Panel
NTN	Non-Terrestrial Network
NTP	Network Time Protocol
NTRIP	Networked Transport of RTCM via Internet Protocol
NTS	Network Time Security
NTS-3	Navigation Technology Satellite-3
OCX	Next Generation Operational Control System
OCXO	Oven-Controlled Crystal Oscillators
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPA	Optical Phased Array
ORB	Oriented FAST And Rotated BRIEF
OS	Ordnance Survey
OS Net	Ordnance Survey Network
OSNMA	Open Service Navigation Message Authentication
OSR	Observation Station Representation

P	Precise
PCB	Printed Circuit Board
PDOP	Position Dilution of Precision
PF	Primary Factors
PKE	Passive Keyless Entry
PNT	Positioning, Navigation, and Timing
PNTaaS	Position, Navigation, and Timing as a Service
POD	Precision Orbit Determination
PPDs	Personal Privacy Devices
PPP	Precise Point Positioning
PPS	Pulse-Per-Second
PRN	Pseudo-Random Noise
PRS	Public Regulated Service
PSK	Phase Shift Keying
PTB	Physikalisch-Technische Bundesanstalt
PTC	Positive Train Control
PTP	Precision Time Protocol
Q-INS	Quantum Inertial Sensors
QPSK	Quadrature Phase Shift Keying
QZSS	Quazi-Zenith Satellite System (aka Michibiki)
R&D	Research and Development
RAIM	Receiver Autonomous Integrity Monitoring
RANSAC	Random Sample Consensus
RF	Radio Frequency
RFID	Radio Frequency Identification
RGB-D	Red, Green, and Blue Color Model With Depth
RIMS	Ranging and Integrity Monitoring Stations
RINEX	Receiver Independent Exchange Format
RLG	Ring Laser Gyroscope
RNAV	Radio Navigation
RNN	Recurrent Neural Networks
RNSS	Radio Navigation Satellite Services
ROS	Robot Operating System
ROV	Remotely Operated Vehicles
RSMC	Regional Short Message Communication
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime
RTK	Real-Time Kinematic
RTT	Round Trip Time

SA	Situational Awareness
SAGAT	Situational Awareness Global Assessment Technique
SALHUB	The Royal Institute of Navigation, Satellite Applications Learning Hub
SAR	Search and Rescue
SARPS	Standards and Recommended Practices
SATSOO	Satellite Signals of Opportunity
SBAS	Satellite-Based Augmentation Systems
SBL	Short-Baseline
SCADA	Supervisory Control and Data Acquisition
SDCM	Systems for Differential Corrections and Monitoring
SDD	Service Definition Document
SDRs	Software-Defined Radios
SES	Single European Sky
SF	Secondary Factors
SIGIDWIKI	Signal Identification Guide
SIS	Signal In Space
SLAM	Simultaneous Localisation and Mapping
SLAS	Sub-Metre Level Augmentation Service
SLR	Satellite Laser Ranging Stations
SMA	SubMiniature version A
SNL	Signal to Noise ratio
SNR	Signal-to-Noise Ratio
SOA	Silicon Oscillating Accelerometer
SoCs	A Group Of Processing Units on a Single Chip
SoL	Safety of Life
SOLAS	Safety of Life at Sea
SoOP	Signals of Opportunity
SouthPAN	Southern Positioning Augmentation Network
SPAD	Single-Photon Avalanche Diode
SPARK	Supporting the UK Public Sector in PNT Awareness, Research and Knowledge
SPI	Serial Peripheral Interface
SPS	Standard Positioning Service
SRS	Stanford Research Systems
SSR	State Space Representation
STA	Station
STAP	Space-Time Adaptive Processing
STL	Satellite Timing and Location
SWaP	Size, Weight, and Power
SWIFT	Society for Worldwide Interbank Financial Telecommunications
SWIR	Short Wave Infra-Red
TACAN	Tactical Air Navigation System

TacISR	Tactical Intelligence, Surveillance, and Reconnaissance
TCXO	Temperature Compensated Crystal Oscillator
TDoA	Time Difference of Arrival
TEC	Total Electron Content
ToA	Time of Arrival
ToD	Time of Departure
ToF	Time of Flight
TRL	Technology Readiness Level
TRNAV	A Terrestrial Navigation System
TT&C	Telemetry Tracking and Command Centres
TV	Television
TVOR	Terminal VHF Omni-directional Range
TWR	Two-Way Ranging
TWTT	Two-Way Time Transfer
UART	Universal Asynchronous Receiver-Transmitter
UAV	Unmanned Aerial Vehicle or Unmanned Automated Vehicle
UDP	User Datagram Protocol
UDRE	User Differential Range Error
UHF	Ultra-High Frequency
UK	United Kingdom
UKF	Unscented Kalman Filter
ULSs	Uplink Stations
UL-TDoA	Uplink Time Difference of Arrival
UPL	User Protection Levels
US	United States
USB	Universal Serial Bus
USBL	Ultra-Short-Baseline
USD	United States Dollars
UTC	Universal Coordinated Time
UWB	Ultra-Wideband
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VCSEL	Vertical Cavity Surface-Emitting Lasers
VCSO	Voltage Controlled Saw Oscillators
VCXO	Voltage Controlled Crystal Oscillators
VDES	VHF Data Exchange System
VDES-R	Dedicated Ranging Mode VDES
VGA	Video Graphics Array
VHF	Very High Frequency
VIO	Visual-Inertial Odometry

VLBI	Very Long Baseline Interferometry
VO	Visual Odometry
VOR	VHF Omni-directional Range
VORTAC	Co-Located VOR and TACAN
VOT	VOR Test
VPU	Vision Processing Units
VR	Virtual Reality
VRS	Virtual Reference Station
WAAS	Wide Area Augmentation System
WAD	Wide Area Differential
WCDMA	Wideband Code Division Multiple Access
WMS	WAAS Master Station
WR	White Rabbit
WRS	Wide Area Reference Station
XO	Traditional Quartz Oscillators

APPENDIX C TABLE OF FIGURES

NLA INTERNATIONAL

BLUE ECONOMY SOLUTIONS • NLAI.BLUE

SUPPORTING THE UK PUBLIC SECTOR IN PNT AWARENESS, RESEARCH AND KNOWLEDGE (SPARK)

EXISTING AND EMERGING PNT SERVICES