FRONTIER SI

STATE OF THE MARKET REPORT

LOW EARTH ORBIT POSITIONING NAVIGATION AND TIMING (LEO PNT)

2024 Edition

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FrontierSI respectfully acknowledge the Aboriginal and Torres Strait Islander people of Australia, first custodians of the lands, air and waters that sustain the places we live, work and play. These first peoples have had a vibrant, living culture that has remained in sustainable synergy with the natural environment for tens of thousands of years, and continues to do so. We recognise that the lands of the Aboriginal and Torres Strait Islander people of Australia were never ceded and coexist with the Commonwealth of Australia.

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ACRONYMS

Acronym	Full form
AIS	Automatic Identification System
ANFR	L'agence nationale des fréquences (National Frequency Agency)
APS	Augmented Positioning System
ATC	Air Traffic Control
ATM	Air Traffic Management
CAFS	Caesium Atomic Frequency Standard
CDMA	Code Division Multiple Access
CETC	China Electronic Technology Group Corporation
CORS	Continuously Operating Reference Station
CSAC	Chip Scale Atomic Clock
DARPA	Defense Advanced Research Projects Agency
ESA	European Space Agency
GEO	Geostationary Orbit
GPS	Global Positioning System
GNSS	Global Navigational Satellite Systems
FDMA	Frequency Division Multiple Access
HAS	High Accuracy Service
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICD	Interface Control Document
ICG	International Committee on GNSS
IGSO	Inclined Geosynchronous Orbit
IoD	In Orbit Demonstration
IoT	Internet of Things
INS	Inertial Navigation System
IRIS^2	Infrastructure for Resilience, Interconnectivity, and Security by Satellite
LEO	Low Earth Orbit
LNSS	Lunar Navigation Satellite System
LTAN	Local Time of the Ascending Node
MEO	Medium Earth Orbit
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRTK	Network Real Time Kinematic
OCXO	Oven Controlled Oscillator
OISL	Optical Inter-Satellite Link
OpSTAR	Optical Synchronised Time and Ranging
PHM	Passive Hydrogen Maser
PNT	Positioning Navigation and Timing
POD	Precise Orbit Determination
ppb	parts per billion
PPP	Precise Point Positioning

PRN	Pseudo-Random Noise
R&D	Research and Development
RAFS	Rubidium Atomic Frequency Standard
RF	Radio Frequency
RFI	Radio Frequency Interference
RNSS	Radio Navigation Satellite Services
RTK	Real Time Kinematic
SATCOM	Satellite Communications
SBAS	Satellite Based Augmentation System
SDR	Software Defined Radio
SHF	Super High Frequency
SOP	Signals of Opportunity
SSO	Sun Synchronous Orbit
SSST	Shanghai Spacecom Satellite Technology
STL	Satellite Time and Location
SWaP-C	Size Weight Power and Cost
TAS	Thales Alenia Space
TEC	Total Electron Count
TOA	Time of Arrival
TT&C	Telemetry Tracking and Command
UHF	Ultra High Frequency
UTC	Coordinated Universal Time
VDES	VHF Data Exchange System
VDES-R	VHF Data Exchange System Ranging
VHF	Very High Frequency
VSAT	Very Small Aperture Terminal

EXECUTIVE SUMMARY

This report provides a snapshot of the Low Earth Orbit (LEO) Positioning Navigation and Timing (PNT) market as it stands in December 2024. It marks the first in a series of annual reports designed to monitor the ongoing growth and evolution of both the technology and the market.

LEO PNT is emerging as a transformative force in the global satellite navigation industry. With advancements in technology and reductions in launch costs, LEO constellations are being developed to complement or augment traditional Global Navigation Satellite Systems (GNSS). These innovations aim to address critical challenges of GNSS such as signal vulnerability, urban canyon coverage, slow convergence times and more.

This report outlines the current state of the LEO PNT market, analysing technological advancements, key players, regional initiatives, and technical challenges. It shows that unlike traditional GNSS systems that are run by governments, LEO PNT has a mix of government and commercial players, and is generally driven by market demands. It also demonstrates that there are different approaches to providing PNT from LEO, including developing dedicated PNT constellations, using signals of opportunity (SOP) from non-PNT satellites, and offering integrated communications and PNT services.

With increasing demand for assured PNT services across industries such as autonomous systems, logistics, and critical infrastructures, LEO PNT is poised to play a pivotal role in contributing to the future satellite navigation ecosystem. LEO PNT systems promise unique advantages, including improved signal diversity, enhanced resistance to radio frequency interference, and faster satellite upgrade cycles.

However, this rapid development raises critical concerns about system interoperability, spectrum management, and governance. Coordination among commercial, government, and multi-national players will be essential to ensure these systems can operate harmoniously. Without effective collaboration, fragmentation in standards and competing systems may hinder the global adoption of LEO PNT solutions.

The report primarily focuses on dedicated PNT systems, while briefly addressing SOP and integrated approaches. Significant research is being conducted in the SOP domain, utilising signals from constellations such as Starlink and others. These efforts are steadily advancing, with results nearing metre-level navigation accuracy under certain conditions. However, it is noted that these systems remain in the research phase and are not yet ready for commercial deployment.

The report also highlights the significant growth of satellite communication constellations, which could disrupt the PNT space and reshape market dynamics if they choose to enter the sector.

Technical aspects of LEO PNT systems are analysed and compared to GNSS, revealing key differences in handling precise orbit determination, timescale references, and ionospheric delays. LEO satellites orbit much closer to Earth than Medium Earth Orbit (MEO) satellites, exposing them to additional forces such as atmospheric drag, which must be accounted for. Furthermore, their position within the ionosphere introduces extra complexities in managing ionospheric effects.

LEO satellites cannot carry onboard atomic clocks like GNSS satellites due to size, weight, power, and cost (SWaP-C) constraints. As a result, alternative time synchronisation methods are required, such as time transfer from ground stations, GNSS or geostationary satellites, or employing optical inter-satellite links.

All known LEO PNT initiatives and emerging service providers are profiled including Iridium® STL, Xona Space, and TrustPoint (USA); JAXA and ArkEdge Space (Japan), Centispace, Geely, and SatNet LEO (China); and ESA’s FutureNAV LEO-PNT In-orbit demonstration (Europe), as well as two emerging systems, namely Fergani Space (Turkey) and GNSSaS (UAE).

Currently, Iridium® STL is the only provider offering a commercial service. While it delivers timing accuracy of <100ns, the positioning accuracy remains in the range of metres to tens of meters due to the limited number of satellites in LEO. The other players in the market are still emerging, with most (except for ArkEdge Space) targeting high-accuracy, assured centimetre- to decimetre-level positioning. ArkEdge Space, on the other hand, is developing a VHF Data Exchange System Ranging (VDES-R) for maritime applications.

Space segment is covered, which identified the choice of satellite platform, navigation payload, orbit type and launch costs as key parameters that define the constellation coverage and the number of satellites in view at different locations on Earth. It was found that most emerging providers will have constellations ranging between 200 and 500 satellites across different types of orbits. When it comes to a choice of satellite platform, most providers are using mini satellites in a vicinity of a 100kg. The only exception is TrustPoint who are using a 10kg 6U cubesats.

Importantly, the receiver market is also examined, showing that it is beginning to emerge as various GNSS manufacturers are starting to incorporate LEO PNT signals into their receivers. Currently, this primarily focuses on L-band signals, meaning existing GNSS receivers can be upgraded to receive LEO satellite signals via firmware updates. Xona Space is a frontrunner in this area, having secured partnerships with several GNSS receiver and simulator manufacturers.

All the emerging LEO PNT providers are currently in the early stages of launching satellites into orbit and are expected to achieve initial operating capability (IOC), with at least one satellite in view for timing applications, within the next 2–3 years. Full operational capability (FOC) is anticipated closer to the end of the decade.

In terms of frequency spectrum, Iridium® STL, Xona Space, Centispace, Geely, and SatNet LEO are utilising L-band, while TrustPoint and JAXA will be operating in the C-band. ArkEdge Space is using VHF, and ESA’s FutureNAV LEO-PNT In-orbit Demonstration mission will target L, S, C and UHF bands.

A common set of characteristics has been developed to compare the different systems. Given that the market is still in its early stages, much of the information remains confidential, subject to change, or simply unknown. Therefore, this report offers a snapshot of developments at the end of 2024, which will serve as a benchmark for future editions of this report as the systems evolve and mature over time.

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS), such as GPS, GLONASS, Galileo, and BeiDou, have been the cornerstone of Positioning, Navigation, and Timing (PNT) services for decades. In fact, American GPS, the original GNSS, celebrated its 50th birthday in 2024. These systems continue to be used by billions of people daily, providing PNT services for a wide range of applications, both in defence and civilian domains.

Broadly speaking, the space segment of each GNSS constellation consists of around 30 satellites in a Medium Earth Orbit (MEO) at altitudes of between 19,000km and 23,000km, thus providing between 8-10 satellites in view at any point on or near the Earth surface. GNSS technologies, including various augmentation systems, are integral to modern society, supporting activities like navigating ships, aiding aircraft landings, and providing precise timing information for critical infrastructures. GNSS also provide precise time synchronisation to Coordinated Universal Time (UTC), which has become deeply integrated and relied upon by many industrial sectors, including automotive, finance, telecommunications, maritime, aviation, and energy.

Various research studies from the UK and USA have estimated the economic impact of loss of GNSS equates to around a billion dollars to the economy of each country on a daily basis [1]-[3], although it has later been argued that this number is a huge underestimate, and that it is almost impossible to estimate the real impact accurately, because so much of the economy depends on GNSS.[1] This is especially noteworthy because GNSS signals are inherently vulnerable and lack security measures, leaving them exposed to risks such as unintentional radio frequency (RF) interference, as well as deliberate threats like jamming, spoofing, and cybersecurity breaches.

Whilst GNSS has served, and continues to serve, the global society exceptionally well, there has been a rise in incidents of RF and GNSS signal failures and attacks, both on the ground and in space. Core subsystems of satellites have failed and required replacement. For example, Europe's Galileo ground facility experienced a week-long outage in July 2019 which affected many users worldwide.[2]

Targeted attacks on GPS and other GNSS signals have been reported worldwide. In the US alone, there were two significant GPS disruption events in 2022 in Denver and Dallas airports [4]. More broadly, jamming and spoofing incidents are becoming daily occurrence across regions in Europe, America, the Middle East, Africa, and Asia, especially around the conflict zones affecting thousands of flights every day. Recently, aviation pilots reported frequent navigation signal disruptions along Asia-Pacific Sea routes, posing safety risks to passengers and crew.[3]

GPS jamming also played a key role in the crash of the Azerbaijani passenger flight aircraft on 25 December 2024 – tragically coinciding with the finalisation of this report – in which 38 people have lost their lives.[4]

Cyber-attacks have also attempted to compromise critical PNT infrastructure, with U.S. Space Force (USSF) officials expressing concern over the increasing frequency and sophistication of these threats. As global geopolitical tensions rise, the risk of breaches and disruptions to global services grows.[5]

These threats are not confined to Earth, but extend to the space assets (i. e., satellites). Increasing reports suggest that space assets are frequent targets of ground-based lasers and RF jammers, with recent remarks by the USSF underscoring this concern.[6] Additionally, recent missile and anti-satellite weapon tests have highlighted the vulnerability of GPS and

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[1] https://www.gpsworld.com/the-billon-dollar-a-day-gps-mistake/

[2] https://www.gpsworld.com/why-galileo-experienced-a-week-long-service-outage/

[3] https://australianaviation.com.au/2023/03/qantas-pilots-subject-to-gps-jamming-from-chinese-warships/

[4] http://wikipedia.org/wiki/Azerbaijan_Airlines_Flight_8243

[5] https://www.ssc.spaceforce.mil/Newsroom/Article-Display/Article/3904505/focused-on-the-threat-cyber-attacks-part-1-of-6

[6] https://www.twz.com/43328/u-s-satellites-are-being-attacked-everyday-according-to-space-force-general

similar systems.[7,8] In addition to the inherent vulnerabilities of GNSS, there is a significant challenge in its performance in certain environments such as urban canyons. The world's positioning needs have evolved significantly since GNSS were originally conceived, designed and developed. Autonomous vehicles for example, were not part of the vision, and as a result, GNSS was not tailored to meet their needs. Thus, as we transition further into the era of autonomy – with autonomous cars and delivery drones becoming a reality and their applications expected to grow rapidly in the coming years – GNSS alone will not be sufficient to provide the high-accuracy assured PNT services that will be required [5].

As such, it started to become increasingly clear that GNSS in its current form is insufficient for the demands of today's and tomorrow's challenges, and multi-layered PNT options are needed.[9] Several national and international regulatory bodies have put forth calls to find GNSS alternatives.

In 2021, the National Institute of Standards and Technology (NIST) issued a report on "Foundational PNT Profile: Applying the Cybersecurity Framework for the Responsible Use of PNT Services," where it identified signals of opportunity (SOPs) and terrestrial RF sources as a mitigation category that apply to the PNT profile. In 2023, International Air Transport Association (IATA) invited the International Civil Aviation Organization (ICAO), in coordination with manufacturers and airspace user communities, to develop a global strategy on Alternative PNT to ensure continuity of flight and air traffic management (ATM) operations during interruptions of GNSS [4].

Several alternative PNT technologies are currently being explored with Low Earth Orbit (LEO) PNT constellations emerging as one of the key approaches. LEO PNT constellations offer several advantages over current GNSS systems, including enhanced resilience and improved positioning performance in obstructed and contested environments.

Advances in LEO PNT technology development have moved ahead very quickly over the last five years. This report will attempt to categorise the LEO PNT market and introduce the current and emerging initiatives and service providers. It will also attempt to establish some key metrics by which the service providers can be compared with one another. Furthermore, it will describe competing and complementary architectures that are being used by the different providers and the current state of development of each of these systems.

LEO PNT can be classified into several categories, including dedicated systems, signals-of-opportunity, and integrated (or fused) communication and PNT systems. This report mainly concentrates on dedicated PNT constellations, although the other systems are also reviewed briefly.

This report is the first in a series of annual reports that captures the state of the market of LEO PNT in December 2024. Subsequent reports will monitor the growth and change of the market as it matures over time. It must be noted that the systems described here are still in very early stages of development and many of the details are not available, are commercially sensitive, or simply unknown.

The report is structured in the following way. Chapter 2 provides information on satellite frequencies and signals, which is fundamental to understanding the emerging LEO PNT architectures. Chapter 3 looks at the LEO PNT ecosystem as a whole, examining the key differences between GNSS and LEO PNT, and describing the various LEO approaches to PNT. Chapter 4 describes technical considerations of the LEO PNT systems including precise orbit determination, timescale reference, the impact of the ionosphere, and the resilience aspects. Chapter 5 looks at the space segment, examining the satellite and the constellation design considerations for LEO PNT. Chapter 6 explores the receiver design aspects. Finally, Chapter 7 discusses the current and emerging LEO PNT providers including the various aspects of their respective solutions, and Chapter 8 provides a conclusion.

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[7] https://www.bbc.com/news/science-environment-59299101

[8] https://www.thesun.ie/tech/14157984/china-space-weapons-death-star-satellites-spaceplane

[9] https://www.gpsworld.com/no-silver-bullet-for-us-pnt-many-sources-needed/

2. SATELLITE FREQUENCIES AND SIGNALS

2.1 RADIO FREQUENCIES

Radio Frequency refers to the part of the electromagnetic spectrum of interest to PNT systems, typically between 3 kHz and 300 GHz. These frequencies are used in various communication systems, including radio, television, cellular networks, Wi-Fi, and satellite transmissions. Different frequency bands within the RF spectrum are allocated for specific applications, such as low frequencies for AM radio and higher frequencies for 5G networks and satellite communications. Satellite frequencies make use of specific RF bands known as Super High Frequency (SHF), to receive data from uplink stations and transmit data to users on Earth, as well as other satellites in space.

