A Comparative Study of LEO-PNT Systems and Concepts

Bernd Eissfeller, Thomas Pany, Dominik Dötterböck, Roger Förstner
Institute of Space Technology and Space Applications (ISTA), University of the Bundeswehr (Armed Forces) Munich
D-85577 Neubiberg, Germany

BIOGRAPHIES

Bernd Eissfeller, Ph.D. is full professor ret. of navigation, Institute of Space Technology and Applications (ISTA), Faculty Aerospace Engineering of University of the Bundeswehr (Armed Forces) Munich. He was responsible for teaching and research in navigation, signal processing and system engineering for the European Satellite Navigation Programs (EGNOS & Galileo). Until the end of 1993 he worked in industry as a project manager on the development of GPS/INS navigation systems. He received the Habilitation (venia legendi) in Navigation and Physical Geodesy in 1996. He is nominated by the Federal Ministry for Digital and Transport (Germany) as a SatNav expert for two Working Groups on Galileo at the European Commission (EC). He authored and co-authored about 240 scientific and technical publications.

Thomas Pany is with the University of the Bundeswehr Munich at Space Systems Research Center (FZ-Space) where he leads the satellite navigation unit LRT 9.2 of the Institute of Space Technology and Space Applications (ISTA). He teaches navigation focusing on GNSS, sensors fusion and aerospace applications. Within LRT 9.2 a good dozen of full-time researchers investigate GNSS system and signal design, GNSS transceivers and high-integrity multi-sensor navigation (inertial, LiDAR) and is also developing a modular UAV-based GNSS test bed. ISTA also develops the MuSNAT GNSS software receiver and recently focuses on smartphone positioning and GNSS/5G integration. He has a PhD from the Graz University of Technology (sub auspiciis) and worked in the GNSS industry for seven years. He authored around 200 publications including one monography and received five best presentation awards from the US Institute of Navigation. Thomas Pany also organizes the Munich Satellite Navigation Summit.

Dominik Dötterböck received his diploma in Electrical Engineering and Information Technology from the Technical University Munich. Since 2007, he is a senior research associate at the University of the Bundeswehr Munich at the Institute of Space Technology and Space Applications. His current research interests include signal design, signal-processing algorithms for GNSS receivers and LEO-PNT system analysis.

Roger Förstner received his diploma in Aerospace Engineering in 1998 and a Ph.D. in Aerospace Engineering from the University of Stuttgart in 2002. After 7 years of working as a system engineer at Astrium, he is currently a professor at the Institute of Space Technology and Space Applications of the Bundeswehr University Munich, working in the fields of mission design and space exploration.

ABSTRACT

Currently, about ten dedicated LEO-PNT activities are under way on a worldwide basis. The SOOP (signals-of-opportunity) research within existing mega-constellations and plans for LEO-PNT research satellites are left out of consideration here. Thus, we observe a kind of hype and euphoria for LEO-PNT. However, shortcomings, contradictions and risks in several system designs are observed. In particular, many system designers underrate user segment aspects. In the paper we try to analyze the advantages and disadvantages of the proposed concepts, and to consider the most reasonable and realistic approach for LEO-PNT in a trade-off. We perform systematic assessments of the technical & non-technical characteristics of the LEO-PNT concepts: Orbit and constellation, carrier frequency, bandwidth and signal power issues, atmospheric (rain) and foliage attenuation and C/N_0 as function of carrier-frequency (UHF to Ku-Band). Additionally, satellite platform issues (dedicated satellite versus hosted payload), payload technology and SWAP-budgets, LEO satellite classes are considered. We expect that a LEO payload will also show code- and phase bias delays in the individual satellite signals (not different from MEO). If this is the case and calibration does not solve the bias issue with required

precision, PPP – corrections have to be determined for each LEO-PNT satellite. This has an impact on the complexity of the GSEC (ground segment) of LEO-PNT, because a large number of reference stations and up-load stations will be required based on the visibility constraint of the LEO orbit. The requirement on bias-free pseudorange and carrier-phase LEO-PNT measurements gets very stringent in the case that integer ambiguities have to be resolved for high accuracy and safety critical user segments.

1 INTRODUCTION

MEO-PNT systems and their regional augmentation systems have gained high maturity with about ~120 MEO satellites and 6.5 Billion GNSS L-band receivers in the world market. We have four (nearly) operational global systems (the question on future use of GLONASS is open) and four operational SBAS systems (plus five SBAS systems under development) available. We have to add the regional systems QZSS and NavIC. On the other hand, the user requirements became increasingly stringent for autonomy and safety critical applications over the last decade. For many applications of this kind, significant performance and robustness gaps exist with respect to interference, jamming, spoofing, and availability, integrity and other performance issues like multipath.

One solution to close these gaps is the implementation of LEO-PNT. Currently, several projects are under way. USA: Pulsar, TrustPoint, Blackjack, China: Centispace, Geely, EU/ESA/France: IRIS^2 & FutureNav, Synchrotube, Japan: JAXA LEO PNT (currently no detailed information). Not to forget Iridium Next (STL) and a possible navigation signal on OneWeb 2nd generation (UK). The common mainstream characteristics of these proposals is that a Low Earth Orbit (LEO) will be used and that on space segment level (low-cost) commercial or proprietary satellite busses and navigation payloads are developed which make use of Commercial of-the-shelf (COTS) components. The smaller orbital height of the LEOs allows the use of small-satellite technologies in order to obtain reasonable carrier power levels on the earth-surface. The utilization of many Nano, Micro and/or Mini satellites is matching very well to the New Space paradigm. Since 2017 several papers have been published which give a good generic overview on the technical context and issues of LEO-PNT (Reid et al., 2018, Prol et al., 2022). If you compare the concepts, the main commonalities end very quickly and many distinctions between the current LEO-PNT proposals are present. The systems have many technical and non-technical differences. Especially, the differences in the target users and target market segments and the funding schemes are significant. The parameter space for the definition of a LEO-PNT system is very large. Therefore, it is very difficult to elaborate an optimal solution, which has a viable acceptance chance and market opportunity at user level. The design for a viable business case is besides many technical issues the main challenge.

Compared to MEO-PNT, the LEO-PNT concept has advantages and disadvantages. Let us first start with the primary pros:

- Smaller free-space loss, if the carrier frequency stays the same
- Higher relative line-of-sight velocity between satellite and user
    - More rapid change of geometry between satellite and user (higher Doppler effect)
    - Signal shading by topography and buildings more frequently but for shorter time
    - Multipath effects/oscillations are reduced because of higher Doppler („Whitening" by tracking-loop filter)
    - Convergence time in precise point positioning (PPP) reduced by factor of 10
    - PPP faster and possible more reliable (Integer Ambiguity Resolution)
- Smaller low-cost satellites
- Multiple launch scenario with 30-60 satellites per rocket (lower launch costs)
- Lower capital expenditure for a single constellation (~ 35 % of MEO costs)
- Shorter innovation cycles of ~ 5 years design live
- Commercialization potentially possible
- Classical vision may be realized: Integration of communication and navigation (Fused LEO-PNT)

However, we should not forget that LEO-PNT is associated with several (partly design-dependent) drawbacks. The main cons are:

- Free-space loss, rain attenuation and foliage attenuation extremely strong for higher carrier-frequencies (availability issues)
- Frequency regulations (international ITU and bi-lateral) become necessary for new and existing frequency bands
- LEO-PNT with a hosted-payload (HPL) concept leads to sub-optimal constellation (PNT is not the primary mission goal)
- Higher ground segment (GSEC) effort in case of full independence (resilience) from MEO-PNT (shorter SV visibility < 20 min)
    - Number of sensor stations: ~ 60$^{*)}$ (full resilience), factor 4-5 more than MEO
    - Up-Link antennae: ~ 300$^{*)}$ (in case of real-time PPP corrections up-link, one antenna per SV)
    - Reference stations for PPP - corrections: ~ 1000 global, factor 6-10 more as MEO

- Carrier-frequencies above 2 GHz : New development and production of der GNSS user receivers becomes necessary
- In case of higher frequencies: User equipment (UE) SWAP-C (size, weight and power, cost) possibly too high due to use of array antennas?
- User equipment not competitive with L-band UE at start of LEO-PNT operation (time-to-market < 5 y)
- Space environment and radiation levels too critical for COTS based payload
- Orbit predictions for LEOs are more challenging because of surface forces (air drag, infrared and albedo radiation) and higher harmonics of gravity field impact
- Supply chain shortages for critical payload COTS in non-space industries
- Because of short space segment life-time capital expenditure (CapEx) is necessary every five years

[*)] Number of infrastructure elements in GSEC are by 60% reducible when using RF- or optical ISLs (inter-satellite links). The numbers will be considerably smaller in case of not-resilient LEO-PNT (augmentations) where orbit and clock determination is based on space borne GNSS receiver (tracking MEO constellations).

Besides all euphoria for LEO-PNT, the impression that MEO-PNT is an old out-of-date approach is misleading. It is not self-evident that LEO-PNT provides per se a higher performance for zero. The dual-use MEO systems lead on the one hand to very expensive satellites and to high launch costs. On the other hand, they have the benefit for the civil users that the space and ground segments are manufactured under a high-quality development and production process (V-development model). This includes a systematic system and sub-system requirements handling process, and an advanced process assurance and quality assurance. The motivation of this paper is to provide a fair but also critical assessment of the LEO-PNT concepts.

2 SURVEY OF LEO-PNT CONCEPTS

In this chapter, we provide an overview and a brief description of the most prominent LEO-PNT concepts currently under development and discussion. For sake of completeness, we have included the historical LEO-PNT systems TRANSIT and INES. We go briefly through the systems and highlight the main characteristics only. For the many details, which could be reported, we refer to the included references and to Table 1.

Iridium Next (USA) provides an operational PNT – functionality (STL) in L-Band with higher power (+30 dB) relative to GPS (Whelan et al., 2011). The signal was developed by Satelles, Inc. and has a bandwidth of about 5.2 MHz. It is a good example for the implementation of a high-power signal in L-Band to achieve robustness against interference and jamming. The number of Iridium Next satellites is 66.

The augmented positioning system (APS) developed by Globalstar and Echo Ridge was an activity in the frame of “Demonstration of Backup and Complementary PNT Capabilities of GPS“ project of the US DOT. It is an experimental built-up in the S-Band of the MSS (mobile satellite service) of Globalstar. It is making use of a SOOP concept (S-band CDMA signals) because no dedicated PNT-signals are generated (Hansen et al., 2021).

OneWeb (UK, EU) played a role after the Brexit in December 2020 by the UK seeking a Galileo alternative. In early 2020, OneWeb filed for Chapter 11 bankruptcy and the British government invested 500 Mio. $ US to stabilize the industrial consortium. In light of this, the idea came up to utilize the communication Ku-Band for a PNT-function. The issue was investigated (Foust, 2021), but the conclusion was that in the 1st generation of OneWeb a PNT function in Ku-Band was unrealistic. The issue was therefore shifted to OneWeb 2nd generation, but the status is unclear.

PULSAR (USA) is a commercial system developed by XONA Space Systems Inc. a Silicon Valley based startup from the Stanford University. From a European perspective, XONA is an excellent example for a New Space company providing commercial LEO services. The strong point of XONA is that the company was able to find high ranking private investors (e.g. Lockheed Martin, Toyota Venture). Additionally, they have many so-called ecosystem partners from the GNSS receiver and chip-set world (e.g. Hexagon/NovAtel, Septentrio, STMicroelectronics) and from the GNSS constellation simulator world (Spirent, Safran, Syntony, Rhode & Schwarz). Originally, the carrier-frequencies for PULSAR (Reid et al., 2022) were supposed to be in L-Band and C-Band. In order to enhance the robustness against interference and jamming the intention is to transmit higher power levels. At the ION-GNSS+ 2023 conference it was stated that C-Band has not the highest priority because the receiver industry is not ready. Thus, presumably the baseline is now to go with dual L-Band frequencies. From the beginning PULSAR had a clear business case in the field of automated driving, being compatible with the user requirements of high accuracy and integrity for autonomous cars. End of

2023 XONA has broadened their scope in the direction of the high volume market. PULSAR makes use of space borne GNSS receiver for ODTS but has a backup ODTS function based on a conventional GSEC.

