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An Assessment of the Future EU Complementary Position Navigation Time (C-PNT) Ecosystem

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Executive summary

Global Navigation Satellite Systems (GNSS), such as the European Galileo and the U.S. Global Positioning System (GPS) become ubiquitous tools with enormously impact on our economy and society. Energy supply networks, transport infrastructures, telecommunications, cloud infrastructures, and financial networks are but a few examples of critical infrastructures strongly relying on precise timing and synchronization services based on GNSS. GNSS has become the backbone of positioning, navigation and timing (PNT) services and its central role is bound to increase in the future, with the advent of a new wave of services and business, like car-sharing, smart logistics, autonomous vehicles, geo-localising applications, precision agriculture and others.

With such critical role of GNSS, any disruptions, unintentional or triggered maliciously with a jamming or spoofing attack, will have severe adverse effects. Given that, the availability of **backups or alternative PNT (A-PNT)** services should be considered as a priority for the resilient and prosperous Europe.

Addressing those, the **Directorate General for Defence Industry and Space** (DEFIS) of the European Commission (EC) released a call for tender (CfT) (DEFIS/2020/OP/0007) in December 2020. Its objective was to assess the seven state-of-the-art A-PNT demonstration platforms, with the scientific and technical lead of the **EC Joint Research Centre** (JRC). Those platforms were tested at the JRC premises and, for some, also at other test sites suggested by the A-PNT platform provider. Starting in September 2021, almost eight months of testing were completed, with the A-PNT platforms demonstrating precise and robust timing provision and transfer and some demonstrating positioning services, both indoor and outdoor. The results of the tests, including the presentation of the minimum technical requirements, the definition of the test plan, and the description of the testing facilities setup for the experiments is presented in a comprehensive report, which was released by JRC in March 2023 [AD. 2]. This report expands it with an assessment of **A-PNT deployment in the European Union (EU)**, providing the potential scenarios, their implications and the investments needed. It is not limited to the technologies under tests in 2021/2022, but it includes all the relevant A-PNT technologies.

Three implementation scenarios of A-PNT in the EU are discussed in the report, i.e.:

1. **Baseline scenario**: No actions are taken with respect to the current situation, despite the likelihood to have an increased social, economic and security risk, due to the lack of resilient PNT infrastructures, in the event of GNSS outage;
2. **Single A-PNT implementation**: This scenario foresees the implementation of a single technology out of those tested in [AD. 2], analysing possible three deployments (local, province/country and EU-Wide);
3. **System of systems scenario**: A market-driven system of systems approach, with the EC responsible for regulations. This scenario uses a mix of PNT infrastructures, leading to a resilient and continuous PNT provision.

The report recommends the last scenario considering the commercial and EU wide benefits and provide a list of concrete actions required for the implementation. Such actions are proposed at Commission level in the form of budget commitments and longer term plans, in order to encourage industries to invest. The report also proposes "low hanging fruits", benefiting not only the implementation but the EU PNT ecosystem and Europe's global standing. They are:

- The development of a resilient European terrestrial time backbone and subsequent capillarity of services;
- The establishment of a wider forum to engage with the entire PNT industry, including both large and small players;
- The development of A-PNT testing standards, ideally in the broader international context. This would lead and consolidate the smaller efforts done by the European member and non-member states.

Within the proposed "**system of systems**", the non-GNSS components would be best referred to as **Complementary (Continuous) PNT (C-PNT)**, given their objective to provide resilience, extend PNT to specific environments that cannot be served by GNSS, and act as limited spatial and temporal backup supporting existing infrastructure.