These frequencies are divided into different bands, each best suited for different purposes, such as communications, broadcasting, navigation, weather monitoring and more. The satellite frequency band spectrum is divided into seven bands (see Figure 1 below).

Table 1 lists the various SHF bands providing their use cases and characteristics. Apart from SHF, Table 1 also includes Ultra High Frequency (UHF) and Very High Frequency (VHF) bands. The reason UHF and VHF are included is due to their relevance in satellite communication and their foundational role in the broader spectrum. While UHF and VHF technically fall outside the SHF range, they are integral to many satellite-based applications, including telemetry, tracking, and command (TT&C) systems, as well as certain communication and broadcasting functions.

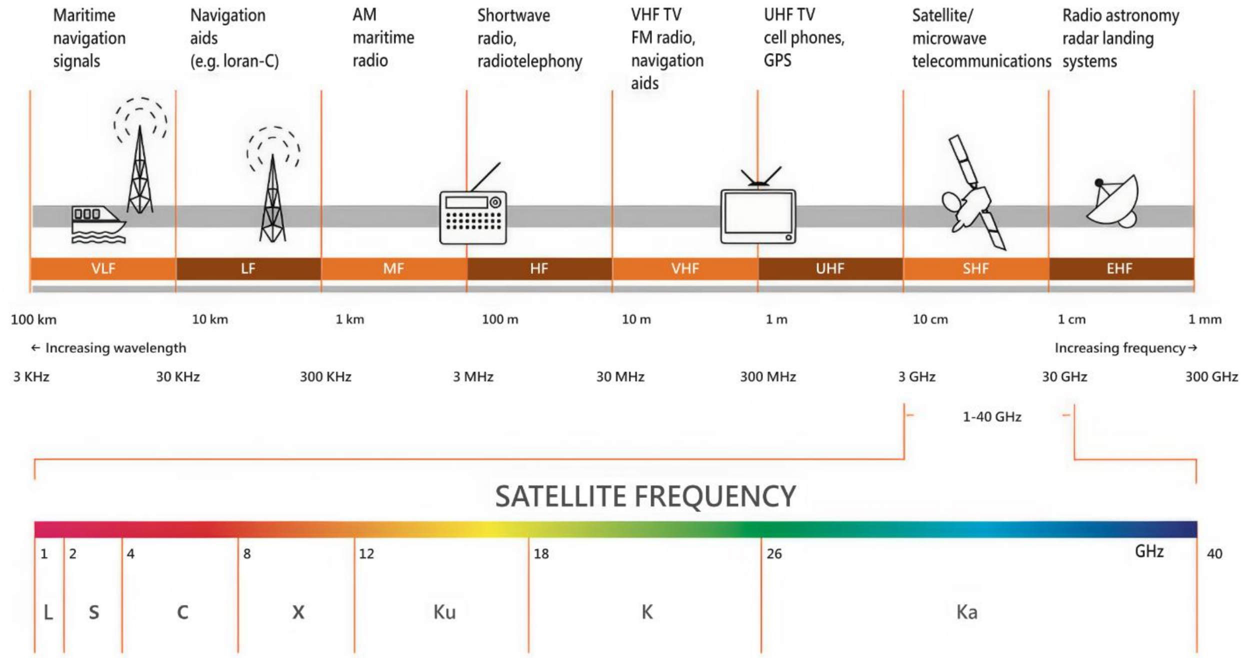

Figure 1. Radio frequency bands.[10]

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[10] https://www.esa.int/Applications/Connectivity_and_Secure_Communications/Satellite_frequency_bands

These bands provide essential support for satellite operations, particularly in environments where lower frequency ranges are better suited for signal propagation through dense atmospheres or over long distances. Including UHF and VHF in the table ensures a comprehensive overview of all frequencies relevant to satellite communication and PNT, facilitating a more holistic understanding for the audience and aligning with the report's goal of providing a complete reference for frequency utilisation across the spectrum.

It should also be noted that whilst technically UHF encompasses 0.3 to 3GHz spectrum, in the context of satellite communications, the lower end of the UHF band (around 300 MHz to 1 GHz) is particularly relevant [6]-[7].

Band	Frequency (GHz)	Wavelength (cm)	Uses	Characteristics
VHF	0.03 - 0.3	1000 - 100	Maritime and aviation communications, TT&C	- Less signal degradation in the atmosphere compared to higher frequency bands - Partial penetration of obstacles like trees
UHF	0.3 - 1	100 - 30	Search and rescue, TT&C, military SATCOM	- Minimal attenuation in the atmosphere, making them reliable in various weather conditions - Partial penetration of obstacles like trees
L	1 - 2	30 - 15	GNSS, satellite phones, maritime and aviation communications	- Good penetration through obstacles like rain, fog, clouds, and vegetation, making it ideal for navigation and mobile communications
S	2 - 4	15 - 7.5	Weather radar, surface ship radar, and some communications satellites	- Offers more bandwidth compared to L-band, supporting higher data rates - Less effective at penetrating atmospheric conditions compared to L-band
C	4 - 8	7.5 - 3.75	Satellite communications, satellite TV networks, raw satellite feeds	- Can penetrate through clouds, rain, and other atmospheric conditions effectively - Provides better resolution than L-band or S-band - Suitable for long-distance and large-area communication.
X	8 - 12	3.75 - 2.4	Military communications, radar applications, and some scientific satellites	- Less penetration through rain, clouds, and foliage compared to lower-frequency bands - More susceptible to rain fade and atmospheric attenuation
Ku	12 - 18	2.4 - 1.7	Direct-to-home satellite TV, VSAT systems for broadband	- Offers significant bandwidth, enabling high-speed data transmission for broadband internet - Limited weather penetration, susceptible to rain, snow and fog - Localised coverage – supports spot beams for targeted regional coverage
K	18 - 26	1.7 - 1.1	Satellite communications, radar systems, astronomy, vehicle radar	- Extremely fast data transmission - Highly susceptible to rain fade and atmospheric attenuation - Limited propagation distance, making it more suitable for localised applications.
Ka	26 - 40	1.1 - 0.75	High-speed internet (broadband satellite), military and commercial communications	- Provides very high data rates, but is more susceptible to weather interference, especially rain - Has a shorter propagation range compared to lower-frequency bands

Table 1. Satellite Frequency Bands

2.2 GNSS FREQUENCIES AND SIGNALS

Understanding which frequency bands are best used for different purposes is crucial in satellite design, receiver design, communication system planning, and avoiding interference between services. 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.

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 broadcasting, and even household appliances like microwave ovens. The ITU has played a significant role in designating the radio-frequency bands utilised by Radio Navigation Satellite Services (RNSS). Allocation agreements for these bands were established during the World Radiocommunication Conferences held in 2000 and 2003[11], where ITU finalised agreements to ensure compatibility and frequency sharing between the various GNSS constellations.

It should be noted that whilst Table 1 provided basic breakdown of the various frequency bands, the actual frequency allocations for various RNSS are defined by the ITU radio regulations [8]. In this context RNSS is a broader term, which covers both global and regional radio navigation satellite systems, whilst GNSS, is a specific category within RNSS that focuses on global systems only.

Before examining LEO PNT signal architectures, it is important to understand GNSS signals. There are currently four global navigational satellite systems, which are GPS, GLONASS, Galileo and Beidou, and two regional navigational satellite systems, Japan's QZSS and India's NAVIC. Figure 2 and Table 2 provide details on the frequencies and signals of all of these systems.

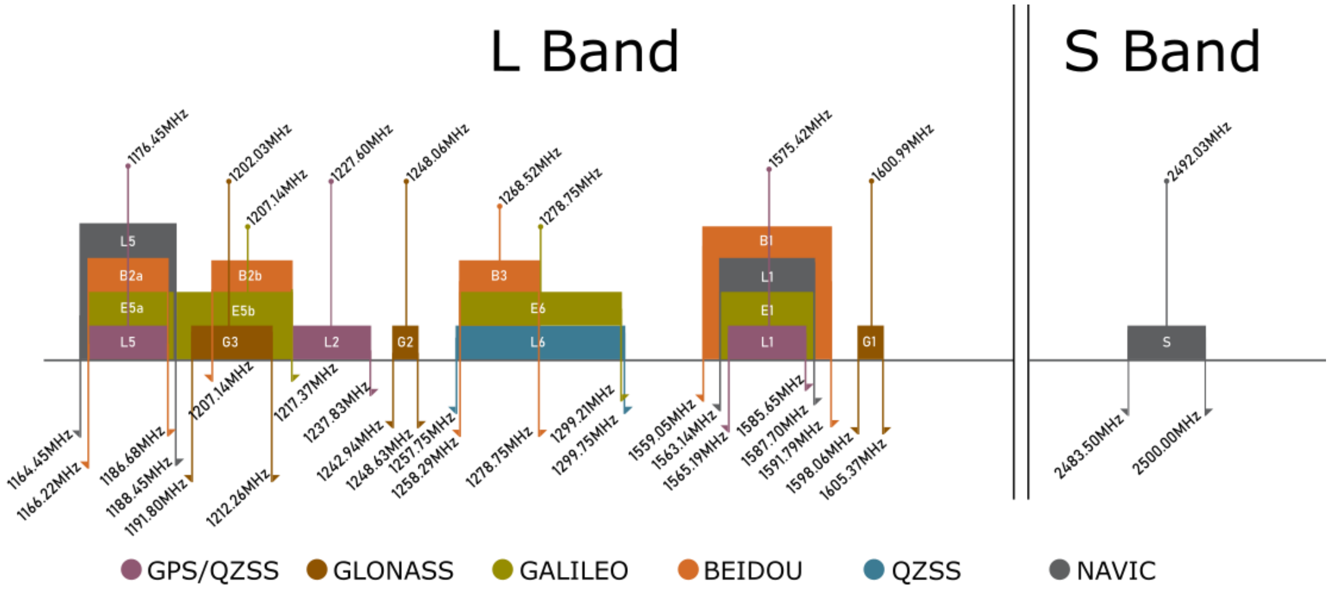

Figure 2. GNSS frequencies and signals.[12]

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[11] https://gssc.esa.int/navipedia/index.php/GNSS_signal

[12] Adapted from: https://www.calian.com/advanced-technologies/gnss/information-support/gnss-constellations-radio-frequencies-and-signals/

Constellation	Band	Frequency (MHz)				Signal	Minimum Received Power (5° Elev) dBW
		Centre	Lower	Upper	Bandwidth		
GPS	L1	1575.42	1573.42	1577.42	±2.0	L1C GPS III	-163.0(D)/-
			1574.397	1576.443	±1.023	L1C/A	-157.0
			1565.19	1585.65	±10.23	L1P(Y)	-161.5
			1560.0	1590.0	±15.0	M Code	-158.0
	L2	1227.60	1217.37	1237.83	±10.23	L2P(Y)	-160.0 (Block IIF)
			1226.577	1228.623	±1.023	L2C	-161.5 (Block IIF)
			1212.0	1242.0	±15.0	M Code	-164.0
	L5	1176.45	1166.22	1186.68	±20.46	L5I/Q	-157.9 (Block IIF)
GLONASS	G1	N/A	1598.062	1605.37		FDMA	
					±0.5	CA	-161.0
					±5.0	P	
	G1a CDMA	1600.995	1595.995	1605.995	±5.0	L1SC	-158.5
			1599.995	1601.995	±1.0	L1OC-D	
			1598.995	1602.995	±2.0	L1OC-P	
	G2	N/A	1242.937	1248.625		FDMA	
					±0.5	CA	-167.0
					±5.0	P	
	G2a CDMA	1248.06	1241.06	1255.06	±7.0	L2SC	-158.5
			1247.06	1249.06	±1.0	L2OC-D	
			1246.06	1250.06	±2.0	L2OC-P	
	G3 CDMA	1202.025	1191.795	1212.255	±10.23	L3OC-D / L3OC-P	-158.5
GALILEO	E1	1575.42	1563.144	1587.696	±12.276	D/P	-157.25
	E5a	1176.45	1166.22	1186.68	±10.23	D/P	-155.25
	E5	1191.795	1166.22	1217.37	±25.575	AltBOC	-155.25
	E5b	1207.14	1196.91	1217.37	±10.23	D/P	-155.25
	E6	1278.75	1258.29	1299.21	±20.46	D/P	-155.25
BEIDOU	B1I	1561.098	1559.052	1563.144	±2.046	BeiDou(II) OS	-163.0
	B1	1575.42	1559.052	1591.788	±16.368	BeiDou(III)/B1A-D/B1A-P	-159(MEO) / -161(IGSO)
	B2a	1176.45	1166.22	1186.68	±10.23	BeiDou(III) I/Q	-163.0
	B2/B2b	1207.14	1197.0	1217.0	±10.0	BeiDou(III) Not	-163.0
	B3I	1268.52	1258.29	1278.75	±10.23	B3C-D/B3C-P	-163.0
QZSS	L1	1575.42	1573.42	1577.42	±2.0	L1C D/P	-163.0(D) / -
			1574.397	1576.443	±1.023	L1C/A	-158.5
	L2	1227.60	1226.577	1228.623	±1.023	L2C	-156.82
	L5	1176.45	1166.22	1186.68	±10.23	I/Q	-158.5
	L6	1278.75	1257.75	1299.75	±21.0	Block II	-157.0
NAVIC	L1	1575.42	1563.14	1587.70	±12.28	SPS	-159.0
	L5	1176.45	1164.45	1188.45	±12.0	SPS	-159.0
	S	2492.028	2476.03	2508.30	±16.0	SPS	-162.3

Table 2. Frequencies and Signals of the global and regional navigation satellite systems.

As shown in Figure 2, GNSS signals, with the exception of NAVIC, are exclusively in the L-band. There are several reasons for this. Frequencies above 2 GHz would necessitate the use of directional beam antennas for signal reception, which would require more complex designs, such as phased arrays, to achieve the necessary focused beam and tracking capabilities, increasing overall system complexity. Pseudorandom Noise (PRN) codes, which are unique sequences of binary signals used to identify and synchronise with specific satellites, require substantial bandwidth for modulation on the carrier frequency, making higher frequencies (1-2 GHz), capable of supporting wide bandwidth, the preferred choice. Additionally, 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 1GHz.

2.3 C-BAND CONSIDERATIONS FOR GNSS

From the previous section, it is evident that, with the exception of the NAVIC, which transmits a single signal in S-band, all other GNSS signals have frequencies in the L-band. However, L-band is not the only band that has been considered for use in GNSS. The potential use of C-band has been explored in the past. Between 1998 and 2004, researchers in the US and Europe examined the feasibility of using the C-band for the Galileo constellation. Ultimately, it was decided against due to the technological limitations of the time, particularly the challenges associated with providing the required satellite payload [9]. Receiver adoption was also a key consideration. At that time Galileo was to be used as a complement to GPS, so having Galileo signals in a different band meant that all the existing GPS receivers would not be compatible with it.

The possible use of C-band was revisited again between 2007 and 2009 [10]. The C-band offers several advantages over the L-band, including reduced spectrum congestion, lower sensitivity to ionospheric delays, and improved resistance to jamming. However, these benefits are offset by several disadvantages. One key drawback is the higher free space loss due to the limitations on the higher signal frequency.

An omnidirectional C-band antenna at 5.015GHz will be 3.2 times smaller in the linear dimension than an equivalent L1 antenna at 1.575GHz due to the fact that the C-band wavelength is 6cm compared to the L1 wavelength of 19cm. As such, the area of the C-band antenna will be 10 times smaller than that of L-band antenna, meaning that C-band antenna will only receive 1/10th the broadcast power of the L-band signal.

However, the trend going forward will be to develop phased array antennas that point beams to overhead satellites. This can be done much more compactly at C band, which constitutes a big advantage.