TABLE 1: LEO-PNT system comparison

System	**Constellation**	**Orbits Height, i**	**Satellite SWAP**	**Frequency Band**	**Power, Signal**	**Funding Concept**
IRIDIUM Next STL, Satelles (USA)	66 SVs on 6 planes, global	780 km, i = 86.4º polar	3 m, 860 kg, 2200 W, DL < 15 y, Iridium Next Bus	L = 1621 - 1626 MHz, Iridium MSS	+ 30 dB dedicated signal	Private
APS-Globalstar (USA)	32 SVs on 8 planes, global	1410 km, i = 52.0º inclined	3 m, 700 kg, 2400 W, DL < 15 y, Globalstar Bus	S = 2483 - 2500 MHz, Globalstar MSS	Yes (TBD) SOOP	US DoT, experimental
OneWeb (UK, EU)	648 SVs on 18 planes, global	1200 km, i = 86.4º polar	1.3 m, 150 kg, 210 W, DL < 5 y, (Airbus) Arrow Bus	Ku=10.7-18.1 GHz (TBC)	Unknown, UK GPS, on hold	Private & UK government
PULSAR (USA)	260 SVs on 6 planes (TBC)	1000 km, i = 52.5º inclined	0.6 m, 150 kg, 200 W, DL = 5 y, Proprietary Bus	L = 1260 MHz & C = 5020 MHz (TBC)	+20 to +30 dB	Private & research funds
TrustPoint	≈ 300 SVs, Planes TBD	500 – 800 km, i = TBD	6 U cube sat, 10 kg,60 W OAP	C ≈ 5000 MHz, no L-Band	No, PSD as legacy GNSS	Private (TBC)
Synchrotube (F)	TBD	TBD	6 U bus	L-Band (TBD) to S-Band (TBD)	TBD	CNES, R&D
Black-Jack (USA)	4 (20), down-sized	550 km, i = 97.6º sun-synchronous	1 m, 200 kg, 108 W, X-Sat Saturn Class Bus (Blue Canyon)	L- ,C-Band & higher; optical: visible to IR (TBC)	Unknown, experimental PNT-Payload SEARGANT	US DoD Budget, experimental
Centispace (CHN)	$^{1)}$120 SVs / 12 planes + $^{2)}$30 SVs / 3 planes $^{3)}$40 SVs / 4 planes	$^{1)}$ 975 km, i = 55.0º , inclined $^{2)}$ 1100 km, i = 87.4º , polar $^{3)}$1100 km, i = 30.0º, inclined	1.3 m, 100 kg, TBD W, DL < 10 y, CAS Microspace WN-100 Bus	CL1= 1569-1581 MHz, CL5= 1170-1182 MHz	Yes, + 3 dB (TBC) compatible with BDS (GNSS)	Government
GeeSpace/Geely (CHN)	240 SVs/ planes (TBD)	620 km, i = TBD, inclined	GeeSat GSP100, 100 kg, < 1500 W (TBC), DL=5 y	L-Band (TBC)	Unknown, compatible with BDS	Private
IRIS^2 (EU)	≈ 200 SVs / planes (TBD)	TBD	700 kg (TBC)	L, C, Ku, Ka (TBD) Com+Nav	Unknown, PNT Hosted Payload	Public Private Partnership (TBC)
INES (F, EU) (historical)	70 SVs on 7 planes	1416 km, i = 62.8º, inclined	Unknown	E1 = 1589.74 MHz, E4 = 1258.29 MHz	No, compatible with GPS	CNES, EU
TRANSIT (USA) (historical)	10-12 SVs on 5-6 planes	1075 km, i = 90.0º, polar	1.0 m, 140 kg, 45 W, DL = TBD	f_1 = 149.98 MHz, f_2 = 399.98 MHz	Unknown	DoD, US Navy

TrustPoint (USA) is another proposal for a commercial LEO-PNT system (80% commercial, 20% governmental). TrustPoint (Shannon, 2022) intends to go with higher frequencies between 2 GHz and 10 GHz, presumably C-Band at ~ 5 GHz. TrustPoint plans to use low-cost 16 U, 10 kg satellites. No L-Band links are foreseen. TrustPoint seems to use a ground based ODTS technique based on so-called LEONS. The use of space borne GNSS is not stated.

Synchrotube (F) is an activity funded by the French space agency CNES under the motto: „Synchrocube, an Accurate and Secure Time Reference". In the Synchrotube project, the initial contractor was Syrlinks (now part of SAFRAN electronics and defense) a first LEO test satellite is built. Synchrotube should provide synchronization functions, if GNSS is not available.

Blackjack (USA) is a pioneering space program (starting in 2017) of DARPA (defense advanced research and program agency) to test various military payloads in the LEO: "Show the military utility for constellations in LEO". The concept is to use a commercially available platform and to integrate a military payload on it (Forbes, no year). Northrop Grumman develops two experimental PNT payloads (SERGEANT). Besides various RF-Links optical space-to-space and space-to-ground links will be used for precise timing. Originally, Blackjack planned with 20 satellites. The project is now downsized to only four satellites. The SERGEANT (software enabled reconfigurable GNSS embedded architecture for navigation and timing) development was handed over to the pLEO (proliferated LEO architecture) program of the space development agency (SDA) inside the US Space Forces.

Centispace (China) is a governmental funded LEO-PNT program to augment the Beidou MEO-PNT system (MU, 2023). Centispace is a dual frequency L-Band system with power levels comparable to GNSS (- 157 dBW). The idea is to provide good compatibility and synergy with MEO-PNT systems. Several ITU Filings were done. The service concept is to provide a high accuracy, an integrity augmentation service and a GNSS monitoring service from space. The applications are directed towards mass market and professional market.

Geely (China) is a private initiative (Geespace, 2023). Geespace builds the SVs in a new satellite factory. It is a subsidiary company of Geely technology group including Geely automobile, an important Chinese and international automotive company (Volvo, Lotus, Polestar, Terrafugia). Thus, the business case of Geely is the provision precise positioning with centimeter accuracy and connectivity for autonomous cars. The envisaged carrier-frequencies and other system parameters are unknown (presumably, it will be L-Band).

IRIS^2 (Europe) stands for infrastructure for resilience, interconnectivity and security by satellite. Its primary mission is secure communication for governmental and industrial purpose by making use of wide-band signals (European Commission, 2023). The space segment consists of several layers: GEO, MEO, LEO. Currently, the project is under development. The LEO layer will contain about 150 to 200 satellites. From the European perspective, it is the first LEO constellation of the European Commission (EC). In the early stage of IRIS^2 the idea came up to eventually fly a secondary or hosted Galileo augmentation payload. As far as we know, a final decision on this point is pending. In parallel, the European space agency (ESA) has started a LEO-PNT project in frame of the FutureNav program. An invitation to tender (ITT) was open asking for proposals on the development of a LEO-PNT in-orbit demonstration (Ries et al., 2023). In March, 2024 to development contracts were awarded to the European industry (Thales & GMV).

3 DESIGN DRIVING USER REQUIREMENTS

As mentioned earlier, MEO-PNT has gained a high level of maturity in nowadays. This took a development time of several decades. The challenge is that the user requirements in some market segments also got more and more stringent with increasing innovation speed.

Because of the slow value chain progress, the MEO GNSS systems could not keep pace with the short innovation cycle of the user segments. Over the years, GNSS technology and markets were developed in a variety of areas (EUSPA, 2022). Centimeter level accuracy in real-time was reached in minutes by some precision RTK and PPP software systems. However, many applications lack from the missing robustness in case of interference, jamming and spoofing, too long initialization times and marginal availability and integrity in challenging environments. This holds especially for high-end and safety-critical applications.

It is important to assess in the system development the target market segments, which should be preliminary supported by a LEO-PNT. In some concepts, it is not clearly stated which kind of user requirements are supported.

TABLE 2: Selection of high-end user requirements (Federal Radio Navigation Plan, 2021, USA)

User Type	Application	Accuracy	Availability	Continuity	Integrity	Alert-Time	Alert-Limit	Reference
Aviation	CAT I-III	16 to 3 m	99 - 99,999 %	>1-8 10^{-6} in any 15 s	>1-2 10^{-7} per approach	6 s – 1 s	4 – 1 m	FRNP, Tab 4-2
Marine	Harbor approach, waterways	10 to 2 m	99,7–99,9 %	TBD	TBD	TBD	TBD	FRNP, Tab 4-4
Road	Collision avoidance, connected vehicles	10 cm	99,9 %	TBD	1-10^{-8}/h (TBC)	5 s	20 cm	FRNP, Tab 4-7
Agriculture	Precision irrigation, cultivation	15 to 2 cm	99,9 %	N/A	N/A	5 s	60 cm	FRNP, Tab 4-10
Geomatics	Hydrographic survey	2 to 30 cm	99%	N/A	N/A	N/A	N/A	FRNP, Tab 4-13
Railways	Positive train control	1 m	99,9 %	TBD	TBD	6 s	2 m	FRNP, Tab 4-9
Precise timing	5 G & DVB	10 ns	TBD	TBD	TBD	TBD	TBD	FRNP, Tab 4-14

If comparing with earlier version of the US federal radio navigation plan (FRNP) the user requirements in the table at the high-end got more and more stringent over time. The observations/conclusions from the table are:

- The users covered are mainly professional users with high performance requirements and need of robustness
- The LEO-PNT system availability in this case for A-PNT should be in minimum 99% and in many cases higher than 99,9%: This has a consequence on the link availability of the system as function of frequency and radio propagation conditions (rain attenuation at higher frequencies)
- Some of the professional users require cm-level positioning accuracy: The system should support integer ambiguity resolution in PPP, RTK and combined PPP-RTK methods
- Integrity is a challenge for users who operate in the field of safety critical navigation: The impact of LEO-PNT on A-RAIM is important.
- The user receiver SWAP-C (size, weight & power, cost) should not exceed the form factors of the current L-band equipment in the existing markets: If this is the case, acceptance problems of the GNSS user segment could result.
- Of course many other user classes exist with lower performance requirements
- Message aside: The SOOP method using mega-constellations in Ku-Band, Ka-Band concept is only an option for A-PNT, if it will fulfill the high-end user requirements. May be it plays a role in a wider sense of PNT resilience concept?

4 FREQUENCY AND SIGNAL ISSUES

The carrier frequencies (and their bandwidth) used for LEO-PNT are the top-level system parameters. Because they determine the performance parameters for the user in terms of available C/N_0 (accuracy, jamming & spoofing resistance, availability, TTFF), complexity of user receiver, complexity of payload and platform. Unfortunately, the *dilemma* of satellite navigation lies in the problem that higher frequencies give better accuracy, lower multipath and (partly) better jamming resistance, but on the other hand, the link-budget gets more and more critical when moving upwards the frequency axis.

4.1 Regulation and Compatibility

In the LEO-PNT discussion, several frequency-bands are under consideration: UHF/VHF, L, S, C and Ku/Ka. The regulation status is very complex and in detail described by an ITU presentation (Hon Fai, 2016). The L1 – Band (1559-1610 MHz) is co-primary for RNSS and ARNSS. It is already heavily occupied by all the existing MEO GNSS systems. Strong restrictions exist with respect to compatibility. Besides ITU requirements, many bi-lateral agreements exist. The L-Band between 1215-1300 MHz is in principle reserved for RNSS services. A new joining system is not allowed to generate interference to the existing services. In the E6 Band

(1260-1300 MHz), other users are allowed on a secondary basis. Secondary services are amateur radio and military radars. Navigation receivers have to protect themselves against narrow-band and pulsed interference. The E6 band is not authorized for commercial use in the US. The lower L-Band (1164-1215 MHz) is also a RNSS band. In this band the aeronautical ground based DME (distance measurement equipment) is working. The sum of all RNSS users transmitting in the band have to fulfill a power flux density limit of $\leq$ -121.5 dB (W/m^2/1MHz) for the radio determination of the international space station $\leq$ -129 dB (W/m^2/1MHz). The S-Band 2483.5-2500 MHz contains co-primary allocations for different services: Fixed, mobile, mobile-Satellite and radio determination Satellite (RDSS). C-Band 5010 – 5030 MHz is also an RNSS band. RNSS services have to protect the microwave landing system ($PFD_{max} < -124.5$ dBW/m^2) above 5030 MHz and the radio astronomy band below 5000 MHz ($PFD_{max} < -196.5$ dBW/m^2). Especially the radio astronomy requirement is very stringent and leads to the need of carefully designed payload filters. In the Ku-Band currently no RNSS services are filed up-to now. The brief discussion shows that it is a complex and time-consuming task to allocate frequency slots for a LEO-PNT service. This very evident, if higher power levels shall be transmitted.

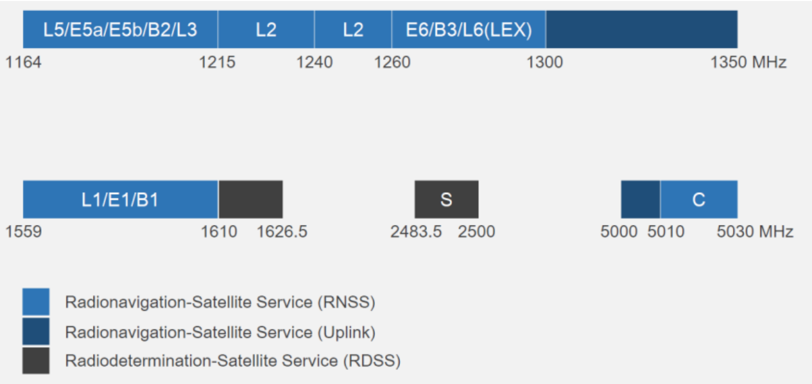


FIGURE 1: GNSS frequency-bands in use (Hon Fai, 2016)

4.2 Link-Budgets and Carrier-to-Noise Ratio

Classically, in the GPS L1, L2 Link-Budget a total atmospheric loss of 0.5 dB is considered. This value is associated with a link availability of 99,999 %. The values for atmospheric attenuation depend heavily on the assumed rain rate (e.g. Rec. ITU-R PN. 837-1, statistical rain-rate model by regions) in mm/h. On a global basis the following rain-rates have to be used: Percentage of time the link is lost: 0.1 % (60 mm/h) und 0,01 % (150 mm/h). For Europe the comparable rain rates are of course smaller: 0.1 % (12 mm/h), 0.01 % (32 mm/h) and 0.001 % (60 mm/h).