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1 Introduction

According to the analysis reported in the European Radio Navigation Plan (ERNP) [RD. 1], the total economic benefits of Positioning, navigation and timing (PNT)/GNSS services, for 1999-2027 period, were estimated as 2 trillion euros in the European territory (defined as the 27 European Union Countries plus the UK, Norway, and Switzerland). Today, Global Navigation Satellite Systems (GNSSs) are the backbone of PNT services and its central role is bound to increase in the future with the advent of a new wave of services and business, like car-sharing, smart logistics, autonomous vehicles-ships-aircrafts, geo-localising applications, precision agriculture and others. The Earth Observation and GNSS Market Report [RD. 2], issued by EUSPA, also lists global challenges such as digital revolution, climate change and global pandemics that the society has to face, mentioning how PNT and GNSS play a vital role in contributing to innovative solutions addressing those challenges.

On the other hand, it is worth considering possible GNSSs outages or disruption that might strongly impact services or application relying on global satellite systems. Various studies, e.g., [RD. 3] and [RD. 4], have estimated economic losses of around 1 billion euros per day, due to an eventual GNSS unavailability. Indeed, GNSS jamming incidents reports increase in number and frequency, most of them caused by the so-called Personal Privacy Devices (PPDs), illegal in most of the countries. GNSS spoofing incidents are less frequently reported, but they are also increasing in number and their dangerousness has been demonstrated through dedicated tests and trials [RD. 5] [RD. 6].

For these reasons, US [RD. 7]-[RD. 9], UK [RD. 10] and other nations are investigating and plan to deliver 'resilient' PNT services or GNSS back-up services in their territories. In addition, PNT services and notably its timing capabilities are exploited by critical infrastructures (CI) which are strategic for modern society, such as telecom, energy, finance and transports (road, maritime, aviation). Therefore, due to the major role of GNSS in the economy and society, and the importance of the risk of the disruption or denial of GNSS services, there is a need of alternative-PNT (A-PNT) capacity, without common modes of failure with GNSS [RD. 11].

Within this context, the call for tender (CfT) 506573-2020 [AD. 1] launched by the Directorate General for Defence Industry and Space (DEFIS) of the European Commission (EC) had the main goal of assessing the maturity of technologies, able to deliver positioning, and/or timing information, independently from GNSS. Such technologies are also required to be effective backup in the event of GNSS disruption, and, if possible, in environments where GNSS services cannot be delivered. Back-up and complementary technologies are referred hereafter as *alternative PNT* which, together with GNSS, constitute *resilient PNT* services. A performance assessment campaign on a total of seven state-of-the-art A-PNT demonstration platforms has been conducted, with the scientific and technical lead of the EC Joint Research Centre (JRC). This Call for Tender will be referred as "A-PNT study" or "2021 A-PNT study" for brevity in the rest of the document.

1.1 Scope and structure of the document

The 2021-22 A-PNT study consisted of three elements, presented in two reports:

- The demonstration activities, forming the Test Campaign run by the JRC and allowing to understand the proposed technologies. It was presented in 'Assessing Alternative Positioning, Navigation, and Timing Technologies for Potential Deployment in the EU' [AD. 2]. It summarises the test results, including the minimum technical requirements, the test plan, and the description of the testing facilities setup for the experiments;
- This report complements the above mentioned analysis and proves an assessment of the implications and costs of deploying A-PNT infrastructures in EU.

Following current section, that includes the lists of applicable and reference documents, this report is structured as follows:

- Section 3 analyses the proposed implementation plans for the EU;
- Section 4 analyses the possible implementation scenarios for an EU deployment;
- Section 5 draws the conclusions.

1.2 Applicable and Reference Documents

This section lists all the applicable and reference documents relevant for the scope of this report.

1.2.1 Applicable documents

#	Issue	Title
[AD. 1]	506573-2020	'Services - 506573-2020 - TED Tenders Electronic Daily', 7 December 2020. Available at: *https://ted.europa.eu/udl?uri=TED:NOTICE:506573-2020:DATA:EN:HTML*
[AD. 2]	1.0	JRC132737, Bonenberg, L., Motella, B. and Fortuny Guasch, J., Assessing Alternative Positioning, Navigation and Timing Technologies for Potential Deployment in the EU, 2023. Available at: *https://publications.jrc.ec.europa.eu/repository/handle/JRC132737*
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1.2.2 Reference documents