Additionally, C-band signals are more susceptible to attenuation caused by environmental factors such as foliage, heavy rain, and other obstructions. The 2009 study concluded that the use of C-band for GNSS was unlikely before 2020, by which time technological advancements could potentially mitigate some of these issues [11].

Another critical consideration was the compatibility of user equipment. Receivers would need to include multi-frequency components to process signals across both the L-band and C-band, which may significantly increase the complexity, cost, power consumption, and size of GNSS receivers. Various antenna designs were evaluated, including single antennas and array systems with digital beamforming capabilities.

Although the research demonstrated that C-band could theoretically be incorporated into a GNSS such as Galileo, this has not been realised. However, as this report will demonstrate, the C-band is expected to play a significant role in the emerging LEO PNT ecosystem.

3. LEO PNT ECOSYSTEM

This chapter provides some insights into the LEO PNT ecosystem, noting the fact that the term 'ecosystem' is distinct from the 'market'. Whereas the market focuses on the economic and commercial dynamics, the ecosystem refers to the broader framework of technologies, stakeholders, and systems that enable the operation, development and integration of LEO PNT. The chapter firstly discusses the inherent differences between GNSS and LEO PNT, and then examines the different ways that PNT services can be provided using LEO satellites.

3.1 GNSS VS LEO PNT – KEY DIFFERENCES

GNSS and LEO PNT have several key differences, with the most significant being the orbit of the satellites. GNSS constellations are in MEO at altitudes between 19,000km and 23,000km. A GPS satellite takes nearly 12 hours to complete a full orbit, which translates to 6 to 8 hours for the length of a typical "pass" from horizon to horizon. It also means that around 30 satellites per constellation in MEO are enough to provide a global coverage, with 8-10 satellites in view at any point on Earth (except for the polar regions).

LEO PNT satellites are typically in orbits between 500km to 1,200km altitude, which implies an orbital period of between one to two hours. As a consequence, a horizon-to-horizon pass is typically between 10-15 minutes in length, depending on the type of orbit. This means that LEO PNT constellations require many more satellites than their GNSS counterparts. Typically, between 200-300 satellites would be required to provide the same number of satellites in view from Earth as GNSS, depending on the constellation design.

Precise Orbit Determination (POD) becomes more challenging in LEO as a number of additional forces need to be considered, such as atmospheric drag, solar radiation pressure, Earth albedo and thermal radiation effects. Ionospheric delay adds another layer of complexity for LEO PNT systems. The ionosphere, a layer of the atmosphere between 70-1000 km, consists of ions and free electrons formed by solar radiation and charged particle interactions with the upper atmosphere that can reflect and modify radionavigation signals travelling through it. Since LEO PNT satellites are orbiting inside the ionosphere, it means that space weather effects will have a larger impact on them, making POD even more challenging.

Timescale reference also presents an inherent challenge. GNSS receivers typically have a number of atomic clocks onboard, such as caesium, rubidium or hydrogen maser. The clocks are synchronised to the system time, which is in turn synchronised to UTC. LEO PNT constellations will likely consist of micro or mini satellites weighing between 20kg to 200kg each, compared to GNSS satellites that weigh around 2,000kg. Due to size, weight, power and cost (SWaP-C) constraints, it is impractical for large LEO PNT satellite constellations to accommodate these clocks onboard, so other ways to provide timescale reference to UTC are needed. This could be done via GNSS satellites, geostationary satellites, or through ground stations on Earth.

The rapid movement of LEO satellites offers certain advantages compared to the slower GNSS satellites in MEO. One key advantage is the easier computation of integer ambiguities – the unknown number of whole carrier phase cycles at the initial epoch of a measurement. Larger distance travelled by LEO satellites compared to MEO at much lower elevations will make the computation process easier. The fast-changing geometry should also help with positioning in urban canyons and other obstructed areas, due to the higher satellite density (more frequent visibility of multiple satellites from any given location), faster Doppler dynamics (better exploitation of Doppler shifts in signals, enhancing positioning accuracy), and improved satellite visibility (broader distribution of satellites across different altitudes and orbits, leading to better accuracy).

As LEO satellites are closer to the Earth, their signals will be much stronger, providing additional benefits such as enhanced resistance against signal jamming, as well as the potential for signals to penetrate buildings. There is also opportunity to encrypt and authenticate the signals, which will make them robust against spoofing attacks.

Another key difference is that GNSS are operated by government organisations. This differs significantly from the emerging LEO PNT constellations many of which are operated by private corporations. There are a few reasons for that including:

- **Historical development** – original GNSS, such as GPS and GLONASS were initially developed for military and strategic purposes, and only later became critical for civilian use. LEO PNT in contrast is driven by private sector innovations, which can cater to both commercial and government interests, but are not fundamentally tied to national security concerns.
- **Regulatory control** – since GNSS were originally intended solely for national security, governments have historically maintained full control over the design, launch, and operation of these systems. LEO PNT systems, on the other hand, are part of the emerging commercial space economy. Private companies are leading the development and operation of these constellations, and creating new revenue models by offering premium PNT services. At the same time, it should be noted that these companies are still bound by the spectrum regulations from the ITU.
- **Funding and business model** – governments fund GNSS as public infrastructure, which means that the systems are operated as public good, and the services are provided without a charge to the users, whereas LEO PNT providers expect to generate revenue by providing enhanced PNT services.
- **Technological advancements and market demand** – traditional GNSS are sufficient for most PNT needs, however they have limitations, particularly when it comes to resilience, and positioning in obstructed environments. LEO PNT services promise to fill the gaps of GNSS in areas that are more market-driven and commercially viable, while supplementing GNSS in contested and denied environments.

A critical factor in designing a LEO PNT system is clearly defining its intended purpose. Will the system augment GNSS, such as by reducing the convergence time for a Precise Point Positioning (PPP) service or enhancing positioning accuracy in urban canyons? Or will it function as a fully independent system, delivering PNT services without relying on GNSS? The system's architecture will vary significantly based on these criteria.

Economic factors are nearly as important as technical considerations when assessing the viability of LEO PNT systems. Unlike GNSS, which is freely available to users, LEO PNT services will most likely operate on a commercial basis. Some critics argue that this business model will make it difficult for LEO PNT systems to compete with GNSS.[13] This perspective has some merit, as GNSS and certain augmentation services, such as the Satellite-Based Augmentation System (SBAS) and the recently introduced Galileo High Accuracy Service (HAS), are available at no cost to users. Some countries (e.g., Australia), even have free access to Real-Time Kinematic (RTK) corrections, however they are typically basic (i.e., single base), and are provided to the users as is, without any assurance or technical support. However, while the abovementioned fundamental GNSS services are free, premium solutions offering high accuracy and reliability, do require commercial subscription services. The viability of paid access models to more sophisticated GNSS services may in turn indicate that commercial LEO PNT services can be similarly competitive in tapping into certain user markets.

The unique characteristics of LEO, such as reduced latency, higher signal strength, and better coverage in challenging environments, provide a significant opportunity to enhance positioning performance as well as reliability beyond what GNSS can achieve alone. By leveraging these advantages, LEO PNT systems may justify their cost and establish themselves as a valuable alternative for users requiring accuracy, assurance and reliability.

3.2 TYPES OF LEO PNT SERVICES

LEO PNT services can be broadly categorised into three groups. The first one is dedicated PNT systems that aim to offer high accuracy positioning services [12]-[14].

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[13] https://www.gpsworld.com/eab-qa-could-a-new-pnt-constellation-replace-gnss/

The second category involves signals of opportunity, which refer to using signals from non-PNT satellites (e.g., Starlink) to compute positioning and time information [15]-[17]. The last category involves fused communications and PNT systems [18]-[21]. These three groups are briefly described below.

3.2.1 Dedicated PNT Systems

Dedicated PNT systems are satellite constellations specifically designed to provide PNT services as their primary function. In this regard, they share similarities with GNSS, however, there are key differences in their design and operational requirements. As explained in Section 3.1, PNT systems deployed in LEO differ significantly from their GNSS counterparts in MEO, particularly in terms of the number of satellites required to achieve global or regional coverage as well as many other technical aspects [22]-[23].

Table 3 provides a list of the current and emerging dedicated LEO PNT providers and some basic constellation characteristics, noting that all of these constellations are covered in detail in Chapter 7. JAXA, ESA and SatNet LEO are government organisations, while Iridium, Xona Space, TrustPoint, Centispace, Geely and ArkEdge Space are private companies. Apart from ESA's FutureNAV LEO-PNT In-orbit Demonstration (IoD), which is a mission consisting of 10 satellites as an enabler of a future LEO PNT operational constellation in Europe, all the others are intended to be developed as operational constellations that will feature between 200 and 500 satellites each.

The size of the constellation varies depending on several factors, including the specific constellation design, the type of orbits chosen, the required number of satellites in view, and the need for robust coverage in high-latitude regions, such as around the poles. These differences highlight the unique challenges and opportunities presented by LEO-based PNT systems compared to traditional GNSS solutions.

Company	Country	First Launch	Launched	Frequency Band	Total Planned
Iridium	USA	2017[14]	66	L	66
Xona Space	USA	2022	1 tech demo	L	258
TrustPoint	USA	2023	2 tech demos	C	300
JAXA	Japan	-	0	C	480
ArkEdge Space	Japan	-	0	VHF	50-100
Centispace	China	2018	5 tech demos	L	190
Geely	China	2022	0	L	240
SatNet LEO	China	2024	0	L	506
ESA's FutureNAV LEO-PNT IoD	Europe	-	0	L, S, C, UHF	10 demos (up to 263)

Table 3. Current and emerging dedicated LEO PNT providers.

3.2.2 Signals of opportunity

Signals of opportunity refer to the use of radio signals from satellites that were not specifically designed for PNT services. This concept generally involves extracting Doppler shift, pseudorange, and/or carrier phase measurements from these signals to compute the user's position. These signals are typically derived from satellites used for communications, and other non-PNT applications [24]-[25].

Although opportunistic navigation is not the main focus of this report, it is important to acknowledge the significant advancements occurring in this field, as they provide valuable context for understanding the role of dedicated LEO PNT systems.

One of the main challenges in using SOP for PNT is that the structure of the signals is not standardised, nor designed for navigation purposes, meaning that the users will firstly have to decode the signals. However,

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[14] 2017 refers to first launch of second-generation NEXT satellites.

progress is evident on that front, as the structure of Starlink signals has already been decoded and published [26]-[27], and it is expected that the others will follow.

Further to this, the onboard clocks are generally not as stable [28], and the satellite ephemeris are not as precise as those from dedicated PNT systems [29]. Despite these challenges, significant research is being conducted to refine the use of SOPs for navigation. While much of the focus is on the Starlink constellation whose signal in the Ku-band has been studied in detail, the use of other LEO constellations are also being investigated [30]-[32].

The new paradigm of cognitive opportunistic navigation has proven to enable the successful exploitation of multiple LEO constellations (e. g., Starlink, OneWeb, Orbcomm, Iridium, and NOAA) for PNT [33]-[35]. The most recent results demonstrated the ability to achieve metre-level navigation accuracy on a ground vehicle with LEO constellations [36].

Another recent study that investigated the timing properties of Starlink signals has found that they have large and unpredictable variations in frame timing, which can differ from beam to beam, making them currently unsuitable for purely opportunistic PNT. However, the study also found that the Starlink satellite payload is in principle capable of supporting pseudorange-base PNT with positioning and timing accuracy comparable and potentially even exceeding traditional GNSS. One way that the timing issue could be resolved without any modifications to the payload or signal structure, is by setting up a network of reference stations covering a certain area, that would measure the Starlink frame time of arrival (TOA), compute a clock model and distribute it to the users [37].

It should be noted that if a network of reference stations is set up, it could also be used to compute satellite orbit errors and potentially atmospheric corrections, making it very similar to the current Network Real-Time Kinematic (NRTK) GNSS positioning from Continuously Operating Reference Station (CORS) networks.

While advancements in opportunistic navigation using LEO satellites have shown promising results, it is important to emphasise that these technologies are still in the research phase and should be approached with caution. They are not yet mature enough for industrial or commercial deployment. Challenges such as unstable clocks, large satellite orbit errors, and, most significantly, the unknown signal structures, prevent these systems from being fully operational for widespread use at this stage.

What these results truly underscore is the significant potential of dedicated PNT systems in LEO, which benefit from purpose-built satellites, sensors, signal structures, ground infrastructure, and support from commercial receiver manufacturers.

3.2.3 Fused Communications and PNT systems

The last category of LEO PNT systems involves fused communications and PNT systems, which means an integrated constellation providing both communications as well as PNT services. There is a significant number of satellite constellations which are currently being developed for communications, high speed internet, telematics, IoT, air traffic management and more, which in principle could also provide some PNT services.

Table 4 lists the various communication constellations in LEO, current and emerging, including the number of satellites launched, total amount of planned satellites and the frequency band that they are using. It should be noted that the list may not be complete, and whilst care has been taken to ensure the various parameters are correct, some of the information might be out of date, and should be used with caution. This is especially true when it comes to the number of satellites launched, as the exact figures are updated frequently.

Whilst a PNT service is not the prime purpose of these constellations, some of them do provide PNT offerings, which are described below:

- Iridium NEXT constellation has a hosted PNT payload from Satelles, which provides a commercial Satellite Time and Location (STL) service in L-band, fully independent of GNSS. In 2024 Satelles was acquired by Iridium and the service was rebranded as Iridium® STL (more details in Section 7.2.1).
- Globalstar has partnered up with the US-based hardware and software manufacturer Echo Ridge to collaborate on an assured PNT service in S-band

called Augmented Positioning System (APS). Due to the low number of satellites in orbit (48), the service is not intended for high accuracy applications. In 2021, Echo Ridge was acquired by Parsons Corporation.

- China SatNet is developing the Guowang mega-constellation, which will consist of nearly 13,000 satellites, with the first launch in December 2024. In addition, China SatNet is working on the SatNet LEO PNT constellation mentioned in the previous section (more details in Section 7.2.8).
- Similarly, GeeSpace, which is a subsidiary of Zhejiang Geely Holding Group, is building a broadband mega-constellation called GEESATCOM, consisting of 5,676 satellites. It is also planning to have a dedicated PNT constellation of 240 satellites (more details in Section 7.2.7).
- Skykraft, an Australian startup deploying a LEO constellation for air traffic management, is looking to develop a collaborative, open-source PNT architecture in the S-band, to be adopted by different satellite constellations in LEO to provide PNT services. The advantages of this approach include cross-provider compatibility, shared development costs, broader adoption and wider end-user accessibility.
- ArkEdge, a Japanese start-up is developing a VHS Data Exchange System (VDES) for maritime use, which is mainly a communications system, but will also have a dedicated ranging component called VDES-R, which can be used to position ships at sea independently from GNSS (more details in Section 7.2.5).
- Eutelsat OneWeb is actively developing its Gen II satellites, expected to include some PNT features. While specific details remain unavailable, the satellites are being designed to align with the objectives of the EU's IRIS² program.

Company	Constellation	Country	First Launch	Launched	Frequency	Total Planned
SpaceX	Starlink	USA	2019	7000+	Ku, Ka	42,000
China SatNet	Guowang	China	2024	10	Ku, Ka	12,992
SSST	G60	China	2024	36	Ku	12,000
Hongqing Technology	Honghu-3	China	-	0		10,000
GeeSpace	GEESATCOM	China	2022	30		5,676
Lynk	Lynk	USA	2022	6	L	5,000
Amazon	Kuiper	USA	2023	2	Ku, Ka	3,236
Skykraft	Skykraft	Australia	2023	10	S	2,976
EutelSat OneWeb	OneWeb Gen I	France, UK	2019	634	Ku, Ka	648
Rivada	OuterNET	USA	-	0	Ka	576
CASC	Hongyan-1	China	2018	1	Ka, L	320
SpaceRise	IRIS²	EU	-	0	Ka, S	290
Sateliot	Sateliot	Spain	2023	6	L	250
Telesat	Lightspeed	Canada	-	0	Ku, Ka	198
AST SpaceMobile	Bluebird	USA	2023	5	L, S	168
ArkEdge	ArkEdge	Japan	-	0	VHF	50-100
Iridium	NEXT	USA	2017	80	L	80
Globalstar	Globalstar	USA	1998	48	S	65
Orbcomm	Orbcomm	USA	1995	31	L, S	31

Table 4. Current and emerging satellite communication providers in LEO as of December 2024.