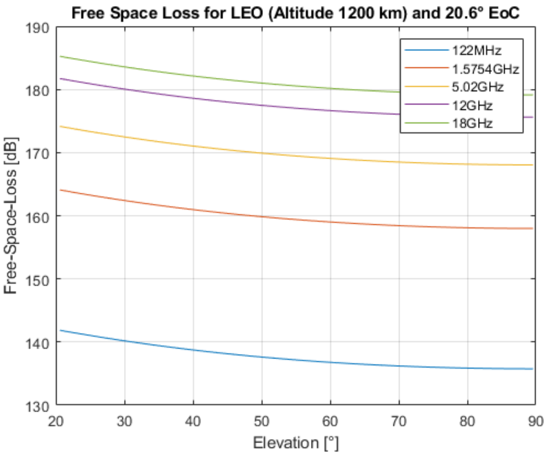


FIGURE 2a: Free-space loss as function of frequency

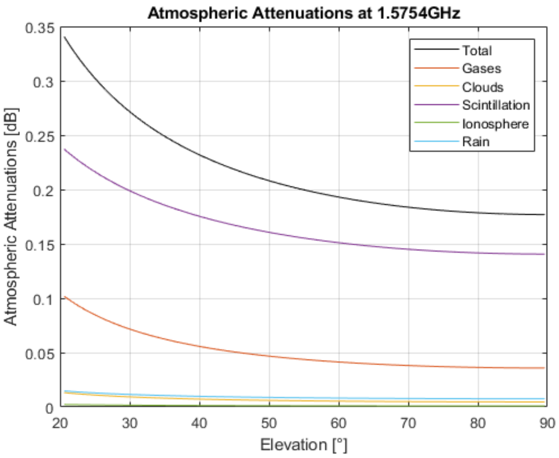


FIGURE 2b: Atmospheric loss at L-Band (60 mm/h)

In real terrestrial environments, users are moving under trees. This means that additionally the foliage attenuation has to be taken into account. The effect of canopy of a certain size (line-of-sight obstruction) are computed based on ITU-R P.833-10 (ITU, 2021). The values for Ku-Band are also very high, corresponding to attenuation levels that are typical for L-band in an indoor situation.

TABLE 3: Foliage attenuation as function of frequency and diameter d of trees (El = 45°)

Carrier frequency	Foliage attenuation (d = 5 m)	Foliage attenuation (d = 50 m)
0.4 GHz	5 dB	8 dB
1 GHz	7 dB	14 dB
5 GHz	13 dB	22 dB
12 GHz	17 dB	31 dB
18 GHz	25 dB	36 dB

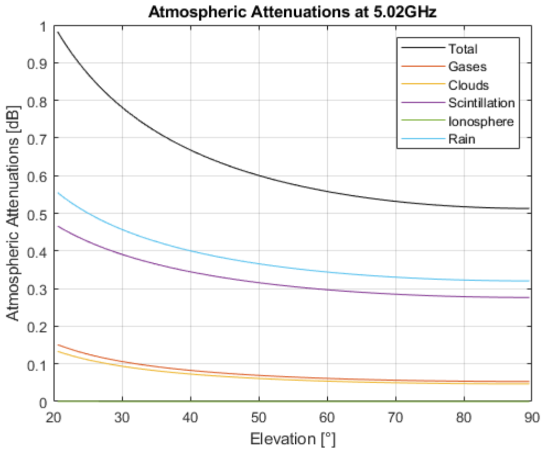


FIGURE 2c: Atmospheric loss at C-Band (60 mm/h)

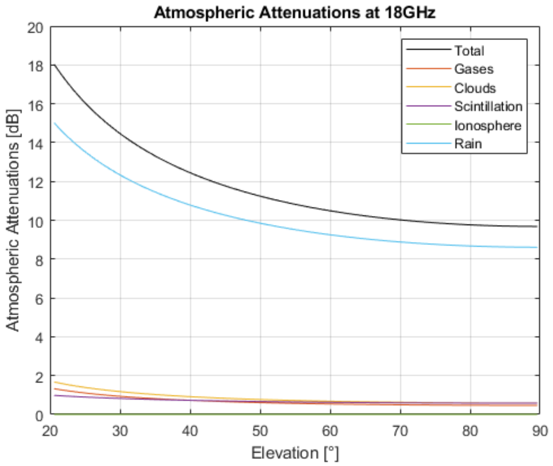


FIGURE 2d: Atmospheric loss at Ku-Band (60 mm/h)

The result here is that even for a rain rate of 60 mm/h (global availability of 99.9%) the value for the propagation loss (free space plus atmospheric loss) is on a level of -203.0 dB for Ku-Band. In case of 99.99% required availability the rain-fall attenuation is considerably higher by around 20 dB. Case of Ku-Band: With an gain of the payload antenna on the order of 7 dBic @ 1200 km, and HPA (high power amplifier) output power of 8 dBW, and N_o = -204 dBW/Hz assuming an omnidirectional ± 0 dB UE antenna a C/N_o = 16.8 dB-Hz is approximately found (El = 20°). This value is identical to the right corner (blue curves) of Figure 3 (1200 km).

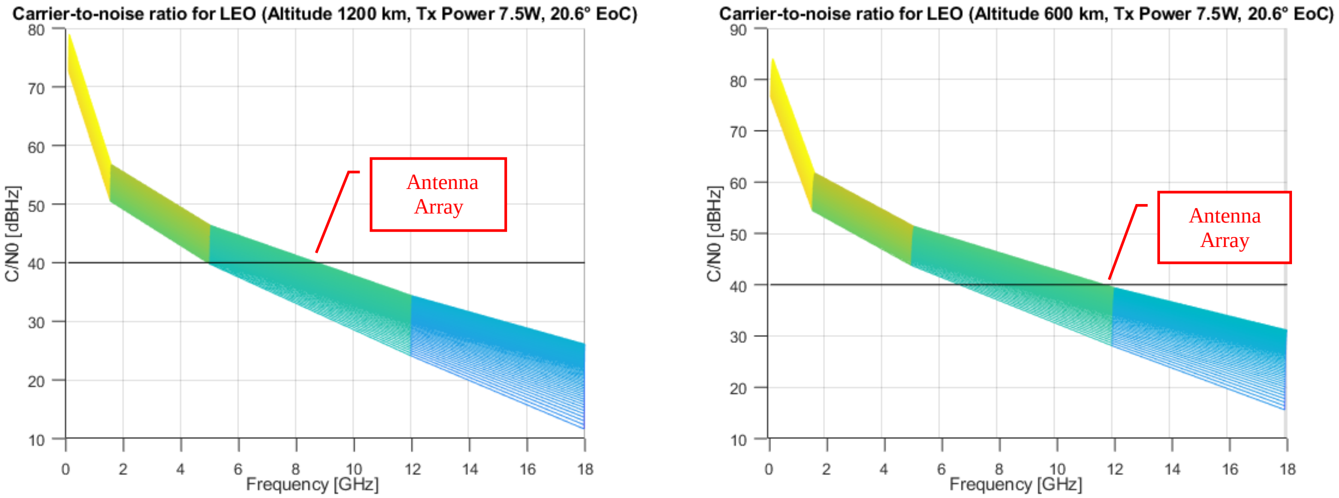


FIGURE 3: Attainable C/No as function of frequency (Availability = 99.9%), different orbital altitudes and varying elevation band

The interesting point from Figure 3 is that C-Band works with LEO-PNT (in contrary to MEO-PNT) with a single (± 0 dB) antenna element and reasonable RF-power transmitted by the LEO payload. A margin of about 5 dB exist for anti-jamming resistance. With respect to L-Band the effect of higher C/No is significant. In L-Band we could reduce the transmitted power by some dB. Approximately at 8 GHz (1200 km) a break point exists, which is important for the user receiver complexity: For frequencies above 8 GHz directive antennas (CRPAs) become step-by-step necessary.

4.3 Interference and Spoofing Resistance

If the design goal of LEO-PNT is assured PNT (A-PNT) a higher interference and jamming resistance should be provided in comparison to MEO-PNT. A higher jamming resistance is also supporting a higher spoofing resistance, because a spoofing attack typically starts with a jamming attack (intention that the receiver is losing lock).

In signal design, there are **two** ways to achieve higher robustness against interference and jamming. The first approach is to provide higher signal power (XONA, Satelles). The second approach is to increase the bandwidth of the signal. Both methods are not easy to implement because they could cause compatibility conflicts with existing signals and within the (bi-lateral or ITU) frequency regulation process. A pragmatic mix of both concepts could be a constructive solution.

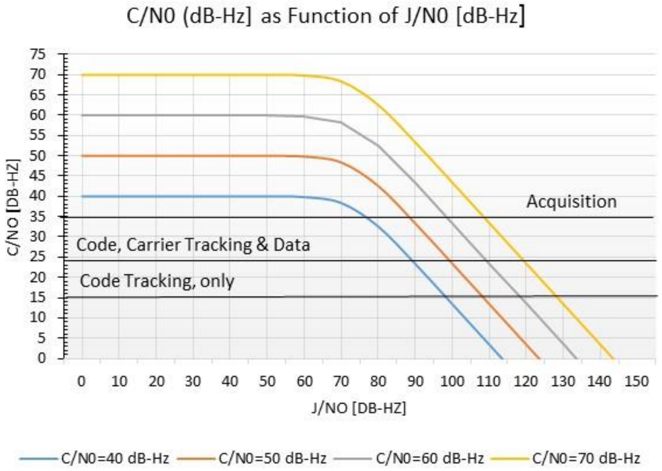


FIGURE 4a: Degradation of C/N_o by jammer J/N_0 for a 10 Mc/s and Q =2.2 (BLWN jammer) for higher power levels

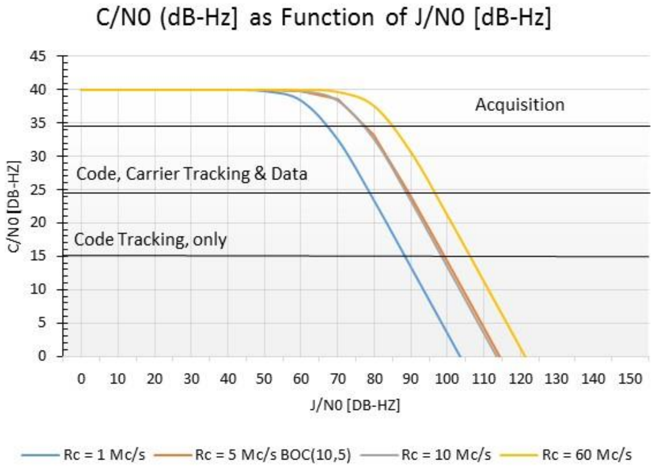


FIGURE 4b: Degradation of C/N_o by jammer J/N_0 for different chipping rates and Q =2.2 (BLWN jammer)

From the comparison of 4a and 4b we see that higher power is more efficient in the sense that a smaller signal bandwidth could be kept but with improved jamming resistance. The processing load on the user receiver is smaller. Please remember, that the typical acquisition threshold is at 34 dB-Hz, the threshold for code- and carrier-tracking and data demodulation at 24 dB-Hz and code tracking only (high sensitivity) at 15 dB-Hz. If C/N_o drops below a specific threshold the receiver function is lost. Thresholds are of course only approximate values. We follow here the formalism in Kaplan, 1996. The main improvement of jamming resistance for higher carrier frequency comes from the fact that higher attenuation L_{add} by foliage, obstacles, and canopy leads to lower received jamming power J at the UE input (assuming same path d, same antennas, and same output power J_o of jammer):

$J = J_o – 20 \log_{10} (4\pi\, d/\lambda) - L_{add}$.

4.4. Thermal Noise and Multipath

Mainstream thinking of signal designers often leads to very large bandwidth because the thermal noise errors and multipath errors on pseudorange and carrier-phase level will get very small. It is theoretically right that higher carrier-frequencies open the opportunity to assess larger bandwidth for a GNSS signal. However, the user receiver aspects have to be considered very seriously in parallel.