#	Title
[RD. 1]	European Radio Navigation Plan 2023. (2023), European Commission; Publications Office of the European Union. Available at: *https://joint-research-centre.ec.europa.eu/system/files/2023-06/ERNP%202023.pdf*
[RD. 2]	European Union Agency for the Space Programme. EUSPA EO and GNSS Market Report.2022 / Issue 1. LU: Publications Office, 2022. *https://data.europa.eu/doi/10.2878/94903*.
[RD. 3]	O'Connor, Alan C., Michael P. Gallaher, Kyle Brannon Clark-Sutton, Daniel Lapidus, Zack Oliver, Troy J. Scott, Dallas Wayne Wood, and Elizabeth G. Brown. 'Economic Benefits of the Global Positioning System (GPS)', 31 May 2019. *https://www.rti.org/publication/economic-benefits-global-positioning-system-gps*.
[RD. 4]	Innovate UK, UK Space Agency, Royal Institute of Navigation. 'The Economic Impact on the UK of a Disruption to GNSS', June 2017. *https://londoneconomics.co.uk/blog/publication/economic-impact-uk-disruption-gnss/.*
[RD. 5]	Junhwan Lee, Erick Schmidt, Nikolaos Gatsis, David Akopian, "Thwarting GNSS Spoofing Attacks," Inside GNSS, September 28, 2022. Available at: https://insidegnss.com/thwarting-gnss-spoofing-attacks/
[RD. 6]	M. L. Psiaki and T. E. Humphreys, "GNSS Spoofing and Detection," in *Proceedings of the IEEE*, vol. 104, no. 6, pp. 1258-1270, June 2016, doi: 10.1109/JPROC.2016.2526658.
[RD. 7]	Bartock, Michael, Suzanne Lightman, Ya-Shian Li-Baboud, James McCarthy, Karen Reczek, Joseph Brule, Doug Northrip, Arthur Scholz, and Theresa Suloway. 'Foundational PNT Profile: Applying the Cybersecurity Framework for the Responsible Use of Positioning, Navigation, and Timing (PNT) Services'. National Institute of Standards and Technology, 29 June 2022. *https://doi.org/10.6028/NIST.IR.8323r1.ipd*.
[RD. 8]	Hansen, Andrew, Stephen Mackey, Hadi Wassaf, Vaibhav Shah, Eric Wallischeck, Christopher Scarpone, Michael Barzach, and Elliott Baskerville. 'Complementary PNT and GPS Backup Technologies Demonstration Report. Sections 1 through 10', DOT-VNTSC-20-07, January 2021. Available at: *https://rosap.ntl.bts.gov/view/dot/55765/dot_55765_DS1.pdf?download-document-submit=Download*