A key point when discussing fused systems is the significant bandwidth available in higher frequency bands like the Ku-band. For example, a single Starlink channel is 240 MHz wide, which is wider than all existing RNSS bands combined (see Table 2), and Starlink offers eight such channels. These large bandwidths are highly advantageous for multipath mitigation and achieving precise positioning and timing.

4. TECHNICAL ASPECTS OF LEO PNT

This chapter describes some of the key technical aspects of LEO PNT systems, including precise orbit determination, timescale reference, ionospheric delay, and resilience to RF interference. These technical aspects are only covered at high level to give the reader an understanding of the main issues that need to be overcome when considering a LEO PNT system. A more detailed analysis of the various technical considerations of LEO PNT can be found in [22]-[23], as well as many other references throughout the report.

4.1 PRECISE ORBIT DETERMINATION

POD of LEO satellites plays a crucial role in Earth observation and space science applications that require highly accurate satellite positioning. Over recent decades, POD methods have evolved significantly, enabled by advances in GNSS technology, improved force modelling capabilities, and enhanced analysis techniques. This section provides an overview of current POD methods, key applications, and existing limitations.

4.1.1 Methods and implementation

The three main approaches to LEO satellite POD are dynamic, kinematic, and reduced-dynamic methods. Each has distinct characteristics and applications [38]. The choice of method largely depends on the user's requirements. Dynamic POD is often favoured by space agencies for operational mission control, kinematic POD is primarily used by research institutions for gravity field studies and atmospheric sensing, while reduced-dynamic POD is widely adopted by both scientific and commercial satellite operators due to its balance of accuracy and robustness.

Dynamic POD relies on solving the satellite equations of motion by considering all forces acting on the satellite. The Earth's gravity field exerts the dominant force on LEO satellites, requiring high degree and order spherical harmonic gravity field models. Time-variable gravity effects must be considered, along with tidal effects from solid Earth, ocean, and pole tides which are typically modelled separately. Third-body gravitational forces from the Sun, Moon, and to a lesser extent other planets, are incorporated using precise planetary ephemerides. These corrections are essential for achieving sub-decimetre POD accuracy.

Solar radiation pressure presents a significant challenge in dynamic modelling. This includes direct solar radiation as well as Earth albedo and infrared radiation effects. Accurate modelling requires detailed knowledge of the satellite's surface properties and attitude, becoming particularly complex for satellites with large solar panels. Additionally, for satellites below approximately 1000km altitude, atmospheric drag becomes a major perturbation. This force can be highly variable, for example due to solar and geomagnetic activity, as well as atmospheric density and composition. It requires sophisticated atmospheric density models in order to compensate its effect on the satellite. The drag effect depends strongly on the satellite's cross-sectional area and remains one of the largest error sources for low-altitude satellite POD.

In contrast, kinematic POD takes a fundamentally different approach by relying solely on GNSS observations made by an onboard GNSS receiver. This method processes dual-frequency code and phase measurements, typically forming ionosphere-free linear combinations to eliminate first-order ionospheric effects. Success depends on having precise GNSS orbits and clocks, careful cycle slip detection and repair algorithms, and proper handling of antenna phase centre variations [39]. While this approach avoids force model errors, it requires continuous high-quality GNSS tracking data. The kinematic solution is more sensitive to poor GNSS satellite geometry and generally exhibits higher noise than dynamic solutions. Additionally, it cannot provide orbit prediction capability during data gaps.

The reduced-dynamic approach has emerged as the most effective POD method by combining the strengths of the dynamic and kinematic techniques. This method uses dynamic models as a foundation while incorporating GNSS observations to constrain the solution. It estimates empirical parameters and stochastic accelerations to account for force model deficiencies. The relative weighting between dynamic models and observations can be optimised based on data quality and application requirements. This flexibility and robustness have made reduced-dynamic POD the favoured approach for many operational LEO missions.

4.1.2 Achievable accuracies

The accuracy achieved by POD methods depends on multiple interrelated factors. Satellite characteristics play a major role – including orbital altitude, surface properties, attitude control capability, GNSS receiver quality, and antenna configuration. Data quality is equally important, encompassing GNSS observation noise levels, data completeness, number of tracked satellites, multipath effects, and phase centre stability.

Typical accuracies range from 10-50 cm for pure dynamic solutions, 5-20 cm for kinematic solutions, and 2-5 cm for reduced-dynamic processing. However, these figures can vary considerably based on specific mission characteristics and processing strategies. The highest accuracy is generally achieved in post-processing mode using reduced-dynamic methods with careful parameter tuning [40].

4.1.3 Current limitations and challenges

Despite significant advances, several challenges persist in LEO satellite POD. Dynamic model limitations remain a primary concern. Atmospheric density modelling presents particular difficulties due to the complex and variable nature of the upper atmosphere. Solar and geomagnetic activity can cause rapid density changes that are difficult to accurately model. Solar radiation pressure modelling also remains problematic, especially for satellites with complex geometries or varying attitude. Thermal radiation effects, while smaller in magnitude, are difficult to model due to their dependence on satellite temperature distribution and surface properties.

GNSS-related issues present another set of challenges. Multipath effects from the satellite body itself can contaminate measurements, particularly for smaller satellites where antenna placement options are limited. Phase centre variations must be carefully calibrated, ideally through in-flight calibration procedures [41]. Receiver clock stability affects measurement quality, especially for high-rate applications. Data gaps and cycle slips require sophisticated detection and handling procedures.

Orbit prediction presents significant challenges when satellite orbits are computed at ground stations. This is further complicated by orbit validation issues in kinematic processing when performed onboard the satellite. Another critical challenge is the linear relationship between the orbits and clocks, particularly when non-atomic clocks are used. Recent research has demonstrated the complexity of these challenges in various contexts, from high-precision time transfer and relative orbital determination to real-time clock estimation with predicted orbits and orbit prediction using antenna phase centre calculations [42]-[44].

4.1.4 Future developments

Several promising developments may address current limitations. Enhanced force models utilising machine learning techniques show potential for improving atmospheric density prediction and radiation pressure modelling. Advanced GNSS processing capabilities, including multi-constellation solutions and new signal types, may enhance measurement quality and geometry. Better antenna calibration techniques and multipath mitigation strategies could reduce systematic errors.

Analysis strategies continue to evolve, with an emphasis on reducing latency while maintaining accuracy. Real-time POD capabilities are advancing through improved algorithms and faster computers. Enhanced stochastic modelling techniques offer better handling of model deficiencies. Automated quality control procedures are becoming more sophisticated. The availability of precise GNSS orbital and clock correction through space links is another major step toward real-time high-accuracy POD [45].

4.2 TIMESCALE REFERENCE

Precise time measurement is a core aspect of satellite-based navigation infrastructure. The observables are constructed by precisely tracking the transmission and reception time of the navigation signal. The transmission time is maintained by synchronising the onboard clock of navigation satellites with atomic clocks on the ground. It should be noted that communications with the ground station can suffer long gaps. As a result, the onboard clocks of navigation satellites must be stable enough to drift within permissible limits during the communications gap. Currently, for GNSS, this gap is typically 8-12 hours. Containing the ranging error within 1.5 m between this gap requires clock drifting of less than 10^{-13} s/day, which can be achieved using atomic clocks.

A Rubidium Atomic Frequency Standard (RAFS) generally offers good short-term stability, but less than Caesium Atomic Frequency Standard (CAFS) and Passive Hydrogen Maser (PHM) over long periods. The typical accuracy of RAFS is around 10^{-12} s/day. These are smaller and less expensive compared to Caesium and Hydrogen Maser clocks, making them suitable for compact applications. They are commonly used in GPS satellites. A CAFS provides better long-term stability than RAFS, making it a standard for defining the second. Their clock drift is around 10^{-14} s/day, which is significantly less than Rubidium. However, CASFs are larger and more expensive than Rubidium clocks, which can limit their use on smaller platforms. PHM offers the best stability, particularly for long-term applications and can achieve accuracies of about 10^{-15} s/day. However, PHMs are larger and more expensive than either Rubidium, or Caesium clocks, which can restrict their use to specialised applications.

Note that for global coverage, a large number of satellites are required in a LEO PNT constellation compared to GNSS. As a result of scalability, traditional space-qualified atomic clocks that are used in GNSS are not suitable because of high SWaP-C.

Alternatively, less accurate clock technologies, such as Oven-Controlled Crystal Oscillators (OCXOs) and Chip-Scale Atomic Clocks (CSACs), can be considered for onboard timing in applications where SWaP-C constraints of traditional atomic clocks (e.g., Rubidium or Caesium) are prohibitive.

While both OCXOs and CSACs have poorer frequency stability than the atomic clocks used on GNSS satellites they have much lower SWaP-C. OCXOs are based on a macroscopic quartz crystal and exhibit superior short-term stability over a second, but suffer from poor accuracy and excessive timing drift in the longer term due to environmental sensitivities. Good quality OCXOs can achieve stabilities at the level of 10^{-12} at 1 second. Their long-term stabilities typically drift to several ppb/days. CSACs on the on the other hand are referenced to atomic transitions. Whilst their short-term stability is at a level of 10^{-10} at 1 second, they have the potential to achieve better stabilities than the OCXOs in the long term, e.g., at the level of 10^{-11} at one day [46]. Maintaining the ranging error within the required limit will require frequent clock updates from highly stable timing sources. This can be achieved in a number of ways, as described below.

The first method to provide frequent clock updates to the LEO satellites is by establishing dense networks of ground stations that can communicate stable time information from the ground to the navigation satellites (see Figure 3) on a (near-) continuous basis noting that LEO satellites do not follow the same ground-observed arcs in each orbit cycle, unlike GNSS.

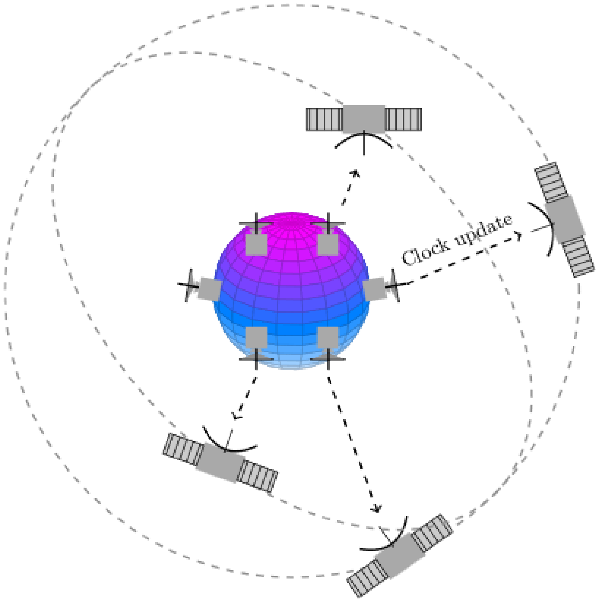


Figure 3. Timing synchronisation using ground stations.

It should also be noted that clock prediction between ground or inter-satellite updates can be a challenge.

Another approach to maintaining a precise time scale using low SWaP-C clock technology is to utilise existing GNSS satellites and/or satellites in the geostationary orbit (GEO), such as SBAS, for time transfer from the ground (see Figure 4). This will not require many ground stations to transmit the precise time. However, in this case, the PNT constellation will be dependent on the GNSS or SBAS, which may impact the resilience of the LEO service.

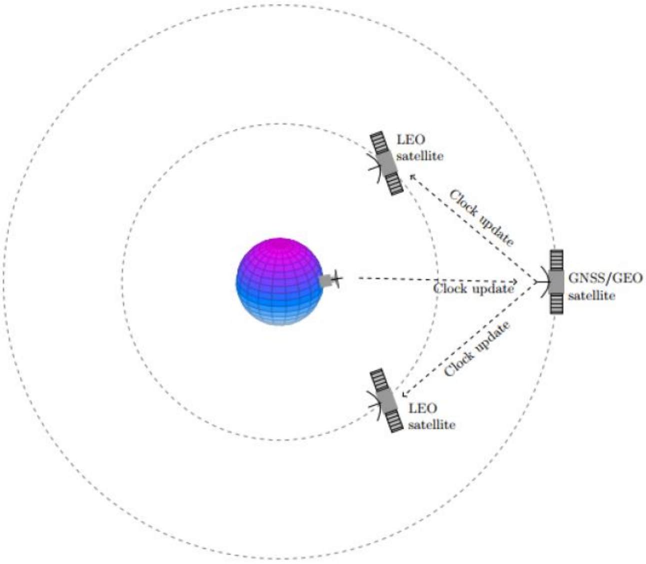


Figure 4. Timing synchronisation using GNSS or GEO satellites.

Finally, Optical Inter-Satellite Links (OISL) offer another solution for synchronising time between satellites in LEO. These links utilise laser-based communication to establish high-bandwidth, low-latency connections between satellites, allowing for precise time synchronisation across a constellation. By exchanging time-stamped data via optical beams, satellites can compare their onboard clocks and correct any discrepancies in real-time (see Figure 5).

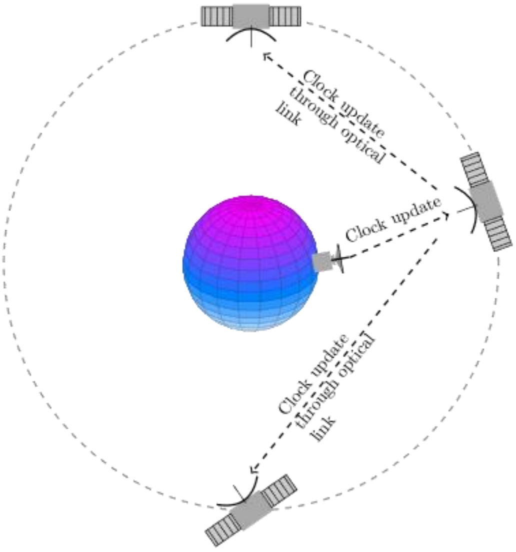


Figure 5. Timing synchronisation using optical inter-satellite links.

This method offers significant advantages over traditional RF links, as optical signals are less susceptible to interference and atmospheric delays, providing more accurate synchronisation. However, despite the advantages, OISLs are still an emerging technology, and their long-term reliability in the harsh space environment is not yet fully proven.

In order to advance this technology, ESA has launched an IoD mission called Optical Synchronised Time and Ranging (OpSTAR). OpSTAR's objectives are to: i) demonstrate the use of OISLs for time synchronisation & ranging; ii) assess benefits of a new system architecture based on OISLs; iii) demonstrate and measure performance improvement at system/user level; and iv) develop open standards for PNT based on OISLs (physical, data link and network layers) [47].

In summary, a low SWaP-C onboard clock is a requirement for a cost-effective LEO-PNT constellation. Using traditional space-qualified atomic clocks in a large number of LEO-PNT satellites is not economically scalable. An alternate approach needs to be implemented that enables the use of low SWaP-C onboard clocks while preserving the ranging accuracy.