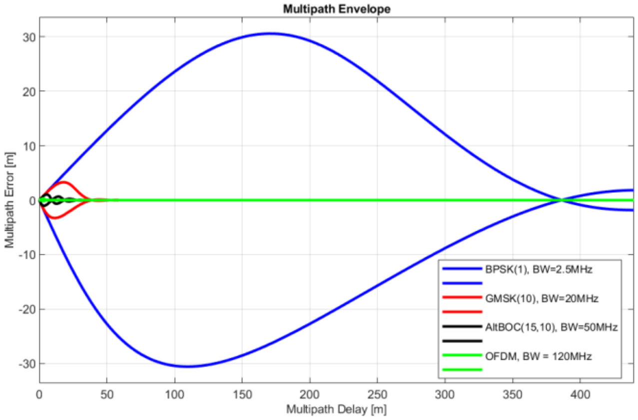


FIGURE 5a: Multipath Envelopes as function of bandwidth

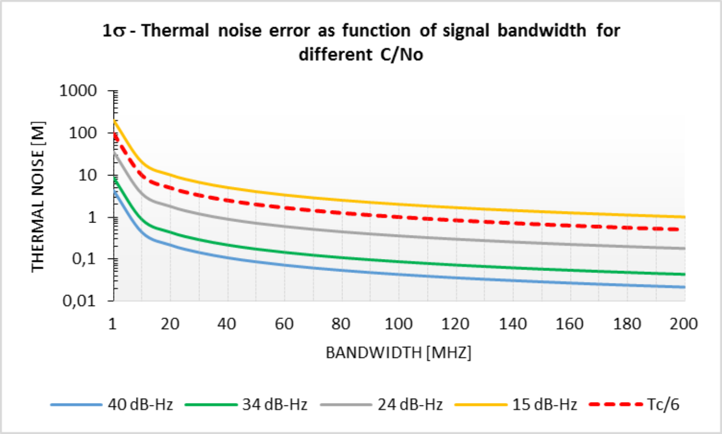


FIGURE 5b: Pseudorange thermal noise as function of bandwidth

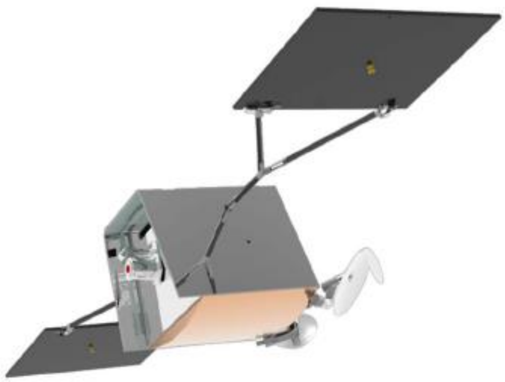
For the multipath envelope, a multipath-to-signal ratio of 0.13 (-9 dB) is used. For a 120 MHz bandwidth, the multipath amplitude is small and lies between ± 0.5 m. The 1σ - ranging error due to thermal noise was computed for an unaided non-coherent E-L discriminator with correlator-spacing d = 1.0, B_L = 1 Hz and pre-detection integration T = 0.01 s.

5 PLATFORM AND PAYLOAD ISSUES

The navigation payload and the supporting satellite platform are the main elements of a LEO-PNT space segment. Therefore, we will bring together some information, estimates and issues of the platform and satellite. The form-factors of the payload have to match the size, weight, power and cost budget of the satellite. Finally, the number of satellites per launcher and overall launch cost is determined.

5.1 Platform Concepts and Satellite Classes

Two concepts for the satellite platform are possible: A dedicated satellite solution (most LEO-PNT concepts are using this option) and a hosted payload (HPL) approach.

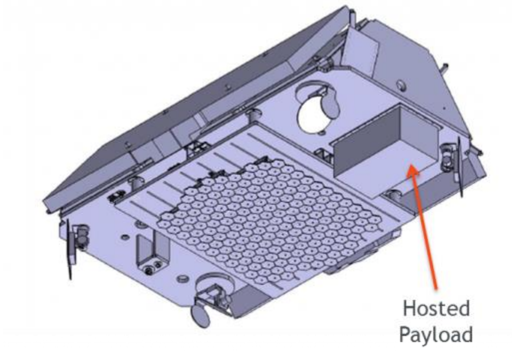


Satellite specification: Commercial bus
Example: Airbus Arrow platform

- SWAP: 1.3 m, 200 kg, TBD W OAP , DL < 5 years
- Payload SWAP: 100 kg, 50 x 50 x 50 cm , 210 W OAP
- Launcher option: 36 - 48 SVs on Falcon 9 & LVM 3

In use: OneWeb 2nd Generation

FIGURE 6a: Dedicated small satellite platform, Image: OneWeb, Azzarelli (2016)



Satellite and payload specification: Commercially available
Example: Iridium Next Hosted payload (HPL)

- SWAP: 30 x 40 x 70 cm, 50 kg, 50 W OAP , DL < TBD
- Data rate: < 1 Mbps, orbit average ≈ 100 kbps
- Satellite: 700 kg class
- Launcher option: 10 SVs on Falcon 9

In use: Aireon ADS-B payload on Iridium next

FIGURE 6b: Hosted payload concept (Iridium Next), Image: Iridium (NASA Spaceflight 101, 2024)

In the dedicated satellite solution, the service provider (private or public) has to pay for the space segment SSEC (satellite, payload, and launcher) and GSEC development and production. Additionally, operational cost will apply. In the HPL concept, the cost model is different: The HPL service provider has to build the payload. He will pay a hosting fee, power fee and data service (communication) fee to the primary mission company. The investment costs are cheaper because the HPL service provider is only paying a proportional fee for the launch of the payload HPL mass. The two referenced examples in Figure 6 a and 6 b show only the upper envelope of a potential LEO-PNT real-world realization.

TABLE 4: Satellite classes

Satellite Class	**Weight (dry), 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

We will show in the next chapter that a discrete payload may be compatible with the two concepts in terms of their SWAP. The reference satellite assumed in Figure 6a belongs in the lower mini to micro satellite class. In our view, possible future ambitious development goals shall clearly go in the direction of higher integration in order to exploit the benefits of Nano satellites while keeping good quality.

5.2 Payload Issues

In the following, we show a generic structure of a LEO-PNT payload. The mass and power budgets are shown in an associated table. The budget values hold for a discrete integration of all sub-systems.

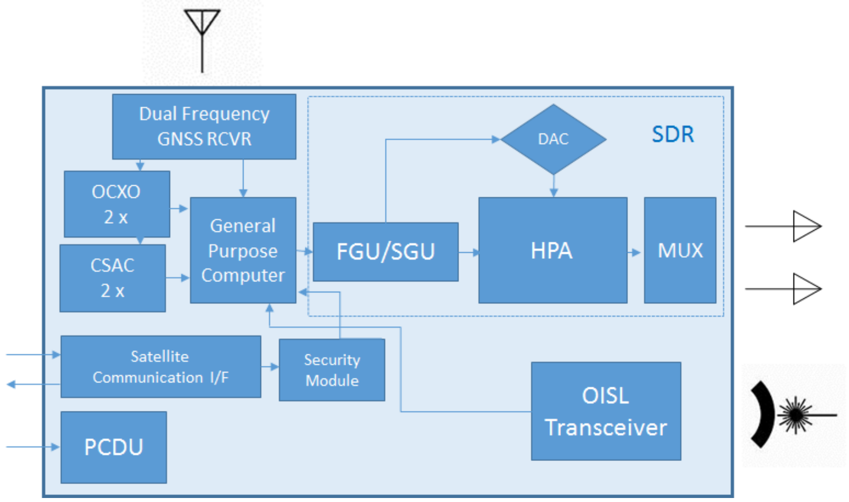


FIGURE 7: Block diagram of generic LEO-PNT payload

By use of higher integration of the sub-systems smaller budget values will be found (highly integrated navigation payload). The assumed technical parameters for the navigation payload are approximate values. The concept is a dual frequency payload making use of an L-Band 2 Watt RF-Link and a C-Band 1 Watt RF-Link at the transmitter side. The values of the RF-output power are rather low (2 W, 1 W) but a working guess. This is due to the limitations of the XLINK SDR amplification gain based on COTS components. With the efficiencies of this XLINK SDR system a 5 W RF-Link in L-Band would need a DC power of 20 W (and 40 W DC power for an C-Band link for 5 W RF power). Totally, one would have to add nearly 24 W DC power to the budget. The efficiency figures of the XLINK system are low (0.25, 0.13). They refer to the HPA only. The input DC power of 16 W is distributed between the SDR and the HPA.

TABLE 5: Exemplary payload budgets (implementation with discrete parts); manufacturer names are only given to illustrate the subsystems

Sub-System	**DC Power Consumption**	**Mass [kg]**	**Redundancy [No. of Units]**	**RF-Output Power**
Dual Frequency GNSS Receiver, PODRIX, Beyond Gravity	15 W	3 kg	1 (2) cold	N/A
OCXO (Ovenized Crystal Oscillators) for Space (MicroSemi)	1.5 W	0.1 kg	2 hot	N/A
CSAC (Chip Scale Atomic Clock) (MicroSemi)	120 mW	0.035 kg	2 hot	N/A
General Purpose Computer (Multi-Core ARM Processor & GPUs)	30 W	2 kg	1 (2) cold	N/A
Software Defined Radio (SDR) Earth & Space GmbH, Berlin XLink-L[2] for L-Band link (P, D)	16 W	0.2 kg	1 (2) cold	33 dBm = 2 W (Efficiency = 0.25)
Software Defined Radio (SDR) Earth & Space GmbH, Berlin XLink-X[2] for C-Band link (P, D)	16 W	0.2 kg	1 (2) cold	30 dBm = 1 W (Efficiency = 0.13)
Commercial Encryption Module	0.5 W	0.1 kg	1	N/A
Communication I/F Satellite	2 W	1.2 kg	1	N/A
PCDU, Interfaces, Harness, Structure, small electronic parts	2 W	30.0 kg	1	N/A
Optical Inter-Satellite-Link Transceiver (OISL), TESAT Scot 80	60 – 80 W[1]	15 kg[1]	2 hot	TBD
Σ Budgets	**81.1 W**	**36.8 kg**	**84.8 W / 36.9 kg**	

[1]OISL assumed to be a sub-system of the satellite platform; [2]Transmitter antenna assumed to be in the satellite budgets

However, the budget values (85 W + 24 W and 37 kg) are compatible with the payload limits described in Figure 6a (210 W, 100 kg). There is even a margin for a third frequency or adding the OISL to the payload budget. The hosted payload of Figure 6b (50 W, 50 kg) is setting more stringent limits. Optimization and higher integration is necessary in this case.

5.2.1 GNSS based Orbit and time determination (ODTS)

The role of the GNSS receiver for ODTS depends on the autonomy & resilience concept of the LEO-PNT: In some concepts (e.g. TrustPoint, XONA, Centispace) the ODTS is (partly) based on the classical ground based concept (monitor stations, ground processing, and up-link facilities). Others claim to keep the ground segment lean relying solely on ODTS based on a space borne GNSS receiver. In the latter case, the GNSS receiver becomes a central element in the system. If we go for high accuracy ODTS (fulfilling high-end user requirements), a dual frequency receiver is necessary. Although, the LEO-PNT satellite will fly above 1000 km there is still residual ionosphere and plasma sphere present with a magnitude of 1 TECU, which leads to a delay error of 30 cm at GPS L5.

In the case of the space-borne GNSS receiver, the receiver is observing pseudorange and carrier-phase to GPS or Galileo satellites. Here it is important, that the same signals are combined as in the case of MEO clock determination (GPS $P(Y)_1$-$P(Y)_2$ and Galileo E_1-E_{5a}) in the respective control segments. Otherwise, a differential code bias is introduced. In anyway, the receiver group delay bias between the two frequencies must be known. An additional problem is that the space borne receiver will generate an all-in-view solution for position and clock-offset, i.e. the clock-offset is an average about the clock parameters (Rubidium, H-Maser) in the visible sub-set of the MEOs. Because the LEO is moving fast the MEO sub-set will change permanently and jumps in the clock-offset estimation will occur. The accuracy of the clock-offset will not be better as the average over the GPS and Galileo clock model terms in the least-squares estimator.

Another issue is the output of a very precise timing signal < 0.1 ns (3 cm). It is somehow strange that high-end space receivers like PODRIX (Beyond Gravity, RUAG) or Viceroy (General Dynamics) specify the standard 1 PPS output with 50 ns (1σ) accuracy (equal to 15 m). This is by far not good enough for generating a precise space-clock by slaving an OCXO and/or a CSAC to the GNSS system time. A high precision timing interface with a closed loop operation has be developed. We refer to this point later again. Some protagonists claim to augment ODTS with data of a (GEO based) PPP correction service. Technically, this looks like a good idea, but the performance and the HMI (hazardous misleading information) risk tree of the LEO-PNT gets dependent on a third party service. Being only dependent on space borne GNSS for ODTS leads of course to a single point failure potential, if GNSS is lost, in the sense of resilience.

5.2.2 Interference between Transmitted Power and GNSS Signal Reception

Basically, an interference problem exists onboard the LEO satellite, if a space borne GNSS receiver for orbit determination is flown on the one hand (in L-Band), and signals are transmitted down to the earth also in L-Band on the other hand. The signals leaving the (down-pointing) LEO antenna have an amplitude in the 1 – 10 Watt region, whereas the signals received by the (top - pointing) antenna are on the 10^{-16} W level. The transmitter acts like a strong interferer to the space borne GNSS receiver. Careful electrical and mechanical design together with guard-bands/slots (frequency-choice or pulsing) and mitigation techniques (interference cancellation) can be applied. A payload design without a GNSS receiver (classical approach) or using higher and/or lower carrier frequencies has some advantage here. Some protagonists (Korogin, 2022) claim that a TDMA (pulsing scheme) for transmit path is necessary. However, recent research work at our institute (to be published at the ION-GNSS+ 2024) indicates that simultaneous reception and transmission on the Galileo E1 band for the purpose of pseudolites operation caused less problems than expected, well noting that the transmitted signal power was relatively low. From those experiments, we see indications that the following countermeasures could allow transmission and reception on the same frequency band: isolation of transmit and receive antenna on opposite side of the satellite (>100 dB), cancellation of the transmitted signal within the received signal (>30 dB) spreading code (>20-30 dB).