#	Title
[RD. 9]	Mason, Richard, James Bonomo, Tim Conley, Ryan Consaul, David R. Frelinger, David A. Galvan, Dahlia Anne Goldfeld, 'Analyzing a More Resilient National Positioning, Navigation, and Timing Capability'. RAND Corporation, 17 May 2021. Available at: *https://www.rand.org/pubs/research_reports/RR2970.html*.
[RD. 10]	GOV.UK. 'Satellite-Derived Time and Position: Blackett Review', 2018. Available at: *https://www.gov.uk/government/publications/satellite-derived-time-and-position-blackett-review*.
[RD. 11]	Wildemeersch, Matthias, and GUASCH Joaquim Fortuny. 'Radio Frequency Interference Impact Assessment on Global Navigation Satellite Systems'. JRC Publications Repository, 31 March 2010. Available at: *https://doi.org/10.2788/6033*.
[RD. 12]	Koelemeij, Jeroen C. J., Han Dun, Cherif E. V. Diouf, Erik F. Dierikx, Gerard J. M. Janssen, and Christian C. J. M. Tiberius. 'A Hybrid Optical–Wireless Network for Decimetre-Level Terrestrial Positioning'. Nature 611, no. 7936 (November 2022): 473–78. Available at: *https://doi.org/10.1038/s41586-022-05315-7*.
	Content Removed
[RD. 36]	National Science And Technology Council, NIST (ed.) (August 2021) *National Research And Development Plan For Positioning, Navigation, And Timing Resilience*. *https://www.whitehouse.gov/wp-content/uploads/2021/08/Position_Navigation_Timing_RD_Plan-August-2021-1.pdf*
[RD. 37]	GAO (2021) Defense Navigation Capabilities. (GAO-21-320SP). May 10, 2021. *https://www.gao.gov/products/gao-21-320sp*
[RD. 38]	Jungwirth, R., Smith, H., Willkomm, E., Savolainen, J., Villota, M.A., Lebrun, M., A, A., et al. (2023), Hybrid Threats: A Comprehensive Resilience Ecosystem, Other, European Commission DG Joint Research Centre; Publications Office of the European Union, available at: https://doi.org/10.2760/37899 .
[RD. 39]	O'Connor, A.C., Gallaher, M.P., Clark-Sutton, K., Lapidus, D., Oliver, Z.T., Scott, T.J., Wood, D.W., Gonzalez, M.A., Brown, E.G., and Fletcher, J. 2019, June. Economic Benefits of the Global Positioning System (GPS). RTI Report Number 0215471. Sponsored by the National Institute of Standards and Technology. Research Triangle Park, NC: RTI International. *https://www.gps.gov/governance/advisory/meetings/2019-11/gallaher.pdf*
[RD. 40]	London Economics, Danish Inter-Governmental Space Committee, *Denmark's economic vulnerability to a loss of satellite-based PNT*, 20 March, 2019. *https://londoneconomics.co.uk/blog/publication/denmarks-economic-vulnerability-loss-satellite-based-pnt-march-2019/*

1.3 Acronyms

This section lists the acronyms used throughout the document and their definition.

Abbreviations	**Definition**
AIS	Automatic Identification System
A-PNT	Alternative PNT
ASIC	Application-Specific Integrated Circuits
ASSP	Application-Specific Standard Product
C-PNT	Complementary (Continuous) PNT, proposed replacement for the A-PNT concept
CfT	Call for Tender
CI	Critical Infrastructure
DARPA	Defence Advanced Research Projects Agency
DEFIS	Directorate General for Defence, Industry and Space
DOT	US Department of Transport

EC	European Commission
EO	Earth Observation
ERNP	European Radio Navigation Plan
ETSI	European Telecommunications Standards Institute
EU	European Union
EURAMET	European Association of National Metrology Institutes
EUSPA	European Union Agency for the Space Programme
G2G	Galileo 2nd Generation
GDOP	Geometric Dilution of Precision
GLA	General Lighthouse Authorities
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
INRIM	Italian National Institute of Metrology Research
JRC	Joint Research Centre
KPI	Key Performance Indicator
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
NMI	National Metrological Institutes
NPL	National Physical Laboratory
NTP	Network Time Protocol
ODTS	Orbit Determination and Time Synchronization
OTA	Over The Air
PHM	Passive Hydrogen Maser
PNT	Positioning, Navigation and Timing
PoC	Proof of Concept
PTP	Precise Time Protocol
PUT	Platform Under Test
RETSI	Resilient Enhanced Time Scale Infrastructure
SatCom	Communication Satellites
SoSA	System of Systems Approach
STS	Secure Time Synchronization
SyncE	Synchronous Ethernet
TaaS	Time as a Service
TRL	Technology Readiness Level
UTC	Coordinated Universal Time
WR	White Rabbit

3 Proposed implementation plan for EU and its cost assessment

Seven technologies were selected through the DEFIS 2021-22 A-PNT study (OPNT BV, Seven Solutions SL, SCPTime, GMV Aerospace and Defence SAU, Satelles Inc, Locata Corporation Pty Ltd, Timing Solutions, and Locata Corporation Pty Ltd, Positioning Solutions) with the objective to address three major elements:

- The testing of the proposed technologies;
- The delivery of a Technical Report, presenting the technology description and the expected performance, and summarizing the main tests results;
- The delivery of an Implementation Report of the technology/service, including cost and schedule elements, if the technology were to be deployed in the EU.