4.3 IONOSPHERIC EFFECTS ON LEO PNT SIGNALS

The ionosphere is a layer of the atmosphere that extends from approximately 70km and 1000km above the Earth's surface. The ionosphere is a critical atmospheric layer for the propagation of radio navigation signals. The solar radiation ionises atmospheric gases, creating free electrons and charged particles in the ionosphere, which can refract and delay radio signals, introducing errors in GNSS or any other radionavigation systems passing through it. The impact is particularly pronounced for lower-frequency signals, which are more susceptible to ionospheric disturbances. Variations in ionospheric density caused by solar activity, geomagnetic storms, or the diurnal cycle can lead to unpredictable signal behaviour, such as scintillation and phase shifts, which degrade signal quality.

To mitigate these effects, GNSS users often include ionospheric models or use dual-frequency signal transmission, allowing receivers to estimate and correct for ionospheric delays, thereby enhancing accuracy and performance. For LEO PNT, the ionosphere presents an additional set of challenges compared to GNSS.

First of all, LEO satellites are typically orbiting inside the ionosphere. Satellite drag and space weather effects have a larger impact on LEO satellites compared to MEO satellites. It is known that LEO satellites may become “lost” for extended periods due to their own navigation systems being impacted by space weather [48]-[49]. The accuracy of satellite orbit determination and prediction is an essential aspect of a PNT system. Hence, POD which takes into account various atmospheric and ionospheric parameters to maintain a high level of positioning accuracy, becomes even more complex for LEO satellites, as described in Section 4.1.

Secondly, signals transmitted from LEO satellites for PNT applications are also more likely to be affected by space weather and other ionospheric effects (e.g., scintillation, plasma bubbles, etc.). Simulation studies have shown that under the same disturbed ionospheric conditions, signals transmitted from LEO satellites experience deeper, faster, and more frequent fades, as well as larger magnitude phase disturbances and faster frequency disturbances than the same signals transmitted from MEO satellites [50]. These effects can significantly compromise the availability and accuracy of user receiver PNT solutions, necessitating more robust and resource-intensive signal processing that may not be feasible for many military and commercial applications [51].

Tropospheric effects may also become a more serious issue for signals transmitted from LEO satellites. This is because, in LEO constellations, receivers often rely on a larger number of satellites at low elevation angles, which increases the path through the atmosphere and makes the signals more susceptible to both ionospheric and tropospheric interference. In contrast, in MEO there are typically more satellites with higher elevation angles, resulting in less atmosphere to pass through and potentially less impact from tropospheric effects.

4.4 RESILIENCE TO RF INTERFERENCE

Jamming and spoofing are significant human-induced RFI incidents threatening the resilience of current GNSS systems. LEO PNT has the potential to greatly improve resilience to jamming and spoofing compared to GNSS. The design and implementation of LEO PNT constellation and signal structure have a key role to play in this respect. The emerging LEO PNT providers can benefit from decades of GNSS experience, and thus build systems that are an improvement to the current state-of-the-art.

LEO PNT satellites orbit the Earth at much lower altitudes, hence, their received signals are much stronger than GNSS signals coming from MEO satellites. For example, it has been shown that one could receive Starlink LEO signals with a carrier-to-noise ratio of around 70 dB-Hz [52]. Additionally, there is an opportunity to leverage new frequency bands, such as S- and C-bands, and not rely on the L-band only. These systems offer enhanced signal diversity, which helps improve resistance to interference, as interference usually affects only specific parts of the spectrum, with intentional interference typically targeting the L-band. Additionally, some of these bands may support the use of higher signal power, further strengthening their reliability and robustness in challenging environments.

Stronger resistance to jamming also enhances resistance to spoofing, as spoofing attacks often begin with jamming attempts designed to disrupt the receiver's lock on the satellites [23].

Moreover, advanced signal designs could incorporate cutting-edge security features, including enhanced anti-spoofing mechanisms and robust data and signal authenticity checks. Such features would make it significantly harder for malicious actors to compromise or manipulate the system. The ability to protect against both jamming and spoofing from the outset could make LEO PNT systems a transformative step toward secure positioning, navigation and timing.

By integrating the abovementioned features into their architecture from the start, LEO PNT systems can address current vulnerabilities in global PNT systems, paving the way for a new era of resilient and secure positioning technologies.

Furthermore, the flexibility of LEO PNT systems, which can evolve and adapt to new challenges and security threats, makes them a promising solution for future-proofing critical infrastructure in an increasingly connected world. As these systems are deployed and refined, their ability to seamlessly integrate with existing technologies and provide reliable, secure PNT services will be key to their widespread adoption and long-term success.

5. SPACE SEGMENT

The space segment forms the backbone of LEO PNT systems, encompassing a constellation of satellites designed to transmit RF signals that deliver precise PNT services to appropriately equipped users worldwide. There are two critical components comprising the space segment: the satellites themselves and the configuration of the satellite constellation. Together, these elements impact the system’s performance, coverage, and cost-effectiveness.

This chapter introduces some aspects of the space segment, with a focus on the launch cost, satellite platform, onboard navigation payload, and constellation design. Key considerations include selecting instrumentation and techniques suitable for LEO PNT missions, optimising orbital parameters, and estimating system costs. Special attention is given to the integration of the payload with the satellite platform, ensuring compatibility in terms of SWAP-C constraints.

5.1 LAUNCH COST

In 1994 Lt Col John London III wrote a US Air Force sabbatical paper called “LEO on the Cheap, methods of achieving drastic reductions in Space Launch Costs” and drew a parallel on the interaction between launch cost per kilogram and space mission design [53]. A key insight was that launch costs make up about a third of total mission costs, the satellite(s) make up another third and all other operational expenses the remaining third. While details vary, and the exact results also depend on accounting treatments, the fundamental principle and ratios are surprisingly robust and have remained relevant for the 30 years since the paper was published.

In the early days of space exploration, significant advances were made in both launch reliability and the cost per kilogram of payload to orbit. By the late 1960s, the Saturn V rocket set a benchmark for minimum cost per kilogram to orbit, a standard that remained largely unchallenged until the launch of the Falcon 9 in 2010. This 45-year period marked a relative stagnation in the space industry, characterised by slow, incremental progress rather than bold innovation and risk-taking. This trend was particularly evident in the United States, where the world's largest space industry, despite being rooted in a free-market economy, saw its share of the global commercial launch market dwindle to near zero.

The arrival of SpaceX, with entrepreneurial drive, and NASA's adoption of fixed-price commercial resupply contracts have disrupted the status quo, dramatically reducing launch costs and fostering a culture of innovation and continuous improvement. Consequently, launch costs have significantly declined since the 1960s (see Figure 6).

Because launch cost is a major contributor to overall space mission cost, the whole mission design and satellite design choices can be heavily influenced by this single parameter.

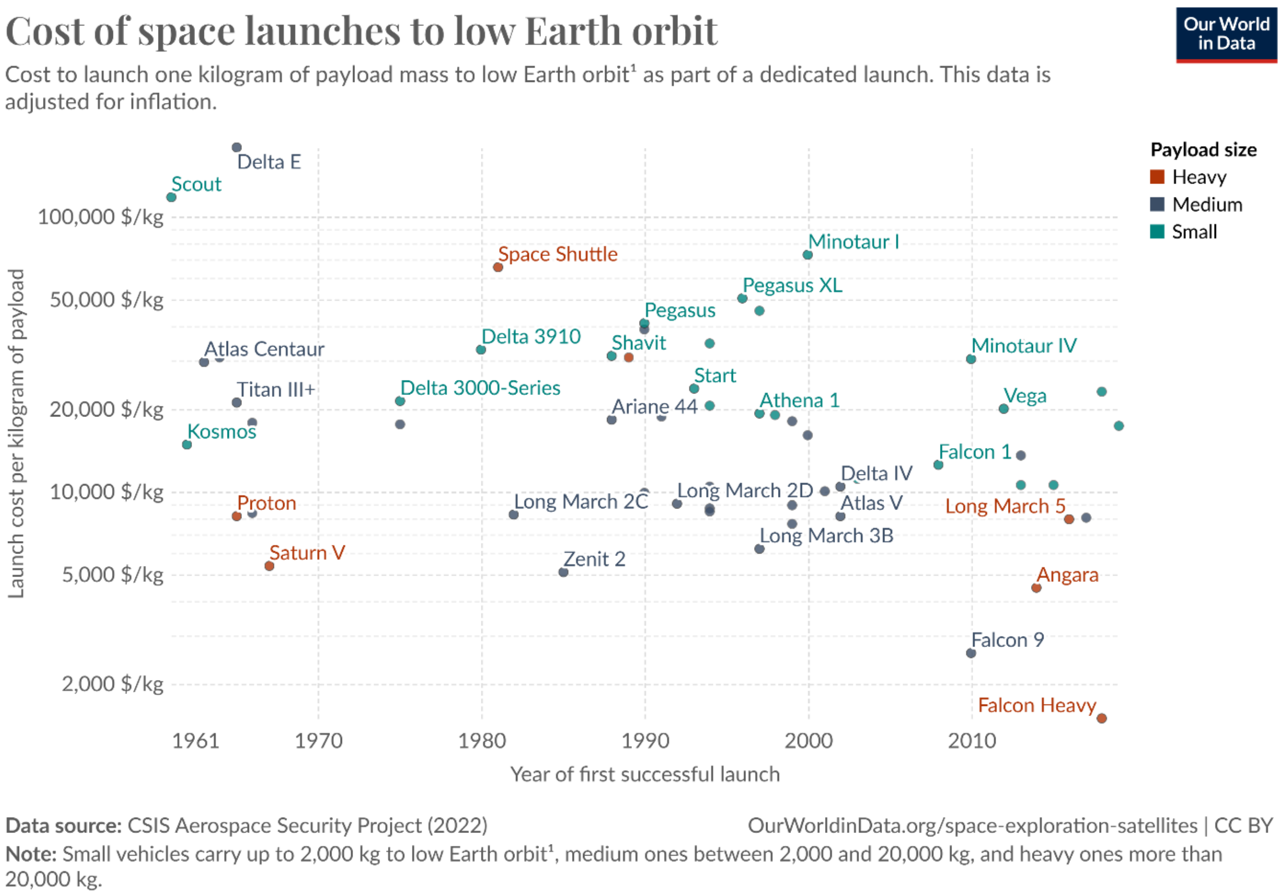
5.2 SATELLITE PLATFORM

The satellite platform discussion centres around two key components, which are the satellite bus and the navigation payload. These are briefly discussed below.

5.2.1 Satellite Class

The selection of the satellite class is a critical decision for LEO PNT systems, as it directly impacts performance, deployment costs, and operational efficiency. Satellite classes are typically defined by their mass and mission capabilities, ranging from nanosatellites and microsatellites to large satellites. Each class offers distinct advantages and challenges, making the choice dependent on mission objectives, available budget, and technical constraints. Satellite weight is an important factor, but power requirements are equally as important, as power consumption relates directly to the requirements of signal transmission.

An often-quoted advantage of LEO satellites is that they have less signal space loss due to their ray path being much shorter than those of MEO satellites. However, one must also take into consideration that for the signals to cover the same space volume as a MEO satellite, a LEO satellite must have a much wider antenna beam which is associated with a reduced gain. This gain reduction must be taken into consideration in the signal power link budget plan. Additionally, if higher frequencies than L-band are used, directional antennas will be needed.



Cost of space launches to low Earth orbit

Cost to launch one kilogram of payload mass to low Earth orbit¹ as part of a dedicated launch. This data is adjusted for inflation.

Data source: CSIS Aerospace Security Project (2022) OurWorldinData.org/space-exploration-satellites | CC BY

Note: Small vehicles carry up to 2,000 kg to low Earth orbit¹, medium ones between 2,000 and 20,000 kg, and heavy ones more than 20,000 kg.

Figure 6. Cost of space launches to Low Earth Orbit over time.[15]

Table 5 lists details related to the various satellite classes including weight, power and cost [23], noting that these are general figures as they can vary a lot according to many different factors.

Satellite Class	Weight (kg)	Solar Panels (kW)	Cost, M$ US
Pico	< 1	< 0.05	< 0.4
Nano	1 – 10	< 0.5	0.4 - 2
Micro	10 – 100	< 1	4 - 8
Mini	100 – 500	1 - 2	15 - 40
Small	500 – 1000	2 - 4	55 - 100
Medium	1000 – 2000	4 - 10	100 - 150
Large	> 2000	>10	> 150

Table 5. Satellite classes.

For LEO PNT systems, micro and mini satellites often strike a balance between cost, capability, and scalability [12]. These satellites can accommodate robust navigation payloads while remaining compatible with cost-efficient rideshare and dedicated small-launch vehicles. Their relatively compact size allows for high-volume deployments, enabling the creation of dense constellations essential for global coverage and redundancy. However, CubeSats in the nano satellite class are also increasingly being considered for LEO

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[15] https://ourworldindata.org/grapher/cost-space-launches-low-earth-orbit

PNT systems due to their lower production and launch costs (e.g., TrustPoint).

On the other hand, larger satellites (500 kg and above) offer greater payload capacity and onboard processing power, making them suitable for advanced PNT capabilities, such as integrating additional sensors or hosting multiple payloads. Despite these advantages, their higher production and launch costs make them less viable for the dense constellations required in LEO.

Ultimately, the choice of satellite class must align with the intended constellation architecture, ground segment capabilities, and economic constraints. Advances in miniaturisation, manufacturing, and propulsion technologies continue to expand the range of viable satellite classes for LEO PNT missions, offering greater flexibility in meeting diverse operational needs.

5.2.2 Navigation payload

The navigation payload is the core component of a LEO PNT satellite, responsible for generating, modulating, and transmitting signals to deliver precise positioning and timing information to users on the ground. Its design and capabilities significantly influence the system's accuracy, reliability, and global coverage.

In general terms, the LEO PNT payload will at a minimum consist of a software defined radio (SDR) for signal generation, a timing source, a GNSS receiver, onboard computer for data processing, and various RF transmission chain components, and an antenna to transmit the navigation signals to ground-based receivers. Some satellites will also include optical transceivers to enable inter-satellite links.

Antenna design for LEO satellites is important, as many types of antennas will produce very strong signals at nadir (directly under the spacecraft), and decreasing power levels towards the horizon. Different options for LEO satellites include wire, reflector, reflectarray, membrane and horn antennas [22].

LEO PNT systems generally perform best with the maximum number of satellites. As a result, PNT satellites are designed to deliver services across the broadest possible area of the Earth, even though this results in a lower power density (W/m²) on the surface. This design requirement essentially assumes that the total constellation power per square meter on Earth remains constant. However, the critical question is whether this power should be delivered by a single satellite or distributed across multiple satellites. The advantage of observing the greatest possible number of satellites is to strengthen the positioning model by improving observables' geometric distribution, and also because time and frequency of arrival estimates improve non-linearly with increases in signal power, hence, many weak signals are better than a few strong ones.

Traditionally, satellite-based PNT signals have been code division multiple access (CDMA) systems, and GLONASS excepted, all the satellites share the same frequency channel. This design requires relatively good power balancing between emitters. The demand for power balancing drives us towards an antenna system that provides equal power density (W/m^2) at the Earth's surface in the coverage area. The requirement for power balancing also frustrates efforts to increase overall constellation signal power.

A key advantage of LEO PNT is its rapid upgrade cycle, with one crucial aspect being signal total power. As such, upgrade paths that ensure interoperability while significantly boosting signal power should be considered a fundamental design requirement. For LEO PNT, the flexibility and speed of upgrades are ultimately more critical than initial performance.

5.2.3 Additional satellite and payload considerations

Additional factor that needs to be considered is whether to use a dedicated satellite, or a hosted navigation payload on a third-party satellite. GNSS systems all use dedicated constellations of satellites. With LEO PNT, both options are possible. Dedicated PNT constellations, such as Xona Space and TrustPoint, rely on dedicated satellites since their primary focus is on providing PNT services. Constellations primarily designed for communication or other non-PNT applications, such as Iridium, would typically employ a hosted navigation payload.