5.2.3 Payload Code and Phase delays

A problem area, which is usually neglected in the LEO-PNT discussion, are the issues of delays between the clock reference point and the antenna phase center of the payload. Even, if the orbit coordinates and internal time are determined with high accuracy based on a GNSS space receiver, H/W delays will be present in the electronic circuits and processing systems. There is no evidence, that in a LEO-PNT payload such code biases and carrier-phase biases will not exist. As we know from MEO-PNT payload technology and user receiver technology, these frequency and bandwidth dependent biases are present in a real RF-system. As mentioned the ODTS GNSS receiver will have a 1 PPS – external output interface, which is used to slave an onboard clock (TCXO, OCXO, CSAC) to the system time Galileo and/or GPS. Based on this 1 PPS signal, several H/W & S/W sub-systems are synchronized. The problem is that various delays/latencies (different for each carrier-frequency and each pseudo random noise modulation) are generated by the sub-sequent electronics and the processing systems. Not to forget the antenna phase center offset (PCO) and phase center variation (PCV). By using COTS components instead of high-precision space electronics the situation with respect to delay and bias stability will not get easier. A certain portion of these delays (code biases, inter-frequency biases, phase biases) remain stable (code level more stable as carrier-phase level). In addition, temperature dependent and radiation dependent variations and aging effects will be present. In the late 90ties, NovAtel made investigations on their GPS/GLONASS MiLLenium-G chards on such front-end issues (Neumann, 1999): They found biases around 1 to 3 m over frequency for code and 0.02 – 0.03 cycles (6 mm) on carrier level. Aging effects: 5-10 cm over 8 weeks. Temperature variations of front-ends by (12-15° C) can cause biases in the range of (10-30 cm) and temperature variations between (20-40° C) can cause variations in the range of (50-100 cm). These are of course only indicative values, which cannot be transferred 1by1 to the LEO-PNT payload, but they show that such issues have to be expected when using COTS components. In the DLR funded pseudolite research at UFAF around 1998 we also found in the STel (Stanford Telecom) pseudolite code biases of up to 2 m, and carrier phase biases up to 15-25 mm. Thus, a fundamental question is how to control and work on these potential biases in the LEO-PNT system. There are *three* ways to deal with these biases: Pre-mission factory calibration, hardware calibration loop (e.g. GPS IIIF), determination the biases by aid of a PPP correction network of reference stations (e.g. IGS, Trimble RTX). Antenna phase center variations of the transmit antenna are around 20 mm in MEO satellites. By factory calibration, about 60% are captured. Remaining PCVs are about 8 mm. The values look small but they get relevant, if the goal is to determine integer ambiguities in the user segment.

5.2.4 Space Radiation Issues

Looking to the generic block diagram of a LEO-PNT payload it gets clear that many, silicon chips (SiO_2) are used in their sub-systems. As very well outlined by Reid et al., 2018 these chips are very sensitive to space radiation. LEOs in the altitude range 500-1200 km are flying in the Level II radiation environment. Besides altitude, the orbital inclination is an important parameter. Reid et al., 2018 explains that industrial SiO_2 chips (integrated in industrial COTS) will fail over 5 years, if they are exposed to a total ionizing dose between 5 – 20 krad (Si). This range is easily exceeded above 500 km. Thus, the solution outlined by Reid et al., 2018 was to use the selected COTS (tolerance of 30 krad (Si)) based on intensive radiation testing. Taking into account potential supply chain problems in the commercial semiconductor world, a significant risk with respect to the availability of the LEO-PNT COTS components remains. Cyber issues built-in into digital COTS is an additional risk area.

6 CONSTELLATION AND ORBIT ISSUES

Orbit and constellation design for a LEO-PNT is an important task: The constellation size, orbital altitude and inclination determine the visibility and performance pattern of a space based PNT system. The performance in terms of visible satellites, PDOP, HDOP, VDOP, and TDOP is of importance here. Many studies have been done on this topic. The number of orbital planes have to be harmonized with the launcher capabilities. With 30 to 60 satellite per launch a complete orbital plane will we filled with satellites. Besides this, a replenishment strategy should be envisaged in case of malfunctioning satellites. One main difference in Table 1 between the LEO-PNT proposals are exactly the orbital altitude and the orbital inclination. The orbital design has to do with the market focus of the system provider. The statistical satellite concentration is high around the latitude of the inclination. With an inclination around i = 55° the main industrial geographical areas are covered, whereas with polar orbits (i = 87) more satellites are found in the northern and/or southern hemisphere. Hybrid constellations (sub-constellations) with different inclination are possible.

An argument which is often brought forward by the protagonists of LEO-PNT, is the saying, that with LEOs a better coverage in urban canyons is achieved: This might be true, but a significant price has to be paid in number of satellites, launch and operational cost, if an elevation requirement for the PNT service is set for El = (30° – 60°).

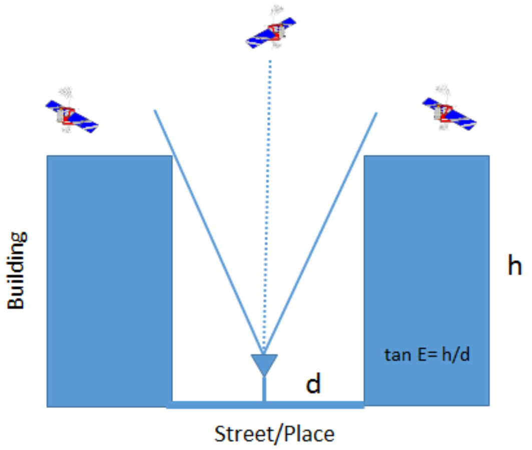


FIGURE 8a: Urban canyon problem

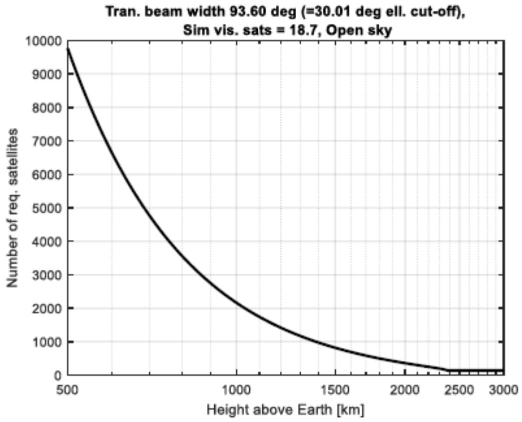


Figure 8b: Number of required satellites in orbit for El = 30°

Based on a tool of the University of the Bundeswehr Munich the required number of satellites as function of elevation angle and orbital altitude was computed. For a 30° elevation requirement, already 1200 satellites are needed for 1200 km orbit if on average around 19 satellites shall be visible (this number was chosen to mimic a multi-GNSS satellite visibility).

TABLE 6: Satellite visibility for increasing elevation angles as a function of orbital altitude and constellation size

Altitude		600 km			1200 km		
Number satellites in orbit		200	1200	3000	200	1200	3000
Mean number of visible satellites	El = 10°	< 4	24	61	9	55	138
	El = 20°	< 4	15	38	7	37	90
	El = 30°	< 4	6	15	< 4	19	41
	El = 60°	< 4	< 4	< 4	< 4	< 4	6

7 USER SEGMENT ISSUES

It is common understanding that LEO-PNT should preferably broadcast in L-band with GNSS-like signals to ease the adaption on existing GNSS chips. However, spectral regulations discussed above may lead to necessity to use higher frequency bands. We assume at this point that the first LEO-PNT customers using higher carrier-frequency belong to the professional market (high accuracy,

safety-critical, security-critical, timing, space). The small receiver form-factors of the high-volume market could not be met in all likelihood. Therefore we take typical professional L-Band receivers as reference: It will be a triple frequency device, with three RF-front-end chips (one for each frequency band), a digital ASIC for signal processing and a microprocessor for PNT operations. Indicative SWAP values are 80 mm x 50 mm board size, 30 g weight, and 1.5 W power consumption. Such an L-Band receiver has typically 300+ digital channels. The price depends on many other H/W & S/W features and the specific manufacturer (several k $). Such a receiver provides mm level to cm level accuracy based on RTK, PPP or RTK-PPP corrections for four constellations.
The user receiver/equipment (UE) issues for a LEO-PNT implementation are straightforward. On a technical basis, two design drivers for the UE exist: Very wide bandwidth (> 120 MHz) and/or use of a high gain antenna (CRPA, phased array) for carrier frequencies above 8 GHz. Additionally an antenna gain control (AGC) in the standard GNSS receiver is required in case of high power signals.

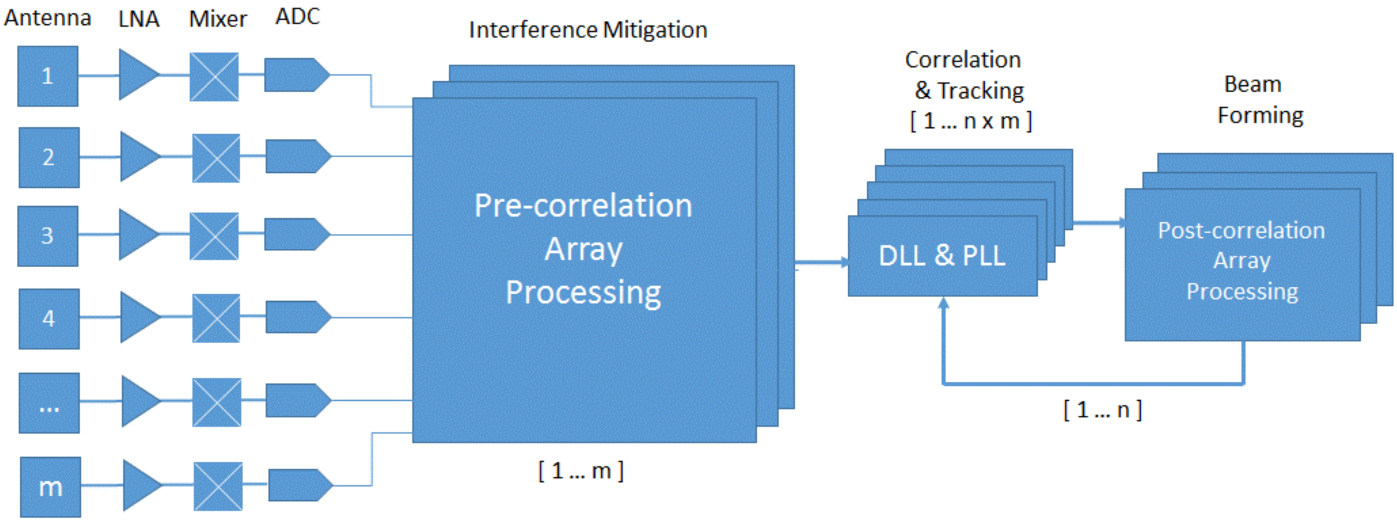


FIGURE 9: The structure of a digital high gain (phased array) receiver (Cuntz et al., 2016)

As shown, such a LEO-PNT receiver for higher frequencies (> 8 GHz) will probably make use of a (planar) phased array providing array processing and digital beam forming. The beam-forming network is necessary to generate a gain of 15-20 dBic above the horizon at the UE in order to increase the C/No to a working level around 40 dB-Hz. In order to provide the beam forming, behind each antenna element a front-end (ASIC) is necessary, including an LNA, mixer, possibly AGC (amplifier gain control) and an ADC. The digitized data flow from each antenna element is input into a pre-correlation array-processing unit (interference cancellation). Digital phase-shifts and weights are applied to scale each elementary signal path. In a next step a bank of correlators and tracking loops (DLL, PLL and/or FLL) are needed. For each antenna element n correlators are implemented (n = number of satellites). Thus, the number of correlators is n x m. Finally, all the array signals are superposed (power combined) in the post- correlation array-processing unit. Here the digital beam-forming operation is performed. Alternatively, analog beam forming or hybrid beam forming is possible. Nevertheless, analog phase shifters and many electronic parts are necessary. At this place we cannot do a power consumption and performance comparison between digital and analog beamforming. Approximately, the receiver SWAP scales up with size of the antenna array (number m elementary patches).

7.1 Antenna Issues

Based on the carrier wavelength and an assumed di-electric constant of the antenna substrate we easily could estimate the size of the antenna (L-Band: $\lambda = 0.2$ m, $\varepsilon_r = 10$ and Ku-Band: $\lambda = 0.02$ m, $\varepsilon_r = 10$). For L-Band (Figure 10) we get D = 0.03 m (single element) and for Ku-Band L = 0.05 m (array of 30 elements) or L = 0.09 m for (array of 100 elements). By use of ceramic materials with large ε_r (100 for Al_2O_3 or 270 for $SrTiO_3$) the size of the antenna could get smaller. A base plane and housing have to be added. The spacing between two array elements is $\lambda/2$.