Separately NextNav volunteered to participate in the study covering their own cost.

The main outcomes of the JRC assessment are summarized in [AD. 2]. The four main technologies were proposed, as listed in table below.

Technology	Company
White Rabbit time transfer	OPNT BV, Seven Solutions SL
Fixed telecom networks time transfer	SCPTime, GMV Aerospace and Defence SAU
Pseudolites PNT	Locata Corporation Pty Ltd, NextNav
LEO PNT	Satelles Inc

Table 1. Technologies adopted by each of the seven selected companies.

All the tested technologies offer interoperability with the EU infrastructures, through adhering to existing standards. Their use requires dedicated user terminals, with requirements unlikely to be fulfilled by historical hardware. All of the technologies are off-the-shelf, though especially software can be proprietary to the service provider.

Each of the participants was requested to address an EU deployment, by considering the following implementation areas:

- Local deployment, which was understood as a deployment along dispersed critical infrastructure, located across the EU, with each location not exceeding 10 km^2 or covering the area of the large EU metropolis. Some participants also considered smaller specific deployments such as dry side port automation, fulfilment centre automation and similar;
- Province and/or country deployment;
- EU-wide deployment, understood as the coverage the whole EU, including in-land waters, main EU transport routes (land, sea and/or air). For the deployment of the specific service (time and/or position) participants were asked to consider a deployment across the country borders and possible interoperability with already existing infrastructure;
- Global coverage, intended as continental or world coverage.

	TRL	Comments
OPNT	TRL8 TRL6	- The hardware for OPNT's wireless monitoring and transmission is TRL8 - RSTU provides OTA time distribution
7 Solutions	TRL9	- Fully productized and deployed in Europe and the US
SCPTime	TRL7	- System prototype demonstration in operational environment. - The current deployment of SCPTime® Architecture in France is an operational prototype of SCPTime®
GMV	TRL7	The key technologies have a different TRL: - Atomic clocks, clock modelling and steering, and time transfer technology are very mature technologies → TRL 9 - DTM is widely used in the broadcast industry, but the use for timing applications is under development → TRL 7 - NTP has been synchronizing the computers connected to the internet worldwide during decades at the level above the ms, but the application of NTP to higher-precision is a relatively new → TRL 6
Satelles	TRL9	- is used today in operational environments by commercial users of STL service devices
Locata	TRL9	- Already in the market
NextNav	> TRL8	- Rated by the U.S. Department of Transportation (DOT) - Purchased a company in EU and is developing a new time correction method for SoO

Table 2. Estimated TRL for each technology

4 Implementation Scenarios for A-PNT development in the EU

As widely discussed, GNSS systems, including the European Galileo and EGNOS, represent the backbone of modern PNT services. The global reach of the time and position service at the unmatched economic cost to the end user, combined with the ease of use and trust, underpins the appeal of the technology. Still, this marvel of engineering has some inherent weaknesses that are feature of the technology and cannot be addressed fully through the design. Due to the very low power on ground, GNSS receivers are prone to reasonably low interference levels and require a reasonably clear view of the sky to achieve the best performance.

Despite those known shortcomings, the 8 months of A-PNT test campaign [AD. 2] reinforced the understanding that GNSS will underpin both current and future EU PNT, as none of the tested A-PNT technologies can fully replace it. Nevertheless, A-PNT technologies are critical for the future resilient PNT in different ways, from the extension of the GNSS capacities to previously not accessible areas, such as deep indoors, urban canyons or underground, through the resilience of multiple UTC sources and enhanced monitoring, to the option of backing up GNSS in the case of temporary and/or local issues or failures.