In a dedicated satellite solution, the service provider bears the full cost of the space segment, which includes the satellite, payload, and launch. In contrast, the hosted payload concept the service provider builds the PNT payload, but pays hosting, power, and data service fees to the satellite provider as well as a proportional launch fee based on the mass of the payload [23].

Additionally, it should be noted that constellations whose primary purpose is not PNT, such as Starlink, whose signals are currently being used as signals of opportunity could potentially play a bigger role in the PNT space should they choose to do so, without significant hardware changes, using existing payload on the satellites. This would include some changes in the overall system architecture. Potentially, some change to the signal structure would be required, which may be possible by tuning the SDRs on the satellites. In any case, the signal structure will need to be shared with receiver manufacturers, at which point these signals will stop being signals of opportunity and become dedicated PNT signals. Additional steps can also be done with regards to the ground segment in order to improve precise orbit determination and clock errors. If the constellation uses OISLs for communications, they can also be utilised for time transfer and synchronisation.

5.3 CONSTELLATION DESIGN

Constellation design plays a key factor in a successful LEO PNT constellation. Constellation design will depend heavily on the type of satellite platform and navigation payload used, as mentioned in a previous section, but other considerations also need to be considered, such as the altitude and the inclination of the orbit [54].

The coverage area of a satellite is limited by its orbit and the size of the area it can observe at any given moment. A satellite in LEO will typically be visible or detectable from about 5% of the Earth's surface depending on the orbital altitude. LEO satellite altitude may become a limiting factor in design in the near future. The number of LEO satellites in orbit is growing rapidly, and it is not clear if existing anti-collision (anti-debris) measures are adequate [55]. There may be a bifurcation of LEO orbits into tightly controlled, high-reliability use of upper LEO orbits (550km+), and a more laissez-faire approach to lower altitudes, especially below manned spaceflight at 400-410 km altitudes. Orbits below 400 km, because of the atmosphere drag, require thrust to achieve any substantial mission duration.

LEO satellites are often observed at lower elevation angles (closer to the horizon) when seen from Earth. Since satellites in low orbits move quickly across the sky and have limited visibility from any given location on Earth, more LEO satellites are needed to ensure continuous coverage and prevent gaps in service. In addition, receivers in complex terrain have a poor view of the horizon and low elevations, so only a fraction of the satellites that are above the horizon may be tracked. Note also that GNSS systems normally implement mask angles to exclude low-elevation signals from navigation solutions due to the increased likelihood of multipath effects.

Since more LEO satellites are visible at low elevations than high, a comparatively large constellation is required, beyond simply desiring 4 or 5 satellites above the horizon. However, this is not necessarily true for all applications – for example, timing to a stationary receiver can be achieved with a single satellite in view, and even intermittent coverage is adequate if the LEO timing service was only constraining the drift of a high-quality clock. Similar cases exist for constraining the drift of an automatic navigation system, such as an aircraft Inertial Navigation System (INS) [56]. Additionally, a LEO service that solely delivers almanac and ephemeris data for signals of opportunity, would only require a receiver to observe a single satellite within the service area [57].

5.3.1 Inclination

Inclination is the angle between the plane of a satellite's orbit and the equatorial plane of the Earth. A pure polar orbit would have 90 degrees inclination. It is a type of orbit that passes over the Earth's poles, travelling in a north-south direction. With an inclination close to 90 degrees, near-polar orbits allow satellites to cover nearly every part of the Earth as the planet rotates beneath them. This unique characteristic makes (near) polar orbits ideal for applications requiring global coverage.

A special orbit called a Sun Synchronous Orbit (SSO) has an inclination of around 98 degrees. Being an angle greater than 90 degrees makes this a retrograde orbit, where at launch, the satellites are sent in a direction against the rotation of the Earth. The SSO is named because the oblateness of the Earth causes the satellite orbital plane to precess at about one degree per day in inertial space, meaning that the orbit remains the same relative to the sun throughout the year. SSO orbits are named after the daylight local time at which they cross the equator. So, a 1030 Local Time of the Ascending Node (LTAN) will cross the equator from south to north at 1030 AM local time over and over again. Because LEO satellites orbit the Earth every 90 minutes or so, the satellites will make this crossing about 15 times per day, with each crossing about 22.5 degrees further west than the previous crossing.

Inclinations of less than 90 degrees may not provide full global coverage, instead spending their time “flying” at low to mid-latitudes. These orbits provide focused coverage over mid-latitude regions, making them ideal for missions requiring regional connectivity or observation without the need for global or polar coverage. Most of the Earth's population is found at mid-latitudes, and in addition, most of the terrestrial surface area of the Earth is at low to mid-latitudes.

A constellation composed only of polar (or SSO) orbits over-services the poles and under-services the equator and mid-latitudes. A constellation composed only of satellites in inclinations less than about 70 degrees does not service the poles. It is possible to have constellations with mixed inclinations, most of the satellites being at, say, 50 degrees inclination to serve low to mid-latitudes, and a smaller number being in polar orbits to serve the poles. The polar orbits will also serve low and mid-latitudes, but less efficiently.

5.3.2 Plane and satellite spacing

A single orbital plane of satellites will only provide instantaneous coverage to a relatively thin swath of the Earth's surface. The Earth will rotate underneath this orbital plane at about 15 degrees per hour (360 degrees / 24 hours). As mentioned previously the orbit will also migrate around the Earth (relative to the sun) by several degrees per day for mid-inclination orbits.

In constellation design, consideration is paid to the coverage area on the ground. For a timing-only service the goal might be to ensure there is at least one satellite visible at all times, because the receiver location is considered known. For a positioning service, observing multiple satellites with a good geometric diversity is desirable, and this leads to other choices in terms of the number of orbital planes, and the number of active spacecrafts in each orbital plane.

5.3.3 Coverage per satellite

All other factors being equal, a LEO PNT constellation is most effective when a sufficient number of satellites are visible, ideally positioned relatively high in the sky. Therefore, for optimum performance, it is desirable to maximise coverage per satellite, subject to being above, say, 5 degrees elevation from a site on the Earth’s surface.

In CDMA systems, power balancing is critical for optimal performance. Additionally, receiver efficiency improves when there are multiple modest-power signals rather than a few high-power ones. Consequently, the design should aim for an antenna capable of providing consistent signal strength, even at low elevations (e.g. down to 5 degrees). However, such an antenna would also be tailored to a specific orbital altitude, meaning changes in satellite altitude must account for and align with this design requirement.

5.3.4 Altitude

Satellites at higher altitudes provide a more extensive line of sight, increasing the area covered by each satellite. The satellite will also provide a high elevation (high in the sky) service to a larger area. Lower altitudes suffer from greater atmospheric drag and will naturally de-orbit in a few years in the absence of active de-orbiting. Low altitude satellites also serve smaller areas, and will offer a high elevation (high in the sky) service to a substantially smaller footprint than a higher altitude satellite. However high LEO satellites can be subject to more radiation than lower altitudes, and without active de-orbiting when decommissioning may remain in space for many hundreds of years, presenting a debris hazard to other satellites. Satellite altitude also affects the orbital period, and for all non-90-degree inclinations altitude also affects the orbit precession rate – being the rate that the orbital plane precesses relative to the Earth.

5.3.5 Receiver insights

Although receiver technology is discussed in the next chapter, its strong relationship with constellation design warrants a broad treatment here, including its implications.

Because receivers are built mainly around digital hardware and software (firmware), progress has been following Moore's Law for decades. In essence the long-term cost of data processing is zero. Over time, advances enable the operation of a significantly larger number of signal correlators, allowing for the decoding and utilisation of a wide variety of digital modulation and data encoding schemes.

In addition, satellite search and tracking techniques can be allocated ever increasing resources over time. This means that new satellites can use new data formats with quite modest impacts on user receiver costs, especially as most receivers are relatively new, being incorporated in consumer devices.

Infrastructure and critical receivers (e.g., aircraft) have much slower upgrade cycles, however they can be served by maintaining legacy waveforms for an extended timeframe (20 years or more), adding new services to the constellation as new signals with backward compatibility.

Many receivers are energy constrained, being battery powered. Radio reception channels are relatively power hungry, and do not improve at the same rate as processing capabilities. Therefore, to minimise cost and energy use, reusing existing receiver chains such as having navigation signals adjacent to communication signals, or at least reducing the required frequency ranges needed for PNT receivers is advantageous.

6. RECEIVER SEGMENT

6.1 BACKGROUND

Receiver manufacturers across the globe are now testing and introducing innovative products designed to process signals beyond traditional GNSS. This shift marks a new phase of evolution in the industry, reshaping the marketplace and creating opportunities for emerging technology companies to enter the user receiver market. A central aspect of this development is the growing adoption of LEO PNT signals, enabling PNT receivers to diversify the signals they process. This diversification enhances navigation solutions by improving accuracy, resilience, and reliability in a variety of environments.

Traditionally, GNSS signals have been made available to the public by governments, with costs to users fully subsidised. However, a significant shift is now underway, with the commercial sector entering the market to offer PNT services. Thanks to advances in launch efficiency and the reduced costs of building small satellites, many of these new PNT service providers are focusing on LEO constellations as their preferred infrastructure platform.

Given this evolution in the market, the GNSS receiver industry is undergoing a pivotal transformation to leverage these opportunities. Historically, GNSS receivers relied on signals transmitted from MEO constellations, such as GPS, GLONASS, Galileo, and BeiDou, to provide PNT solutions. However, with the emergence of LEO constellations offering advantages like higher received signal strength, improved security, and frequency diversity, receiver companies are adapting their strategies to stay at the forefront of this technological shift. Some companies are developing entirely new products to fully leverage the unique attributes of LEO signals, while others are upgrading existing GNSS receivers to integrate these capabilities.

Receiver manufacturers are facing unique challenges and must address various technical and business model considerations, which are often intertwined with one another. Since the new PNT service offerings are evolving, the information that is available to make decisions is dynamic. Some of these considerations include which frequency bands to support, which market to target, and who will pay for the service.

6.2 FREQUENCY BAND AND MARKET

The ITU will ultimately make the decisions of which frequency bands LEO PNT Signals will use. Out of the dozens of reserved radionavigation frequency bands, two primary options are emerging for dedicated LEO PNT systems: the L-band and the C-band. Receiver manufacturers must carefully evaluate which band their products will support, as resources are required to design, implement, and validate a radio front-end optimised for performance within the chosen band.

The L-band, which is the selected band for Xona Space, Geely, Centispace, SatNet LEO and ESA's FutureNAV LEO-PNT IoD, resides in the frequency band near the familiar GNSS MEO satellite signals. This option may appeal to receiver manufacturers with existing product lines to avoid new radio front-end development. Customers might even be able to use the same antennas, potentially reducing the cost of adoption and minimising changes to the overall system for both the receiver manufacturer and the consumer.

Receiver manufacturers should evaluate the risks of reusing a GNSS L-band radio front-end for applications where jamming is a concern. LEO PNT signals that are sufficiently close in frequency to traditional GNSS signals may be subject to a higher in-band jamming to signal power (J/S) ratio. In this case, LEO PNT signals will be most advantageous when highly selective radio front-ends, and/or special antennas are used.

Reusing a GNSS L-band front-end may be suitable for applications where jamming is not a major concern. Instead, the main focus is to improve positioning and timing accuracy, precision, and security with increased coverage, higher signal power, and the security features offered by LEO PNT.

The C-band, which is the selected band for TrustPoint, ESA's FutureNAV LEO-PNT IoD, and JAXA constellations, has historically experienced less jamming compared to the L-band, making it an attractive option for receiver manufacturers to consider in environments where the probability of a jamming event occurring is high. C-band phased array antennas can be made more compact than L-band phased arrays and offer much greater directionality, hence providing enhanced protection against jamming.

Designing a radio front-end for the C-band is generally more complex compared to the L-band. This is due to the challenges associated with higher operating frequencies, which require different filter components and mixers capable of maintaining lower phase noise. These components often necessitate precision manufacturing and specialised materials, contributing to increased costs. Market trends play a significant role in shaping relative component costs, potentially minimising or even eliminating cost differences between the frequency bands.

Receiver manufacturers should expect different receiver-to-satellite ranging accuracies and precisions due to frequency-dependent atmospheric effects, which may determine which market the chosen frequency band is appropriate for. For example, given a total electron count (TEC), ionospheric delays are roughly 10 times smaller at the C-band than at the L-band. However, clouds, rain, and scintillation can cause approximately 5 dB of attenuation for C-band signals, compared to only about 1 dB for L-band signals. While models can account for some of these delays, non-common residual range errors can still lead to inaccuracies in position and timing. High attenuation can cause random ranging errors which are difficult to model. Receiver manufacturers should consider what error compensation parameters and algorithms LEO PNT service providers are offering or, if multiple frequencies are transmitted, which would enable differential delay compensation algorithms.

It is expected that LEO PNT services that operate either in L-band or C-band will provide improved PNT performance and security for commercial and military applications, especially when augmented with existing GNSS. Given the trade-offs mentioned above, the primary factor for receiver manufacturers in choosing a frequency band at this early stage of LEO PNT service deployment is their confidence in the PNT service provider's ability to deliver the service.

Some of the receiver manufacturing companies, such as NovAtel and Septentrio, have publicly stated they are focusing on the L-band, while others, such as StarNav, have disclosed that they develop front-ends compatible with both the L-band and C-band. The first step for receiver companies looking to begin development is to contact the PNT service provider to obtain their proprietary interface control document (ICD).

6.3 SERVICE FEES

Beyond development costs, receiver manufacturers are now engaged in addressing how the costs of LEO PNT services are funded. Traditional GNSS services are funded by the governments maintaining the GNSS system. GNSS receiver manufacturers only need to cover development and manufacturing costs of the user equipment. In contrast, the emerging paradigm involves LEO PNT services provided by for-profit commercial entities and the receiver manufacturer may need to cover that cost if their receiver is LEO PNT service enabled. One potential business model is for receiver manufacturers to generate revenue from the sale of receiver products and charge customers for the LEO PNT service, either through subscription fees or by embedding the LEO PNT service cost into the price of the receiver.

6.4 LEO PNT RECEIVER ECOSYSTEM

New business dynamics are being investigated in this emerging space. Besides relationships between receiver companies and service providers, simulator companies are playing a vital role. GNSS radio frequency simulators have traditionally been a useful tool for receiver manufacturers to test and evaluate their receiver's acquisition, tracking, and PNT solution generation components. Simulator companies are beginning to release new products to support LEO PNT.

Safran, for example, has announced collaborations with Xona Space and TrustPoint to provide simulated signals for their respective constellations.[16,17] Spirent and

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[16] https://safran-navigation-timing.com/xona-pulsar-gnss-simulation-capability/

[17] https://safran-navigation-timing.com/safran-trustpoint-partnership/

Syntony have also announced support for Xona's PULSAR signal.[18,19]

Governments have allocated budgets to support both LEO PNT service providers and receiver companies. This includes research and development to leverage communication satellites that were not designed for PNT, and launching new constellations dedicated to PNT. The United States, Europe, China and Japan are all exploring options for building dedicated LEO PNT systems, which include both government and commercial initiatives.

SpaceX is positioning itself to dominate the LEO satellite market because of their plans to adapt Starlink for military applications in the future, aided by what will likely be increased U.S. funding for space startups.[20] It is anticipated that SpaceX would develop their own receivers for this purpose.

These advancements reflect a dynamic and competitive global race in the development and implementation of LEO PNT systems. A list of receiver companies working with LEO PNT signals is shown in Table 6.