The findings from Figure 10 for the antenna size are, that a Ku-Band GNSS Antenna with 30 elements has only a slightly larger size than a comparable L-Band single-element antenna (a single element C-Band antenna is by a factor of 4 smaller than in L-band).

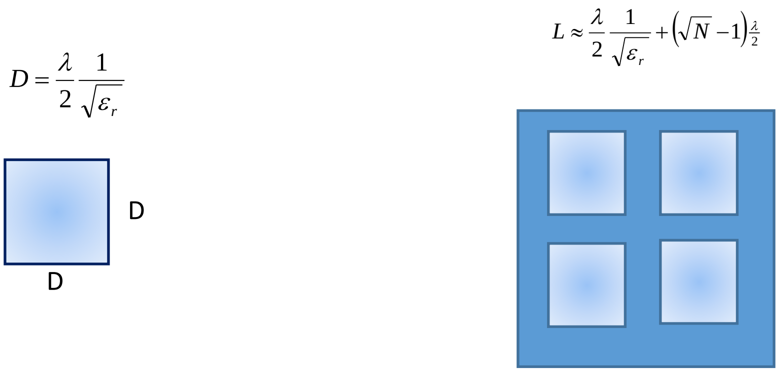


FIGURE 10: Size of single element antennas and antenna arrays

As shown in the plot (Figure 3) in Ku-Band a C/N_o gap between 15 and 20 dB exists. Thus, the interesting point is the question on the size of the array (number of elementary patches). The approximation formula for the computation of the total gain of the array is given by

$$\text{Gain} \approx 10 \log_{10}(N) \tag{1}$$

with N number of antenna elements. It is assumed that the single patch element has a gain of 0 dBic. In order to obtain a gain of 15 dB a 30 element array is necessary. For 20 dB already 100 elements would be required. Thus, antenna size is not the main issue here, but the required computing power and associated power consumption: Behind each antenna element a front-end (ASIC) and associated digital processing structures will be necessary. The power consumption is significantly increased as we see e.g. for TUALAJ 4100-MINI 4-element single frequency CRPA. The total power consumption is 6 W (max), i.e. roughly 1.5 W/antenna path. By scaling we arrive at 45 W for an equivalent L-Band array with 30 elements. The cost figure for 4-element arrays in the market including the digital electronics is on an order of 15 k$. This cost will of course drop down drastically by higher volume serial production, as it is known from MIMO antennas commonly used in terrestrial communication (e.g. WiFi, 5G). In order to reduce the power consumption of the digital beam former higher silicon integration is necessary. As in the traditional GNSS receiver world the question comes up, in what geographical areas the semiconductor fabrication plants are located with respect to supply chain issues. Supply chain issues get more severe by the fact that PNT phased-array antennas are under control of ITAR (international traffic arms regulations) regulations, if the array has more as three elements. An additional problem area for high accuracy, we have to mention, is that the antenna phase center, which is representative for the synthesized output signal, is difficult to control. Because the weights and phases for the elements are permanently changing, an instantaneous antenna phase center (with mm precision) has to be computed in real-time. This requires in anyway a tremendous calibration effort in case of a massive planar array.

7.2 Large Bandwidth Processing Issues

In the context of signal performance (Figure 5) we have shown the known fact that higher bandwidth of a PNT signal leads to lower multipath and thermal noise errors. The other side of the story is that the processing requirements for a 60 Mc/s (BW ≈ 120 MHz) signal are high, compared to L1, L2, and L5 computation. An example which comes close is the Galileo AltBOC(15,10) with a bandwidth of 92 MHz. Currently, only a handful manufacturers of high performance professional receivers have implemented the AltBOC in its full bandwidth. Higher processing requirements lead directly to higher power consumption. Higher silicon integration is again needed.

7.3 Oscillator Issues

A special problem area (usually forgotten) is the higher stress on the tracking loops in case of higher carrier frequencies. The PNT receiver only works, if the tracking loops (DLL, PLL and/or FLL) are in lock. Most critical are the PLL (phase-lock loop) and FLL (frequency-lock loop). The PLL has two important functions: Demodulation of navigation data and measuring the carrier-phase of the signal. The dominant sources of phase error in a phase tracking loop are thermal noise phase jitter, the receiver oscillator's Allan deviation phase jitter, vibration-induced phase jitter and dynamic stress error. The total non-coherent PLL jitter and its corresponding tracking threshold can be expressed as follows (vibration sensitivity of oscillator left out):

$$\sigma_{PLL} = \sqrt{\frac{1}{4\pi^2}\frac{B_L}{C/N_0}\left(1+\frac{1}{2T\cdot C/N_0}\right)+\frac{f_0{}^2}{2}\left[\frac{\pi^2 h_{-2}}{5.2\ B_L^3}+\frac{\pi h_{-1}}{7.5 B_L^2}+\frac{h_0}{7.2 B_L}\right]}+\frac{f_0}{c}\frac{\dddot{R}}{5.2\ B_L^3}\leq\frac{1}{24}\quad[cycles] \qquad (2)$$

C/N_o	carrier-to-noise ratio (in 1 Hz tracking bandwidth)
f_o	carrier frequency
T	pre-detection integration time (duration of data bit)
B_L	noise bandwidth expressed in [Hz] for 3rd order tracking loop
h_0	Allan white frequency noise
h_{-1}	Allan flicker frequency noise
h_{-2}	Allan integrated frequency noise
d^3R/dt^3	jerk in [m/s^3], i.e. third time derivative of the distance between satellite and receiver (user dynamics)

A similar expression exists for a decision directed frequency-lock loop (FLL), if no PLL is implemented for some reason.

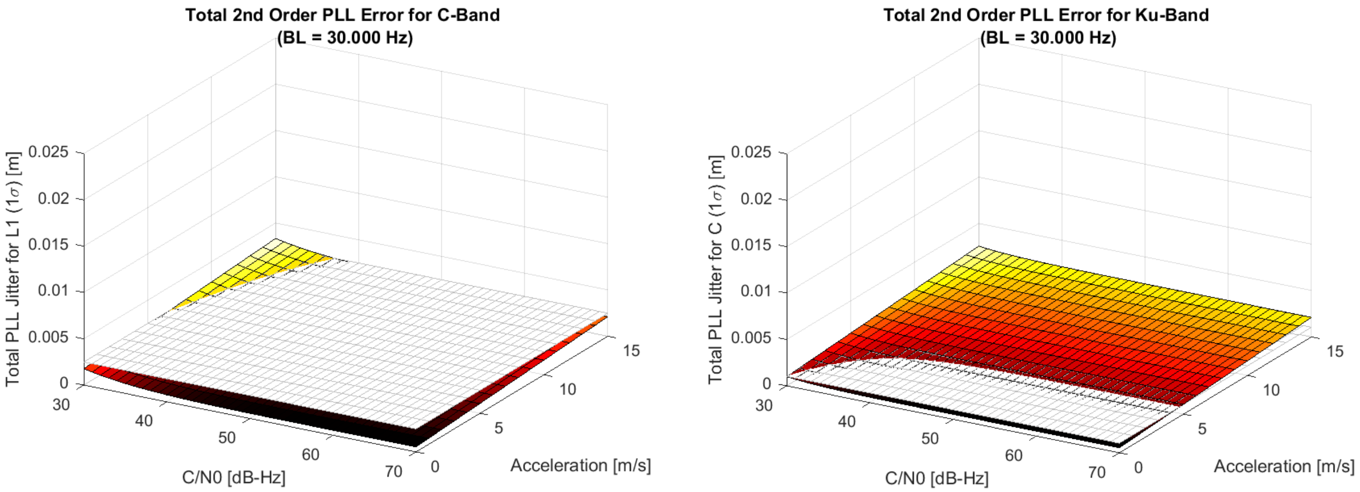


FIGURE 10: PLL stability comparison of C-Band versus Ku-Band (12 GHz) for temperature compensated oscillator (TCXO)

In Figure 10 a TCXO (temperature compensated oscillator) with typical Allan variance parameters is assumed. The term 1/24 [cycles] in Equation (2) defines the constant threshold. The sum of the random error variances and 1/3 of the systematic dynamic error (3σ scaled to 1σ) have to be always below this threshold. We see in Equation (2) two effects: the thermal noise impact ~ B_L (loop-bandwidth) and oscillator noise and dynamic error impact ~ $(1/B_L)^n$. Thus, an optimal choice of the tracking loop bandwidth is necessary for keeping the threshold. By using a low-performance oscillator in high user motion dynamics could pose additional requirements on higher C/No or on higher quality of the receiver oscillator technology. The oscillator and dynamic terms are amplified by higher carrier frequency. This problem area is shown in Figure 10: for C-Band we can expect good PLL stability (grey area). Only for low C/No and higher line-of-sight acceleration a small unstable area remains. For Ku-Band (12 GHz) the stability area of the PLL with respect to C/No and more dynamic user motion is already small. The same TCXO is assumed here. For Ku-Band (18 GHz) no stability will be obtained with a TCXO, i.e. OCXOs or CSACs have to be used. Figure 10 is more on the optimistic side because the vibration sensitivity of the crystal oscillators depending on the vibration spectra of the vehicle is not considered.

TABLE 7: Allan variance parameters for different oscillators

Frequency Source	**White noise h_0** [s]	**Flicker noise h_{-1}** [-]	**Integrated noise h_{-2}** [s^{-1}]
TCXO	$9\ 10^{-20}$ - 10^{-21}	$2\ 10^{-19}$ - 10^{-20}	$2\ 10^{-20}$ - $4\ 10^{-21}$
OCXO	$2.5\ 10^{-26}$	$2.5\ 10^{-23}$	$2.5\ 10^{-22}$
Rubidium (lab)	10^{-23}	10^{-22}	$1.3\ 10^{-26}$
CSAC (literature)	$7\ 10^{-21}$	$2.6\ 10^{-23}$	$3\ 10^{-27}$
Cesium (lab)	$2\ 10^{-20}$	$7\ 10^{-23}$	$4\ 10^{-29}$

A remark: Equation (2) only applies for "receiver-internal" error sources. However, the satellite signal (to be tracked by the PLL/FLL), is additionally affected by the influences of satellite oscillator phase noise. In GPS (ICD-GPS-200) the phase noise of the unmodulated carrier has to fulfill the noise condition of 0.1 rad RMS (PLL with 10 Hz one-sided bandwidth). Of course, this is for the payload oscillator harder to fulfil, if we go to higher frequencies.

7.4 Additional Receiver Issues

Some people are talking about a near-far problem in LEO-PNT, which is stressing the receiver. It is clear that for a LEO overflight (5-15 min) the C/No varies faster. But for carrier frequencies below 6 GHz the C/No variation as function of elevation angles is ± 3 dB (which is the typical variation of MEO GNSS antenna pattern). For higher frequencies this variation gets bigger ± 8 dB. However, the variations are smooth over time. If the LEO-PNT signal is additionally very strong and well above the noise floor, an automatic gain control (AGC) should be able to adjust this power variation before entering into the ADC. Because of the short overflight time of a LEO (≈ 5-15 min for a 600 -1200 km orbit) the acquisition pattern of the receiver looks different. Some channels of the receiver operate in permanent acquisition mode, or a dedicated acquisition unit is used. In case a cold start scenario is considered and no almanac data is available, this has of course some impact on UE higher power consumption. For a warm start scenario where time, position and velocity of the UE are predictable with very good accuracy (from MEO GNSS) the 2-d search space (frequency, time) can be kept small.