In order to better analyse the possibilities for the development of A-PNTs in the EU, three different implementation scenarios are discussed hereafter, i.e.:

1. **Baseline scenario**: No actions are taken respect to the current situation, despite the likelihood to have an increased social, economic and defence risk, due to the lack of resilient PNT infrastructures, in the case of GNSS failures;
2. **A-PNT implementation**: This scenario foresees the implementation of a single technology among those available;
3. **System of Systems Approach (SOSA) scenario**: A market-driven system of systems approach is implemented, with the EU responsible for regulation and standardisation. This scenario utilises a mix of techniques, providing optimal use of timing and position information, based on the best usability of the technologies.

This section first assesses the cost of the inaction (baseline scenario, section 4.1) and then discusses the implementation of the proposed A-PNT candidate technologies and the required actions. In detail, 4.2 focuses on the implementation of one A-PNT candidates, while section 4.3 wides the view to a solution based on several complementary technologies.

4.1 Baseline scenario: the Cost of Inaction

The baseline scenario foresees that no actions will be taken to assist or back up GNSS systems, in the case of failures. The values of the economic losses consequent to such event are discussed in three reports dealing with the cost impact of any loss of GNSS service in a specific country or region. Those are:

- The United Kingdom (UK) study [RD. 4], commissioned by the UK Space Agency and the Royal Institute of Navigation in 2017. It focuses on the impacts of an unexpected loss of GNSS, across different applications domains and considering the economic benefits of the working system. The report estimates that UK would suffer a loss of £5.2 billion over a five-day period. This is mainly attributed to the road, maritime, emergency and justice domains (UK has a large programme of GPS tagging offenders). Some mitigation actions, including A-PNT technologies (some of them tested at the JRC), are also mentioned and discussed.
- The USA report [RD. 39], dated 2019, concludes that the GPS signal as a service provided by the U.S. government, is a public good, enabling productivity, quality, and efficiency benefits that would not otherwise be possible. The benefits become more significant as specialised industry emerges: the 90% of GPS's benefits were accrued since 2010, despite system being operational since early '80.

The biggest beneficiaries are telecommunication and telematics. The cost of 30-day outage for USA is estimated at $30.3-$45.4 billion.

- The last report [RD. 40] focuses on Denmark and, following the UK study methodology, describes both the impact and the possible mitigation actions for a GNSS loss. This report also highlights that the cost estimation might not be straightforward for Europe, due to diversity of European countries from legal, societal and governmental perspective.

Economic losses are inherently difficult to estimate. The report suggests that a careful analysis of the different European Member States would be required before extending or generalising the findings to the whole European context. This includes geographical factors (population density, legal frameworks, cultural and technology differences), scope of analysis (i.e., economic sectors considered, or satellite constellations included in analysis) as well as choice of counterfactuals (resilience of infrastructure, backups availability, choice of treats). Hybrid threats should be also considered in this context [RD. 38], and those are evolving both in scale and complexity. A similar sentiment is shared by [RD. 39], arguing that the cost of GNSS outage might be overstated, possibly by orders of magnitude, as for many industries backups are already operational.

4.2 Implementation of the Tested A-PNT Technologies

The objective of the A-PNT testing activities performed in 2021-2022 was to find and test technologies that provide time, position or both, without the use of GNSS, and without common modes of failure.

The position performance measured during the testing [AD. 2] were in the order of meter-level (Satelles and Nextnav) or even cm-level (Locata) when more complex approach was used. Such performance is consistent to a good extent both for static and kinematic conditions for indoor/outdoor.

As for the time performance, only GMV and Satelles were able to generate (or backup) the UTC time for over 100 days [AD. 2]. While other companies demonstrated GNSS-independent time transfer, they were not able to maintain UTC without additional atomic clocks or a connection to a National Metrological Institute (NMI). It should be noted that, in this case, GNSS would still play a critical role in order to ensure a continuous, consistent timing information, with A-PNT technologies providing augmentation and backup. Three companies among those tested proposed GNSS-independent time provision solutions, namely:

- **SCPTime,** distributing time from an NMI using computer networks. They could guarantee UTC at $10^{-3}s$ without GPS and $10^{-6}s$ with a GPS receiver at the user end. In the case of an outage, users would have up to 24hrs of $10^{-6}s$ of backup. The internal distribution system demonstrated to be resilient, providing multiple weeks of backup. However, even if such a GPS independent scenario would fulfil the current industry requirements, this would not fully address future needs. Therefore such an option would be indicated mostly as a secondary backup. In this context it is to be noted that SCPTime is currently in the process of closing down and further contact with SCPTime would be recommended to understand the reason of the venture's failure.