Receiver Manufacturer	Frequencies Supported	LEO PNT Provider Support
NovAtel	L	Xona
Septentrio	L	Xona
StarNav	L, S	Xona, Globalstar
Syntony GNSS	L	Xona
STMicroelectronics	L	Xona
Furuno	L	Xona
Etherwhere	L	Xona
Auroxat	L	Xona
Qascom	L	Xona
Qinetiq	L	Xona
Parsons Corporation	S	Globalstar
Safran	L	Iridium® STL
Adtran	L	Iridium® STL
Viavi Solutions	L	Iridium® STL
NAL Research Corp.	L	Iridium® STL

Table 6. List of GNSS receiver manufacturers that have publicly announced LEO PNT support.

It can be seen that there are some manufacturers, who support existing services from Iridium STL® and Globalstar, as well as many other manufacturers who have already included support for Xona's PULSAR signal.

TrustPoint has enlisted the support of six product partners to develop C-band capable receivers able to receiver and process TrustPoint's services. Public disclosure of the product partners is expected in late 2025.

No public information is available on receiver partners from other LEO PNT constellations at this stage. With active collaboration among receiver manufacturers, LEO PNT service providers, simulator companies, governments, and consumers the ecosystem is on track to support more reliable and precise navigation and timing services. As LEO constellations approach full operational capability, receiver technology will continue to evolve, incorporating enhanced adaptability, security, and multi-LEO constellation capabilities. This development marks a new era in PNT, with receivers for LEO PNT signals playing a central role in delivering the next generation of navigation solutions for users worldwide.

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[18] https://syntony-gnss.com/news/our-press-release/syntony-gnss-partners-with-xona-space-systems

[19] https://www.spirent.com/newsroom/press-releases/spirent-accepting-orders-for-certified-xona-pulsar-production-signals

[20] https://spacenews.com/pentagon-embracing-spacexs-starshield-for-future-military-satcom/

7. LEO PNT SERVICE PROVIDERS

This chapter profiles LEO PNT service providers for which relevant information is available. As highlighted at the beginning of this report, the LEO PNT market and ecosystem are in early stages of development. Consequently, the information presented here is based on publicly available sources as of December 2024. The chapter begins with a brief background on the topic and then provides a list of existing and prospective LEO PNT service providers.

7.1 BACKGROUND

7.1.1 TRANSIT

The original LEO PNT concept can be traced back to the TRANSIT system, which was sponsored by the US Navy and developed jointly by DARPA and the Johns Hopkins Applied Physics Laboratory. Development of the system began in 1958 and was completed in 1968. The fully operational constellation consisted of 36 satellites in circular polar orbits at an orbital of about 1,075 km and an orbital period of around 107 minutes. Due to the low number of satellites TRANSIT receivers had to make measurements with respect to sequential positions of the satellite as it would pass above it. This process required 10 to 16 minutes during which the satellite would travel between 4,400 and 7,000 km.

Since TRANSIT was mainly used for ship navigation, the speed and direction of the vessel had to be taken into the account during that tracking period in order to compute position. TRANSIT transmitted on two frequencies in the VHF, namely 150MHz and 400MHz, and the typical error of the user's position was between 27-37m [58].

Given modern GNSS, where instantaneous positioning with sub-metre accuracy using code pseudoranges is considered routine, this process may seem cumbersome, and its accuracy appears inadequate. However, at the time, TRANSIT was the only satellite navigation system offering global coverage. Thousands of ships of all kinds have used the TRANSIT system between 1968 and 1991, after which it was made obsolete by the rise of GPS, and eventually ceased offering a navigation service in 1996.

7.1.2 Satelles, Inc.

In recent years, the LEO PNT concept was revived by the US-based company Satelles, which was founded in 2013 and began providing Satellite Time and Location (STL) in 2016. Satelles uses the Iridium network of 66 satellites, at an orbital altitude of 780 km and a near-polar orbit of 86.4°. Satelles STL service is broadcast in the L-band and is fully independent from GNSS. With their near-polar orbits, typically 1-3 satellites are visible in mid-latitudes, while 6-8 can be seen in the polar regions, as illustrated in Figure 7.

Figure 7. Examples of Iridium coverage in different places in the world (https://iridiumwhere.com/).

STL has several key differences to GNSS. STL signals are on average 1000 times stronger than GNSS, which allows them to penetrate buildings, however the signals are pulsed and not broadcast continuously, which can make tracking and acquiring the signal more challenging. STL signals also have cryptographic encryption, which makes them less susceptible to cyber-attacks.

STL can achieve timing accuracies of between 20-100 ns depending on the oscillator used in the receiver, and positioning accuracies of 10-20 m [57]. While STL positioning has use cases in certain industry sectors, it is not suitable for applications requiring high-accuracy, centimetre-level positioning. In 2024, Satelles was acquired by Iridium, and the service was rebranded as Iridium® STL.

7.1.3 Emerging Services

While Satelles can be seen as a pioneer in modern-day LEO PNT, the service could not cater for the needs of high-accuracy positioning users due to the limited number of satellites visible at mid-latitudes.

Achieving high-accuracy positioning would require significantly more satellites in view, and consequently significantly larger satellite constellations across different types of orbits to cater for mid-latitude regions, where most of the users of these services would be located.

By ca. 2017, new concepts had emerged, proposing dedicated constellations in LEO specifically designed to meet this goal. As of December 2024, several initiatives are underway to establish dedicated high-accuracy LEO PNT constellations. These include Xona Space and TrustPoint in the USA; Geely, Centispace and SatNet LEO in China; JAXA and ArkEdge Space in Japan; and ESA in the Europe.

This section provides an overview of the various LEO PNT constellations. Each service is analysed using the same set of criteria for easy comparison. These criteria include some general information, constellation details, signal security architecture, and RF characteristics (Table 7).

Whenever possible, information was collected directly through interviews with representatives from each LEO PNT initiative or service provider. When direct interviews were not feasible, data was sourced from publicly available materials, including conference presentations and scientific journal articles.

It should be noted that at the time of writing (December 2024), a lot of the information is not publicly available as many of the systems are at various stages of design, and therefore, they are still evolving, and many fields are left blank for some systems. As mentioned earlier, this is the first in a series of annual reports that will be published over the next few years, and it is envisaged that future editions of this report will have more data as the various constellations mature.

General Information	Constellation Details	Signal Security Architecture	RF Characteristics
Country of Origin	Orbital Altitude	Signal Structure	Frequency Band
System Ownership	Satellite Class	Signal Encryption	Signal Names
Services provided	PNT Payload Type	Signal Authentication	Signal Frequencies
Target Sectors	Number of satellites in orbit December 2024		ITU Approval Status
Performance Targets	Initial Operating Capability		Modulation Type
System GNSS Independence	Final Operating Capability		Data Rate
Timescale Reference			Chip Rate
Service Area			User Received power

Table 7. LEO PNT Assessment Criteria

7.2 SERVICE PROVIDERS

7.2.1 Iridium® STL

The Iridium satellite constellation was designed in early 1990s as a satellite communications system that could provide voice and data services in the L-band. The first generation of 66 satellites was deployed between 1997-2002 and was only used for communications.

The second generation, called Iridium NEXT, was launched between 2017 and 2019, which also consists of 66 active satellites (plus a number of spares in case of satellite failure). Iridium NEXT satellites communicate with neighbouring satellites via inter-satellite links in the Ka-band, which allows the satellites to have continuous orbit and time information for the entire constellation even at times when some of the satellites are not in view of a ground station.

Apart from communications, Iridium NEXT satellites have a hosted payload from Satelles, which allowed the company to provide STL services as mentioned in Section 7.1.2. Early in 2024, Satelles was acquired by Iridium and the service is now called Iridium® STL.

One key difference of Iridium® STL compared to the other services described in this chapter is that the satellites are in the "small" class that weigh 860kg, which is significantly larger than all the other constellations described in this report.

Another key distinction is that the primary function of the Iridium constellation is communications, not PNT. Furthermore, the limited number of satellites in LEO restricts STL's ability to deliver high-accuracy positioning at centimetre to decimetre levels. Table 8 lists key information on the Iridium® STL service [59].

General Information	
Country of Origin	United States of America
System Ownership	Private
Target Sectors	Critical Infrastructure, Indoor PNT, Cyber Security, Data Centres
Performance Targets	Timing stability 20-100 ns Positioning accuracy 10-20 m
System GNSS Independence	Independent from GNSS
Timescale Reference	Ground stations, inter-satellite links
Service Area	Global
Operational/Demonstration	Operational system
Constellation Details	
Orbital altitude	780km
Inclination	86.4° near-polar
Satellite class	Small (860kg)
Payload Type	Hosted Payload
Constellation Type	Fused Communications and PNT Constellation
No of sats in orbit Dec 2024	66 satellites
Initial Operational Capability	2017 / 40 satellites
Full Operational Capability	2019 / 66 satellites
Signal Security Architecture	
Signal structure	Proprietary

Signal Encryption	Yes
Signal Authentication	Yes
RF Characteristics	
Frequency Band	L-Band
Signal Names	STL
Signal Frequency	1616-1626 MHz
ITU Approval Status	Approved
Modulation Type	QPSK
Data Rate (bps)	
Chip Rate (Mcps)	
User Received power (dBW)	

Table 8. Iridium® STL Constellation Details.

7.2.2 Xona Space Systems, Inc.

Xona Space Systems is a US-based startup founded in 2019, that is developing a dedicated constellation of LEO satellites to provide advanced PNT services. Initial Operational Capability (IOC) is targeted for 2026 and will consist of having at least one satellite in view for provision of timing and to support GNSS augmentation services. This will be followed by Phase 2 which will provide positioning services in mid-latitude regions. Finally, Phase 3 will provide Full Operational Capability (FOC), which will ensure higher performance PNT globally, as well as the ability to operate independently of GNSS.

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 biggest traction among the GNSS receiver and chipset manufacturers as well as the simulator manufacturers, as shown in Chapter 6.

Xona's service and signal is called PULSAR and whilst initially it targeted both L- and C-bands, the company has decided to move away from C-band and to concentrate on dual L-band only, to ensure direct compatibility with existing GNSS equipment. The two PULSAR signals are called X1 and X5. As of December 2024, the exact X1 and X5 frequencies have not been made public. Table 9 lists details on the Xona constellation [60].

Xona's next LEO satellite is scheduled for launch in June 2025.

General Information	
Country of Origin	United States of America
System Ownership	Private
Services Provided	Positioning, timing, GNSS corrections, integrity
Target Sectors	Heavy industry, critical infrastructure, transportation, mass market
Performance Targets	2.5cm with one minute PPP convergence
System GNSS Independence	Xona PULSAR uses GNSS in nominal operations, but can operate indefinitely as a GNSS-independent system
Timescale Reference	GNSS and ground-based atomic timescales
Service Area	Global
Operational/Demonstration	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, X5
Signal Frequency	
ITU Approval Status	Pending
Modulation Type	
Data Rate (bps)	
Chip Rate (Mcps)	
User Received power (dBW)	-136.2 dBW

Table 9. Xona Space Constellation Details.

7.2.3 TrustPoint, Inc.

TrustPoint is a US-based startup headquartered in Washington DC and founded in 2020. TrustPoint is developing a purpose-built commercial LEO PNT constellation based on a service in C-band. As mentioned in Section 2.3, C-band provides some unique advantages for radionavigation including reduced ionospheric path delay and increased resistance to jamming. TrustPoint is initially targeting a decimetre-level core service, which will be followed by a centimetre-level high accuracy service.

One of the standout characteristics of TrustPoint is the use of a 6U CubeSat platform weighing just 10 kg, which includes a <2 kg PNT payload. This makes it the smallest PNT satellite currently in development. The cost per satellite is approximately $250k, which represents a dramatic reduction of 1000 times compared to the cost of a GPS Block III satellite, which is around $250M [61]. This cost efficiency, coupled with its compact design, positions TrustPoint as a disruptive player in the LEO PNT ecosystem, aiming to make precise positioning services more accessible and scalable. They are 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 an FOC with around 300 satellites and provision of a global positioning service from LEO.

Table 10 lists details on the TrustPoint constellation [62].

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/Demonstration	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

Table 10. TrustPoint Constellation Details.

7.2.4 JAXA

Japan Aerospace Exploration Agency (JAXA) is developing a LEO PNT constellation with the primary purpose of augmenting the current GNSS. The main area where the LEO constellation is designed to make an impact is the improvement of convergence time of Precise Point Positioning (PPP) from several tens of minutes to under a minute. The constellation will be rolled out 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. Table 11 lists details on the JAXA LEO PNT constellation [63].

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/Demonstration	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)	

Table 11. JAXA Constellation Details.

7.2.5 ArkEdge Space

ArkEdge Space is a Japanese startup established in 2018 specialising in developing nanosatellites for various missions, such as Earth observation, IoT, and deep 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 Data Exchange System (VDES). They have also recently been selected by JAXA to lead the development of lunar PNT infrastructure, known as the Lunar Navigation Satellite System (LNSS), as part of LunaNet alongside NASA and ESA.

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 [64].

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.

Currently, VDES is optimised to work over water, not land. This is because VDES 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.

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 (it is unknown if all satellites will transmit a PNT signal.) This translates to having one to three satellites in view at any one time. 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. The positioning computation at the user receiver will be similar to TRANSIT, meaning that the receiver will need to track the satellite(s) for a period of time, and take the vessel motion into account, in order to compute position. Table 12 lists details on the ArkEdge VDES-R mode constellation [64].

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/Demonstration	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)	

Table 12. ArkEdge Constellation Details.

7.2.6 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). 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 has already a number of demonstration satellites in orbit allowing some users to carry out performance evaluation trials [65]. Centispace has presented at the 2023 and 2024 International Committee on GNSS (ICG) workshops. The 2023 presentation is publicly available [66], but the 2024 presentation is not, hence, the constellations details in Table 13 are based on the 2023 presentation, with a caveat that some of the information could be out of date.

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/Demonstration	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

Table 13. Centispace Constellation Details.

7.2.7 Geely

Geely Holding is a Chinese multinational automotive manufacturer headquartered in Hangzhou. The company manufactures and sells cars under its own brand as well as with its subsidiaries and joint ventures such as Volvo, Zeekr, Polestar, Proton, Smart and Lotus. In 2018, Geely Holding established GeeSpace with the purpose of launching and operating a GEESATCOM fused communications and PNT constellation.

Not a lot of information is available about the proposed Geely PNT constellation. The authors in [23] have provided some details on Geely in their comparative LEO PNT study, including that it will consist of a 240-satellite constellation. However, the source of the information is not referenced.

In September 2024, GeeSpace announced via their official LinkedIn page that GEESATCOM's deployment will be carried out in three phases eventually totalling 5,676 satellites for high-speed LEO broadband communications.[21] It is envisaged that a subset of 240 satellites will be used for PNT. Table 14 lists details on the Geely constellation based on the two sources mentioned above.

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)	

Table 14. Geely Constellation Details.

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[21] https://www.linkedin.com/company/geespace/posts/?feedView=all

7.2.8 SatNet LEO

The China Satellite Network Group Co. Ltd. (China SatNet), who are in charge of the Guowang mega constellation (see Table 4) has also commenced working on LEO PNT system called SatNet LEO. At this stage no information on 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 publicly available. Only a summary slide from the workshop is available, which refers to a constellation size of 508 satellites by 2030. Table 15 has been included for completeness, but mostly left blank due to lack of information available.

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	
Satellite class	
Payload Type	
Constellation Type	
No of sats in orbit Dec 2024	
Initial Operational Capability	2025 / 168
Full Operational Capability	2030 / 508
Signal Security Architecture	
Signal structure	
Signal Encryption	
Signal Authentication	
RF Characteristics	
Frequency Band	
Signal Names	
Signal Frequency	
ITU Approval Status	
Modulation Type	
Data Rate (bps)	
Chip Rate (Mcps)	
User Received power (dBW)	

Table 15. SatNet LEO Constellation Details.