8 PRECISE POINT POSITIONING (PPP) and RTK networks

One classical motivation for LEO-PNT is to support MEO-PNT Precise Point Positioning (PPP) with LEO signals to reach shorter convergence times for the carrier-phase ambiguity resolution (float and/or integer ambiguities). Various papers (simulations) have been published on the benefits of LEO signals for precise point positioning together with MEO based PPP schemes. At this place, we cannot cite all these papers. In ionospheric-free PPP estimation filters, usually applied by the user, the higher line-of-sight dynamics (LEO Doppler) theoretically helps to speed-up the estimation process. The line-of-sight distance is changing from 1000 km to 3000 km in (≈ 15 min). However, the problem of code and phase bias determination via the GSEC in the LEO payload system needs to be considered as discussed above. There are two application areas of precise positioning which we will briefly discuss in this chapter: The role of LEOs in Precise Point Positioning and the role of LEOs in active CORS (Continuous Operation Reference Station) networks. These issues are very complex and we cannot elaborate a final answer in this paper. The motivation in this chapter is to generate sensitivity for the problem. We start with the basic un-differenced dual frequency observation model for Precise Point Positioning (Kouba et al., 2017) for the MEO-PNT case:

$$
\begin{aligned}
p_{r,1}^{s} &= \rho_r^s + c\left(dt_r - dt^s\right) + c\left(d_{r,1} - d_1^s\right) + T_r^s + I_r^s + e_1 \\
p_{r,2}^{s} &= \rho_r^s + c\left(dt_r - dt^s\right) + c\left(d_{r,2} - d_2^s\right) + T_r^s + \mu I_r^s + e_2 \\
\Phi_{r,1}^{s} &= \rho_r^s + c\left(dt_r - dt^s\right) + c\left(\delta_{r,1} - \delta_1^s\right) + T_r^s - I_r^s + \lambda_1 N_1 + \varepsilon_1 \\
\Phi_{r,2}^{s} &= \rho_r^s + c\left(dt_r - dt^s\right) + c\left(\delta_{r,2} - \delta_2^s\right) + T_r^s - \mu I_r^s + \lambda_2 N_2 + \varepsilon_2 \\
\rho_r^s &= \sqrt{\left(x^s - x_r\right)^2 + \left(y^s - y_r\right)^2 + \left(z^s - z_r\right)^2} \quad and \quad \mu = \tfrac{f_1^2}{f_2^2}
\end{aligned}
\tag{3}
$$

$$
\vec{x} = \left[x_r, y_r, z_r, dt_r, N_1, N_2, T_r^s, I_r^s\right] \tag{4}
$$

In the MEO case, PPP corrections are derived in the monitoring segment for the satellite orbits (x^s,y^s,z^s) clocks dt^s and satellite hardware biases for code and carrier phase (d_1^s, d_2^s, δ_1^s,δ_2^s) and the respective receiver biases ($d_{r,1}$, $d_{r,2}$, $\delta_{r,1}$,$\delta_{r,2}$). This model is a standardized approach of the PPP-community. The vector x is the state-vector: x_r, y_r, z_r, dt_r are the unknown user coordinates and clock error, N_1, N_2 the integer ambiguities, T_r^s, I_r^s the tropospheric and ionospheric slant delays. Usually a dynamic model with process noise input is set-up for x and a sequential estimator (Kalman filter) is applied. The code and phase delays vary as function of carrier-frequency and code bandwidth. The slant tropospheric and ionospheric delays may be related to their vertical values (e.g. VTEC) by including an elevation dependent mapping function. The unknowns are not estimable all together in a regular way. The adjustment system gets singular because of linear dependences in the observation matrix. Therefore, the next step in PPP-algorithms is to determine linear combinations like the ionospheric-free or the Melbourne - Wuebbena combinations.

8.1 Code and carrier phase biases

Time dependent, temperature dependent and aging dependent delays will be present in the LEO-PNT payload. If a real-time calibration loop is implemented onboard the satellite a certain part of the delays might be compensated during signal generation or determined as corrections. But the inclusion of the antenna phase center which is also very sensitive to thermal effects in the space environment would be difficult. An additional issue is the synchronization of the onboard receiver to Galileo (GNSS) system time scale with high precision as outlined earlier.

In the PPP community, the opinions on the handling of LEO-PNT biases go in two directions: If only float ambiguities with decimeter-level accuracy are required, it is allowed to work without the ground-based bias determination. If it is required to estimate integer ambiguities with fast convergence time and centimeter level accuracy, classical PPP corrections via reference stations are required.

We think that simulations including code and phase biases for the LEO signal have to be urgently performed. The question is, how biased low-noise pseudorange measurements, e.g. in C-Band is affecting the MEO-PNT and LEO-PNT float/integer ambiguities N_1 and N_2 in the Kalman filter? For now, we are convinced that also a network of PPP reference stations is necessary to derive the clock errors and bias delays (synchronization errors to GPS-time and/or Galileo-time) in order to achieve highest accuracy. From the perspective of the LEO-PNT business case, it is critical to account for this network of monitoring (and up-link) stations or to exclude high accuracy users (precision agriculture, geo-information, high-end autonomy) which need cm level accuracy from the system application.

8.2 Precise Point Positioning (PPP) with larger frequency spacing

An advantage exists for the ionospheric - free operation with larger frequency spacing (Schueler et al., 2009). It is worth to mention that such a linear combination only effectively cancels the first-order ionospheric effect. In a simplified notation for the variance of the ionospheric-free pseudo-range of carrier frequency *i* we find from (3) by some computations the following very well-known form:

$$\sigma_{iono-free}^2 = \frac{f_1^2}{f_1^2 - f_2^2}\sigma_1^2 + \frac{f_2^2}{f_1^2 - f_2^2}\sigma_2^2 \tag{4}$$

The equation holds for the error propagation of pseudoranges and carrier-phases in metrical units. This formula illustrates that the noise (standard deviation) of the 1st-order ionosphere-free range and carrier phase largely depends on the frequency spacing f_1^2-f_2^2. The larger this spacing becomes, the more accurate the ionosphere-free linear combination will be. For this reason, the ionosphere-free linear combination from Galileo E1-E5a will be slightly less noisy then that of current GPS L1-L2.

TABLE 8: Noise standard deviation of 1st-order ionospheric-free linear combination for pseudoranges and carrier phases

Frequency-combination	Iono-Free Pseudo-Range	Iono-Free Carrier Phase
GPS L1-L2	1.49 m	6.0 mm (factor 3.0)
LGalileo E1-E5a	1.29 m	5.2 mm (factor 2.6)
CGalileo E1-C (5.019 GHz)	0.56 m	2.2 mm (factor 1.1)

Note: A uniform standard deviation of 0.5 m (pseudo-range) and 2.0 mm (carrier phase) is assumed for the uncombined measurements. The factor is the ratio between the noise level of the linear combination and the standard deviation of the original measurement on E1/L1.

The table above illustrates the drastic improvement when E5a is replaced by a C-band measurement: E1-C will allow a 1st-order ionosphere-free linear combination with almost the same low noise level as the original measurements (2.2 mm for the carrier phases in comparison to 2 mm for the original carriers). Whereas in the current GPS scenario, the noise level is 3 time higher than that of the original carriers. Thus, the C-band option offers interesting new accuracy benefits both for precision users as well as for pseudo-range-based positioning.

8.3 Higher frequencies in RTK networks

In 2009 in a study for European Space Agency (ESA) the use of C-Band was investigated for Galileo 2nd generation (as an option). In this context, we investigated the role of C-Band (Schueler et al, 2009) in active GNSS networks. When going to higher frequencies the carrier wavelength gets smaller. In C-Band we get λ = 6 cm relative to λ = 20 cm in L-Band. Because of bandwidth constraints, the pseudorange noise was the same in L- and C-Band. Ambiguity resolution will now be carried out with a Kalman filter simulation employing pseudorange and carrier phase measurements on multiple frequencies. No linear combinations are present in the observation vector, but a geometry-dependent ambiguity search method will perform a decorrelation of the ambiguity space and thus provide "pseudo" linear combinations depending on the covariance matrix on a case-by-case basis. The state vector will contain ambiguity states, the position vector, atmospheric bias states for both ionospheric and tropospheric delays.

Processing was carried out for a subnet of the German SAPOS network (280 reference stations). The scenario shown features medium ionospheric behavior. Travelling ionospheric disturbances (TID) with an amplitude up to 3.7 TECU, a period of 45 min. and a travelling velocity of 180 km/h were included. Furthermore, the scenario employs a network with larger inter-station distances of 100 km, hence remaining atmospheric errors will have more influence.

In Figure 11 the success rates for a correct and incorrect ambiguity fix and/or no-fix are shown: Dual-frequency GPS (L1, L2) has a success rate (percentage of correct ambiguity fixes) of less than 50%. Adding a dual-frequency GALILEO E1+C band system will improve the success level only to 64%, which is still too small for a good RTK service. The interesting point is, that GPS (L1, L2) plus Galileo (E1, E5a) is with 97% success rate better as C-Band instead of E5a. However, a triple-frequency GPS (L1, L2, L5) + GALILEO (E1, E5a, C) constellation apparently performs similar well at a success rate level of 96%.

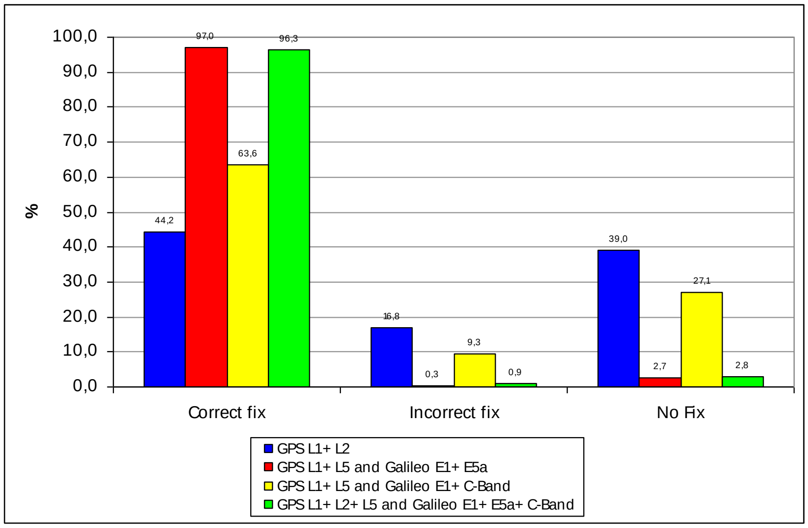


Figure 11: Ambiguity success rate for quick ambiguity resolution within 40 sec using different satellite systems and measurements in L-Band and C-Band

In summary: It is shown, that the RTK positioning performance including C-Band measurements will not become superior to that without C-Band - at least in terms of successful ambiguity resolution. The explanation is that the smaller carrier wavelength together with the same code accuracy in L- and C-Band makes ambiguity resolution more difficult. To which extend only partial ambiguity resolution (e.g. only of L-band carrier ambiguities) would better exploit the C-Band signal is subject to further investigation.

8.4 LEO-PNT in an A-RAIM scenario

Because of the Galileo development, it got essential to investigate the combination of two constellations (GPS & Galileo) in the RAIM concept. It turned out that by combining two independent constellations a more carful probabilistic weighting is necessary. The result was a concept of higher complexity: A-RAIM (Advanced RAIM). A-RAIM has two basic elements: i) *GNSS specific* *constellation performance parameters:* Bounding of fault-free clock and ephemeris distributions, i.e. prior probability of satellite faults p_{sat}, and prior probability of constellation faults p_{const}. ii) *Integrity support message for A-RAIM users*: The GNSS service provider or the aviation authority provides an information flow with nominal basic constellation data (user range accuracy URA, nominal bias b_{max}, p_{sat}, p_{const}). With the emerging LEO-PNT constellations, the question is now on the table on how to integrate one or more LEO-PNTs into the A-RAIM concept. The fault probabilities p_{sat} and p_{const} are essential for the computational effort in the A-RAIM algorithm (fault case assumption & number of sub-sets to be tested). Blanch et al., 2024 presented an initial investigation of the problem. In the paper, the role of mega constellations is discussed for A-RAIM. On the one hand the problem is that LEO-PNT satellites have a higher satellite fault probabilities, whereas the constellation fault probability stays low. This could lead to a simultaneous quadruple fault case. On the other hand more satellite sub-sets solutions have to be tested. The computational effort is rising significantly.

Table 9: A-RAIM fault probabilities

GPS fault probabilities	GALILEO fault probabilities	LEO-PNT fault probabilities
$P_{sat} = 10^{-5}$	$P_{sat} = 10^{-5}$	$P_{sat} \approx 10^{-2}$ to 10^{-3}
$P_{const} = 10^{-8}$	$P_{const} = 10^{-4}$ (constellation failure 2017)	$P_{const} \approx < 10^{-5}$

8.5 GSEC (Ground segment issues)

Some LEO-PNT systems claim a lean ground segment. As outlined earlier, these systems assume onboard orbit and clock generation based on the data of a space borne GNSS receiver. Other systems like Centispace use a classical ground segment with 19+ monitoring stations over China. The protagonists of lean GSEC think that additionally no PPP-like correction system on ground is necessary in LEO-PNT. Onboard ODTS only is a **critical** assumption because of two major aspects:

- *Resilience:* In a strict sense, single point failure mechanisms with full dependency on MEO-PNT should be avoided. A GSEC with 60 monitoring stations on a global basis would be necessary for ODTS (DORIS analogy, CNES)
- *High Precise Point Positioning (PPP) accuracy*: The design question is, if the LEO-PNT precise point positioning contribution for integer/float ambiguity determination is a 30-50 cm (95%) system or strives at 2-5 cm (95%)? In the decimeter float accuracy case, the high accuracy market segment with 24 Mil. users (Table 10) is not served.

In the latter case, it turns out that a significant number of reference receivers (factor 10 on MEO-PNT case) is necessary. This part of the problem means some effort, but the expense is not extremely high. In the IGS (international GNSS service) we have already about 500 global reference stations. The big expense comes from the real-time uplink system. Many gateways antennas are necessary (like in Galileo HAS), where each satellite needs a real-time up-link connection for the transmission of LEO-PNT PPP-correction data to the satellites. Here the optical ISL helps to reduce the expense. Based on these ISLs the number of gateways could be reduced by 60-70% (Iridium versus Globalstar comparison for communication). To the end, the system design depends on the target user needs to be fulfilled.

9 MARKET CONSIDERATIONS

For most of the LEO-PNT systems listed in Table 1 no clear business case is reported to the public. For institutional systems like Centispace this is evident, because commercial success is not a critical criterion. For the systems, which claim to work with a commercial revenue scheme (private investment & service fee), information about their business case is of course proprietary information. However, we might ask ourselves, what are the selling points of LEO-PNT?