7.2.9 ESA's FutureNAV LEO-PNT IoD

The European Space Agency's vision for the future of PNT is a multi-layered PNT "system of systems", which will consist of four layers. The first layer in the systems will consist of existing satellites in MEO, GEO and Inclined Geosynchronous Orbit (IGSO) that will act as reference anchors for the second layer which will consist of LEO PNT satellites to provide PNT diversity in space. The third layer will consist of regional and local terrestrial components such as 5G PNT and WLAN; and the fourth layer will consist of inertial sensors and dead reckoning systems [67].

When it comes to LEO PNT, ESA is currently running an in-orbit demonstration (IoD) space mission called LEO-PNT IoD, within the ESA's FutureNAV programme with the purpose to accelerate LEO-PNT and prepare added-value services for potential future operational LEO-PNT systems in Europe. Two parallel contracts have been awarded for the development of two end-to-end in-orbit demonstrators. These contracts cover the design and development of satellites and payloads, ground segment infrastructure, test user segments, satellite launches, operational management, and service experimentation and demonstrations with end users.

The first LEO PNT demonstrator contract is led by GMV Aerospace Spain, and the second by Thales Alenia Space (TAS) France. Each consortium will be deploying five satellites with a number of signals in different frequency bands for demonstration purposes. Each company will have two types of satellites: a single Pathfinder A nano satellite (12U or 16U CubeSat), and four Pathfinder B mini satellites (30-100 kg). The IoD missions will run over a 3-year period with the satellites being launched incrementally starting from 2025 and an experimentation phase will be held between 2026 and 2027. Some information regarding the missions is shown in Table 16 [67]. At this stage there is little information available to the public.

General Information		
Country of Origin	Europe	
System Ownership	Institutional or Commercial	
Services Provided	Positioning, Timing	
Target Sectors	Professional, critical infrastructure, transportation, autonomous vehicles, mass-market, Internet-of-Things devices, personal safety	
Performance Targets	Decimetre-level positioning; nanosecond-level timing accuracy	
System GNSS Independence	Augmentation to GNSS	
Timescale Reference	GNSS	
Service Area	Regional Demonstrator building up to global operational service	
Operational/Demonstration	Demonstration	
Constellation Details	**GMV**	**TAS**
Orbital altitude	550 km	550 km
Inclination	Quasi Polar Orbit	Quasi Polar Orbit
Satellite class	12U CubeSat (Pathfinder A) 4 x 100kg Microsats (Pathfinder B)	16U CubeSat (Pathfinder A) 4 x 30kg Microsats (Pathfinder B)
No of sats in orbit Dec 2024	First satellite planned in 2025	First satellite planned in 2025
Initial Operational Capability		
Full Operational Capability	2027 / 5 satellites	2027 / 5 satellites
Signal Security Architecture	**GMV**	**TAS**

Signal structure		
Signal Encryption		
Signal Authentication		
RF Characteristics	**GMV**	**TAS**
Frequency Band	L/S, C and UHF Signal in Space and 2-way payload (S-band)	L/S, C and UHF Signal in Space and 2-way payload (UHF-band)
Signal Names		
Signal Frequency (MHz)		
ITU Approval Status		
Modulation Type		
Data Rate (bps)		
Chip Rate (Mcps)		
User Received power (dBW)		

Table 16. FutureNAV Demonstration Mission Details.

ESA's LEO-PNT IoD project is stated to pave the way for a European GNSS LEO layer. Possible opportunities for future operational system are under investigation from both Institutional (in coordination with European Union) and commercial perspectives.

The European Union and ESA have made a joint filing for a LEO PNT system called EU-LNAV through the French national frequency agency (ANFR) with up to 263 satellites. The filing for EU-LNAV has satellites in different altitudes across three frequency bands, namely E5, S-band and C-band [67].

7.3 ADDITIONAL CONSTELLATIONS

Two more emerging LEO PNT constellations are currently being developed in Türkiye and the UAE. While limited information is available about these projects, and technical details remain undisclosed, they are briefly discussed in this section.

7.3.1 Fergani (Türkiye)

Fergani Space is a Turkish space research company founded in 2022.[22] Fergani is currently working on a LEO constellation of around 100 satellites to provide services for marine, aviation, IoT, weather, logistics and enterprise market applications. Fergani constellation will utilise 100kg micro satellite platforms which will operate at an orbital altitude of 500-600km. The constellation will be providing communications and PNT services and will be operating in the L, S, Ku and Ka bands.

7.3.2 GNSSaS (UAE)

UAE is working on a LEO PNT constellation which is called GNSS Augmentation System or GNSSaS.[23] The GNSSaS program aims to deliver a commercial service that augments existing GNSS systems like GPS and Galileo for precise positioning. Funded by the UAE Space Agency and developed by the National Space Science and Technology Centre, the proposed architecture utilises a LEO constellation of satellites. This approach promises enhanced performance and resilience at a lower cost compared to traditional GNSS and augmentation systems.

7.4 SERVICE PROVIDERS SUMMARY

This section provides a summary of the various LEO PNT service providers. Apart from the fully operational Iridium satellite constellation, the rest are just beginning to launch their first satellites into orbit. As such, much of the information on the various systems is currently not publicly available. Over the next 3-5 years, these constellations are anticipated to grow and commence PNT services. Figure 8 shows the various service providers and where they sit on the frequency spectrum. It shows that the majority of the dedicated

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[22] https://ferganispace.com/en/services/satellite-constellations/

[23] https://space.gov.ae/en/projects-and-initiatives/tech-demo/gnssas-leo-pnt?utm_source=chatgpt.com

LEO PNT providers are concentrated on providing L-band services, likely to take advantage of the compatibility and interoperability opportunities with existing GNSS receivers.

However, C-band is also receiving renewed attention as the new unexplored frequency, with JAXA, TrustPoint and ESA's LEO-PNT IoD looking to exploit that frequency range. ArkEdge is working in the VHF spectrum due to the nature of the VDES-R system specifically aimed at maritime applications.

Whilst this report has concentrated on dedicated PNT providers in LEO, the potential impact of fused communications and PNT services should not be underestimated.

If one of the broadband mega-constellation providers, such as Starlink, OneWeb, Kuiper or any other, decides to start providing PNT services alongside communications, it could have a disruptive effect on the whole ecosystem. This scenario is comparable to a retail giant, such as Walmart, entering a small town with only a few little shops and dominating the market. Whether this scenario is realistic or not, remains to be seen, but there are signs that some of the broadband constellation providers are already considering PNT (e.g., Amazon advertising a position for a PNT engineer for Project Kuiper).

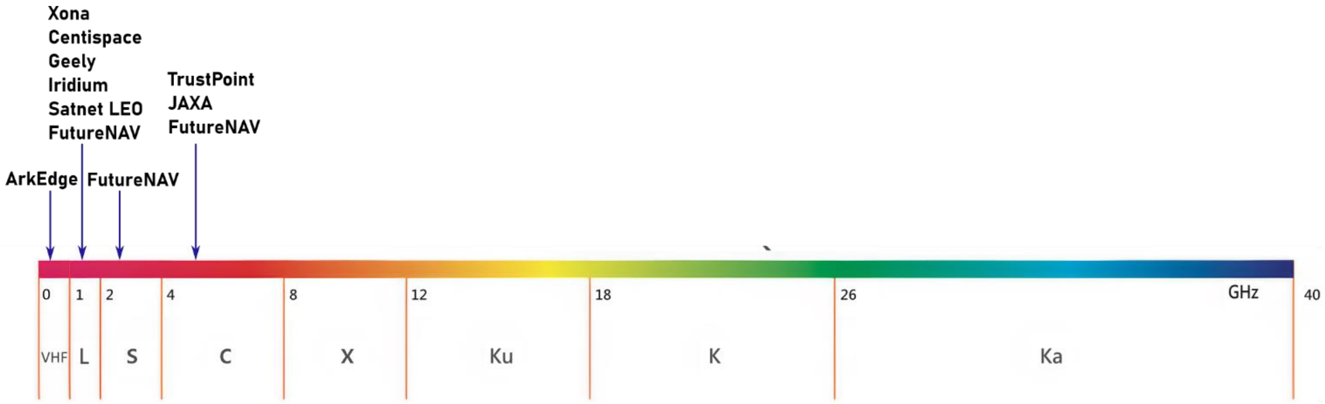

Figure 8. LEO PNT Service Providers and the frequencies used.

7.5 COORDINATION AND GOVERNANCE

With so many LEO PNT systems being developed, it is clear that coordination and governance will be of utmost importance for many reasons:

- Interoperability – ensuring different systems can work together is essential for global users who rely on consistent and reliable PNT services. Lack of interoperability could lead to conflicts or inefficiencies in signal usage.
- Spectrum Management – LEO PNT systems operate within a limited frequency spectrum. Coordination helps prevent interference between systems, ensuring optimal performance for users.
- Avoiding Redundancy – governance encourages collaboration, reducing duplication of efforts among providers and enabling shared infrastructure or resources where feasible.
- Innovation and Cost Efficiency – establishing a cooperative framework can encourage innovation and reduce costs by promoting shared research, technology development, and operational practices.
- User Experience – unified standards and compatibility improve the end-user experience by reducing the complexity of integrating multiple systems into devices and applications.

With GNSS, this task of coordination is relatively straightforward as there are only four global and two regional constellations, all in the same frequency band (L-band), and each operated by governments, allowing for the creation of inter-governmental forums, such as the ICG, to coordinate activities.

With LEO PNT systems, the complexity increases significantly due to the large number of service providers and the broad frequency spectrum they endeavour to cover. As explored in this chapter, dedicated LEO PNT systems will operate across VHF, L, S, and C frequency bands. However, with the potential involvement of broadband constellations in PNT, the frequency range could expand into Ku-band.

Additionally, the LEO PNT providers represent a mix of commercial companies and government entities. The private and competitive nature of the services being offered may introduce challenges for regulation and transparent cooperation.

Realising the emergence of LEO PNT systems, the ICG has introduced annual LEO PNT workshops to provide a forum that brings together various providers for multilateral information exchange. The first workshop was held in June 2023 in Vienna, attended by five service providers, namely Satelles, Xona, TrustPoint, Centispace and ESA. The presentations from this meeting are publicly available on the ICG website.[24] This was followed by the second workshop in June 2024 in Vienna, in which seven companies participated, namely Xona, TrustPoint, Centispace, China SatNet, ArkEdge, JAXA and ESA, however the presentations from the workshop have not been made public.

It is anticipated that the annual LEO PNT workshops will continue to be held in the future, providing a forum for the providers to meet, discuss, and coordinate their efforts in providing LEO PNT services.

There are additional ways that could improve coordination between the various LEO PNT providers, and ICG could also play a role in these. Some of the potential ways to achieve that include:

- **Establishing Standardisation Guidelines**
    - Develop and promote international standards for LEO PNT systems to ensure that systems are compatible, interoperable, and meet minimum performance requirements across the globe.
    - Alignment on technical standards for signals, frequencies, and system architecture.
- **Facilitating Data Sharing and Integration**
    - Encourage the sharing of data among GNSS and LEO PNT providers to create more robust and comprehensive datasets for research, testing, and operational deployment. Promote open-source platforms or collaborations that allow for easier integration of data from multiple GNSS systems and emerging LEO PNT systems.
- **Collaborative Research and Development**
    - Support for joint research projects between GNSS providers, space agencies, and private industry players to advance technological innovation in satellite-based navigation.
    - Support for the development of new algorithms for positioning accuracy, integrity monitoring, and signal robustness in complex environments.
- **Developing a Global GNSS and LEO PNT Roadmap**
    - A long-term roadmap could be developed for the evolution of GNSS and LEO PNT systems, identifying emerging trends, potential challenges, and opportunities for collaboration.
    - The roadmap could include specific milestones for interoperability, coverage expansion, signal reliability, and security.
- **Promoting Regulatory Cooperation and Harmonisation**
    - Collaborate with international regulatory bodies like the ITU and national governments to harmonise spectrum allocations for GNSS and LEO PNT systems to avoid interference between systems.
    - Advocate for consistent regulatory policies for LEO PNT systems, ensuring they align with international standards and facilitate cross-border usage and coordination.
- **Establishing International Working Groups**
    - Set up working groups focused on specific issues allowing experts from around the world to collaborate and share solutions to common problems.
    - These groups could work on developing tools and frameworks for the real-time management of multi-constellation navigation and mitigating signal interference.

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[24] https://www.unoosa.org/oosa/en/ourwork/icg/working-groups/s/wg-s-workshop-leo-pnt-2023.html

8. CONCLUSION

This report provided a snapshot of the LEO PNT ecosystem and market in December 2024. It examined technological advancements, key players, regional initiatives, and technical challenges.

The report began by outlining the satellite frequencies and signals currently employed by GNSS to provide context for the integration of future LEO PNT systems. Notably, all operational GNSS (with the exception of a single signal from the NAVIC system) transmit in the L-band. The C-band was considered for Galileo in the early 2000s, but never eventuated into operational signals.

In the LEO PNT space, most providers also concentrated on the L-band for easy compatibility with current GNSS receivers, however C-band is also getting renewed attention due to its unique characteristics, with at least three emerging providers (TrustPoint, JAXA and ESA's FutureNAV LEO-PNT IoD) looking to exploit it further.

This report also highlighted that unlike traditional GNSS systems operated by governments, LEO PNT features a mix of government and commercial stakeholders and is primarily driven by market demands.

The report categorised LEO PNT methodologies into three main approaches: dedicated PNT systems, signals of opportunity, and fused communications and PNT systems. Although the focus is on dedicated systems, the potential of signals of opportunity and hybrid systems was also discussed. Satellite communication providers operating in the Ku- and Ka-bands were identified as key players with the potential to incorporate PNT services, and having a disrupting effect on the market. Starlink, with its extensive deployment of satellites, is leading this space, though other mega constellations are also emerging.

Technical aspects of LEO PNT systems were explored, including precise orbit determination, timescale reference, ionospheric effects, and resilience to jamming and spoofing. Several options for time transfer and synchronisation were presented including ground stations, GNSS and GEO satellites, and the use of optical inter-satellite links.

Design considerations for both the space and receiver segments were emphasised, as these influence constellation architecture, service performance, and target markets.

It was shown that LEO PNT service providers will have between 200 and 500 satellite constellations depending on the type of satellite platform, navigation payload, regions they want to cover and a number of satellites in view. Most providers are using mini or micro satellites (~100 kg), with TrustPoint being the only exception, employing 10 kg nanosatellites.

Receiver segment challenges are highlighted, such as accommodating the broad frequency spectrum and the increasing number of satellites transmitting navigation signals. The importance of collaboration between receiver manufacturers and service providers is underscored, with Xona leading in partnerships among receiver and simulator manufacturers at this stage.

Profiles of dedicated LEO PNT service providers were presented, including Iridium® STL, Xona Space, and TrustPoint (USA); JAXA and ArkEdge Space (Japan); Centispace, Geely, and SatNet LEO (China); ESA's FutureNAV LEO-PNT IoD (Europe); and emerging players Fergani Space (Turkey) and GNSSaS (UAE). Among these, Iridium® STL is the only fully operational system, while others are at varying stages of development, from ITU filings to tech demonstration missions. Many providers aim to achieve initial operating capabilities within the next 2-3 years, with full operational capabilities to follow by the end of the decade.

The report also highlighted that the rapid development of various LEO PNT systems brings critical challenges, including system interoperability, spectrum management, and governance. Effective coordination among commercial, governmental, and multinational stakeholders will be vital to ensure these systems operate seamlessly. Without such collaboration, fragmented standards and competing systems could impede the global adoption of LEO PNT solutions.

As the ecosystem remains in its early stages, this report serves as a baseline for tracking developments over the next several years. With various providers beginning to launch their first satellites, the space is rapidly evolving and holds immense potential. Stay tuned for the 2025 edition of this report.

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