The conditions for a successful commercial business case are very tough. The main challenge is that institutional service providers treat satellite navigation as public infrastructure and transmit their signals free of charge to the user domain. The MEO-PNT services, including regional and local augmentation achieved very good quality under nominal conditions. The problems in MEO-PNT are the performance gaps with respect to intensive signal blocking/multipath, interference, jamming and spoofing. This is a very serious issue for the safety critical user and the timing community (including of course security critical users). For the high accuracy user domain the precise point positioning (PPP) concept with MEO-PNT works well, but the time of convergence against the precise PNT solution is too long for many applications. Additionally, the degree of resilience for these user categories is not sufficient. We think that a reasonable and successful business case has to offer technical solutions to close the gaps of the MEO-PNT. To built-up a system, e.g. on higher frequencies, which brings the same or even less performance as the existing MEO-PNT services is not a good idea. It results more or less in a technical exercise, which is decoupled from the user needs.

Table 10: Estimation of commercialization potential in LEO-PNT (number of users per category) based on EUSPA Market Report (2022) in the year 2030

Application area	**Cumulative Size of Market [Mil. €] [2021 – 2031]**	**Potential for commercialization (Who would pay a service fee?)**	**Number of Users [Mil.] (Global market)**	**Number of Paying Users [Mil.]**
„High Volume“ GNSS	3504.9	Consumer: No	8900.0	0
„Safety-Critical“ GNSS	34.8	Autonomous driving: Yes Aviation: No [TBC] Marine: No [TBC] Rail: No [TBC]	62.4[1)] 48.8 17.3 5.1	62.4
„High Accuracy“ GNSS	258.6	Smart agriculture: Yes Geomatics & surveying: Yes	19.9 4.2	24.1
„Timing“ GNSS	61.8	Infrastructure/Synchronization: Yes	6.2	6.2
„Security-Critical“ GNSS	69.3 (estimated)	Governmental (civil): No Governmental (military): No	1.5 – 2.5 (TBC)	0

[1)] Telematics Wire (2023): The number of autonomous cars is not explicitly stated in the EUSPA Report (2022) and was separately determined.

We tried to estimate the potential numbers of users (on a global basis) which are willing to pay for a LEO-PNT service. The possible business case is higher robustness (in terms of anti-jamming & anti-spoofing), higher and faster accuracy (precise point positioning in 1 min or less), including integrity and resilience. Based on the EUSPA Market Report 2022 we derived the numbers in Table 10.

The problem of the GNSS market is evident: Only about 93 Mio. users may be identified in the global market, who are used/willing to pay a fee for higher performance, e.g. higher accuracy to Trimble, Hexagon/Veripos, etc. Over 90% of the GNSS market are consumers, who will not pay any fee for PNT. Maybe some (out of 8900 Mio. mass market users) would be willing to pay either for higher performance or a service provider or an equipment manufacturer is paying the fee to increase the value of his products, but this is not so obvious. The global market of paying users has to be shared with the MEO-PNT systems and competing LEO-PNT systems. If the CapEx (Capital Expenditure) and OpEx (Operational Expenditure) over 5 years for a LEO-PNT are known and a reasonable user-fee is assumed, the necessary market share (number of users) of a commercial LEO-PNT may be estimated (and checked for reality). The market owners to be included are in the field of autonomous driving, precision agriculture, surveying & geomatics, infrastructure and timing. We did not do a more detailed segmentation. This is not new, but the numbers are quite interesting. Thus, if a commercial case for a LEO-PNT is valid, it depends on several cost factors and number of paying users.

Note: 62.4 Mil. Autonomous cars in 2030 is more a conservative estimate. Alternative references state the number of autonomous cars as 10% of global car market 1500 Mil. cars, i.e. 150 Mio in 2030. The number of autonomous cars should be a very important element in any business case consideration. However, the market has opportunities, but also risks. If autonomy level 4, 5 comes very late or will not happen as expected the market assumptions in Table 10 will collapse. Therefore, for risk mitigation LEO-PNT shall serve the high accuracy market to be on the safe side. Special consideration shall also be given to other transportation sectors, aviation, rail and maritime. Whereas, the penetration of MEO-PNT into this sectors can be considered to be consolidated, increased jamming/spoofing or significantly higher accuracy/robustness by LEO-PNT may define cases forcing governments to invest in LEO-PNT thus yielding another possibly revenue scheme for a commercial LEO-PNT provider.

CONCLUSIONS

If we conclude the different LEO-PNT system concepts listed in Table 1 and take into account the technical issues raised in this paper we may identify *three* different philosophies:

- *Conservative* concept:
    - Compatibility with L-Band and MEO-PNT
    - Closure of MEO performance gaps
    - Low development risk, high user acceptance, re-use of L-Band user equipment
- *Pragmatic* concept:
    - L-Band baseline (dual frequency) plus C-Band as an innovative element
    - Still limited risk, step-wise adaption of user equipment to C-Band
- *Visionary* concept:
    - Implementation of future vision: Integrated navigation and communication (fused LEO-PNT), probably in Ku-Band, non-terrestrial networks (NTN) for communication
    - High acceptance threshold in user segment
    - New PNT user equipment has to be developed and to be produced in Ku-Band
    - High user equipment complexity and SWAP-C (size weight & power plus cost)

The concept for ODTS is independent of the carrier frequency issue. The decision on ODTS is based on the resilience and accuracy aspects of the system.

The problem in the current LEO-PNT discussion is that most of the players have a different view. Partly, the arguments given are contradictory. The boundaries between the three philosophies outlined are floating. This leads to a controversial discussion on many aspects. Usually, the expectation of a comparative study is to outline the best solution. However, the systems listed in Table 1 are different in the technical parameters and the design target. We can observe that in some of the LEO-PNT concepts, the user needs and the user equipment issues play not a primary role. On a technical basis, user receivers can of course be built for L-, C- and Ku-Band. Based on the lessons learned in the MEO world the GNSS industry will only invest in LEO-PNT receivers, if they see a clear performance advantage and business case with respect to MEO based alternatives. The low power, size, weight and cost paradigm is still valid.

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REFERENCES

Azzarelli, T. (2016). OneWeb Global Access. ITU International Satellite Symposium, Retrieved from ITU. https://www.itu.int/en/ITU-D/Regional-Presence/AsiaPacific/Pages/Events/2016/Sep-ISS2016/home.aspx

Blanch, J., Oak, S., Pullen, S., Lo, S., & Walter, T. (2024). Advanced RAIM for Mega-Constellations. Proceedings of the 2024 International Technical Meeting, The Institute of Navigation, Long Beach, CA, January.

Cuntz, M., Konovaltsev, A., & Meurer, M. (2016). Concepts, development, and validation of multi-antenna GNSS receivers for resilient navigation. Proceedings of the IEEE,Vol. 104, Issue 6, S. 1288-1301. https://doi.org/10.1109/JPROC.2016.2525764

European Commission (2023). Press release on Space: Commission invites the industry to submit proposals to deploy the new EU secure connectivity satellite constellation, IRIS². *EC Media*, March 24, Brussels.

EUSPA (2022). EO and GNSS Market Report. Issue 1. Publication Office of the European Union, Luxemburg: doi: 10.2878/94

Federal Radio Navigation Plan (2021). Departments of Defense, Transportation and Homeland Security, National Technical Information Service, Springfield, Virginia 22161, DOT-VNTSC-OST-R-15-01

Forbes, S. (no year). Blackjack. Retrieved from DARPA: https://www.darpa.mil/program/blackjack

Foust, J. (2021). OneWeb continues to study offering navigation services. Retrieved from Spacenews: https://spacenews.com/oneweb-continues-to-study-offering-navigation-services/

Geely (2023). Aerospace Technology Empowering Future Mobility. Proceedings of Munich Satellite Navigation Summit, Session 9, March 13-15, Munich.

Hansen, A., Mackey, S., Wassaf, H., Shah, V., Wallischeck, E., Scarpone, C., Barzach, & M., Baskerville, E. (2021). Complementary PNT and GPS backup. Department of Transportation. Retrieved from https://www.transportation.gov/sites/dot.gov/files/2021-01/FY%2718%20NDAA%20Section%201606%20DOT%20Report%20to%20Congress_Combinedv2_January%202021.pdf

Ng, H.F. Fai (2016). "RNSS & ITU Radio Regulations", ICG-11, 6. – 11. Nov., Sochi, Russia

ITU (no year). ITU Recommendation ITU-R PN.837-1: Characteristics of precipitation for propagation modelling. Appl. note

ITU (2021). ITU-R P.833-10: Attenuation in vegetation, P-Series Radiowave Propagation.

Kaplan, E. D. (1996). Understanding GPS. Principles and applications (Mobile communications series ed.). Norwood: Artech House, p. 256ff.

Kouba, J., Lahaye, F., & Tetreault, P. (2017). Precise Point Positioning, Springer Handbook, Global Navigation Satellite Systems, Eds. : Teunissen, Montenbruck : Springer International Publishing AG, p. 723 – 747.

Korogin, I. (2022). Xona Pulsar: Obvious and not-so-obvious issues of next-gen GPS. Retrieved from Medium: https://medium.com/@ilyakorogodin/xona-pulsar-obvious-and-not-so-obvious-issues-of-next-gen-gps-80ba053dc96c

Lu, M., Li, W., Yao, Z., & Cui, X. (2019). Overview of BDS III new signals. *NAVIGATION*, 66(1), 19-35. https://doi.org/10.1002/navi.296

MU, X. (2023). Centispace LEO Augmentation Navigation System Status. Workshop on Low Earth Orbit (LEO) Positioning Navigation and Timing (PNT) Systems. Vienna International Centre, Vienna, 9 June. https://www.unoosa.org/documents/pdf/icg/2023/ICG_WG-S_LEO-PNT_Workshop_June_2023/ICG_LEO-PNT_Workshop_2023_01.pdf

Neumann, J.B., Bates, M., & Harvey, R.S. (1999). GLONASS receiver Inter-frequency biases – calibration methods and feasibility. Proc. of ION GPS, Nashville, 1999.

Prol, F. S. , Morales Ferre, R., Saleem, Z.,Välisuo,P. ,C. Pinell, C., Lohan, E. S., Elsanhoury, M. ,Elmusrati, M., Islam, S., Celikbilek, K., Selvan, K. , Yliaho, J., Rutledge, K. Ojala, A., Ferranti, L., Praks, J.,Bhuiyan, M. Z.H., Kaasalainen, S. , & Kuusniemi, H. (2022). Position, Navigation, and Timing (PNT) Through Low Earth Orbit (LEO) Satellites: A Survey on Current Satus, Challenges, and Opportunities. *IEEE ACCESS*, Volume 10, p. 83971-84002. doi 10.1109/ACCESS.2022.3194050.

Ries, L., Anghileri, M., & Prieto-Cerdeira, R. (2023). FutureNAV LEO-PNT, In-Orbit Demonstration and Future System Perspectives. Workshop on Low Earth Orbit (LEO) Positioning Navigation and Timing (PNT) Systems. Vienna International Centre, Vienna, 9 June. https://www.unoosa.org/documents/pdf/icg/2023/ICG_WG-S_LEO-PNT_Workshop_June_2023/ICG_LEO-PNT_Workshop_2023_01.pdf

Reid, T., Neish, A. M., Todd, W., & Enge, P. K. (2018). Broadband LEO constellations for navigation. NAVIGATION, 65(2), 205–220. doi:10.1002/navi.234

Reid, T., Banville, S., Chan, B., Gunning, K., Manning, B., Marathe, T., Neish, A., Perkins, A., & Sibois, A. (2022). PULSAR. A New Generation of commercial satellite navigation. Presentation, ION GNSS+, Denver, Colorado.

Rothmaier, F., Chen, Y-H., & Lo, S. (2019). Improvements to steady state spoof detection with experimental validation using a dual polarization antenna. Proc. of the 32nd International Technical Meeting of the Satellite Division of the Institute of Navigation, ION GNSS, Miami, FL, 967-983. https://doi.org/10.33012/2019.16989

Schueler, T., Wallner, S., & Eissfeller, B. (2009). Entwicklungsstand GALILEO mit einem Ausblick auf die Kombination mit GPS für die schnelle RTK-Positionierung. Zeitschrift für Vermessungswesen, 134 Jg. 6/2009.

Shannon, P. (2022). Leveraging a LEO Satellite Constellation for Accurate & Reliable PNT-Less is More "The Case for Going Aggressively Small". 27th PNT Advisory board meeting, Redondo Beach, CA, Nov. 16-17. https://www.gps.gov/governance/advisory/meetings/2022-11/

Telematics Wire (2023). Autonomous car market to reach 62.4 Million units by 2030. Market Report. Chicago. https://www.telematicswire.net/autonomous-car-market-to-reach-62-4-million-units-by-2030/

Whelan, D., Gutt, G., & Enge, P. (2011). Boeing timing & location. An indoor capable time transfer and geolocation system Presentation Stanford PNT Symposium. Retrieved from https://web.stanford.edu/group/scpnt/pnt/PNT11/2011_presentation_files/13_Whalen-PNT2011.pdf