- **GMV,** offering a combined UTC generation (through two time chains based on a Passive Hydrogen Maser, PHM and owned by GMV) and time transfer using Fixed Telecommunication Networks (FTN) or dedicated GNSS receivers. Given the objective of the exercise, only the former technology was considered as capable of fulfilling the required $10^{-6}s$, with two weaknesses:
    - The $10^{-6}s$ performance is a hard limit for proposed technology, and an accuracy upgrade would not be possible;
    - The proposed development is strongly dependent on existing infrastructure (and offers only a single time generation facility), leading to a single point of failure. There is also dependency on 3rd party (NetInsight AB and SevenSolutions) hardware;

- **Satelles,** offering LEO based UTC time distribution. As the technology is already operational, no R&D activities in Europe is currently planned..

Based on the above findings, we can conclude that the main weakness of the tested (as well as proposed) A-PNT technologies is **the need for UTC provision/generation**, as detailed in [AD. 2]. In this context, **NMIs represent the most resilient, cost efficient and precise sources of UTC**. Secondly, they tie up the MS and EC objectives as NMIs are directly funded by MS. Hence, proposed actions would extend the capacities leading to “more than sum of the parts” outcome.

For the sake of completeness, it is also worth mentioning that:

- Test campaign’s time accuracy requirement was $10^{-6}s$. This should be re-considered, especially when accounting for emerging industries such as autonomous-driving, data centres or intelligent cities. In this context one could expect more stringent accuracy needs, up to $10^{-9}s$;
- Legacy systems might not be able to be updated to the level of the cybersecurity standards demonstrated by the tested A-PNT platforms.

4.3 System of Systems Approach (SOSA)

The discussion presented above indicates that a single A-PNT technology would not be capable of providing full GNSS backup. While all the analysed technologies demonstrated complementing capacity, the provision of UTC in particular would require additional infrastructural investments. Therefore the suggestion is to consider a more expansive, wider approach. In this context, [AD. 2] concluded that:

- While none on the tested A-PNT technologies had the breath of capacity provided by GNSS, they were able to extend EU PNT to areas where GNSS cannot deliver (such as indoors, urban canyons or underground) as well as act as backups (apart from Satelles time, whose performance is limited by the nature of the local oscillators deployed);
- EU based companies demonstrated a competitive advantage in the terrestrial time transfer technology, while the full PNT technologies would require long deployment periods with substantial support by commercial interest;
- Non-GNSS UTC generation requires either LEO based solution (such as the tested Satelles) or terrestrial infrastructure, such as fibre and/or computer networks time transfer from NMIs, which in turn would require both investment and maintenance.

The SOSA considers all the technologies, not necessarily limited to those tested in the A-PNT campaign. It is assumed that, considering its flexibility, cost and versatility, **GNSS remains the undisputed PNT backbone** of EU PNT ecosystem. As part of this, A-PNTs would act as backup for UTC provision and overlay PNT services, with the aim of creating resilient PNT provision. To do so, it is fundamental to:

- Create the backbone terrestrial UTC distribution by connecting NMIs.
- Expanding the PNT provision to areas where GNSS struggles to offer full PNT;
- Address the GNSS vulnerabilities, by increasing the resilience to disruption, introducing contingency and expanding interference monitoring/detection systems;
- Maintain the coherence of this holistic approach by relating each component to the same European Terrestrial Reference Frame (ETRF) and the UTC;
- Provide infrastructures that can be further expanded to meet the demanding requirements of the EU economy and support the development of future technological trends such as self-driving cars, automation, intelligent transport and interconnected society.

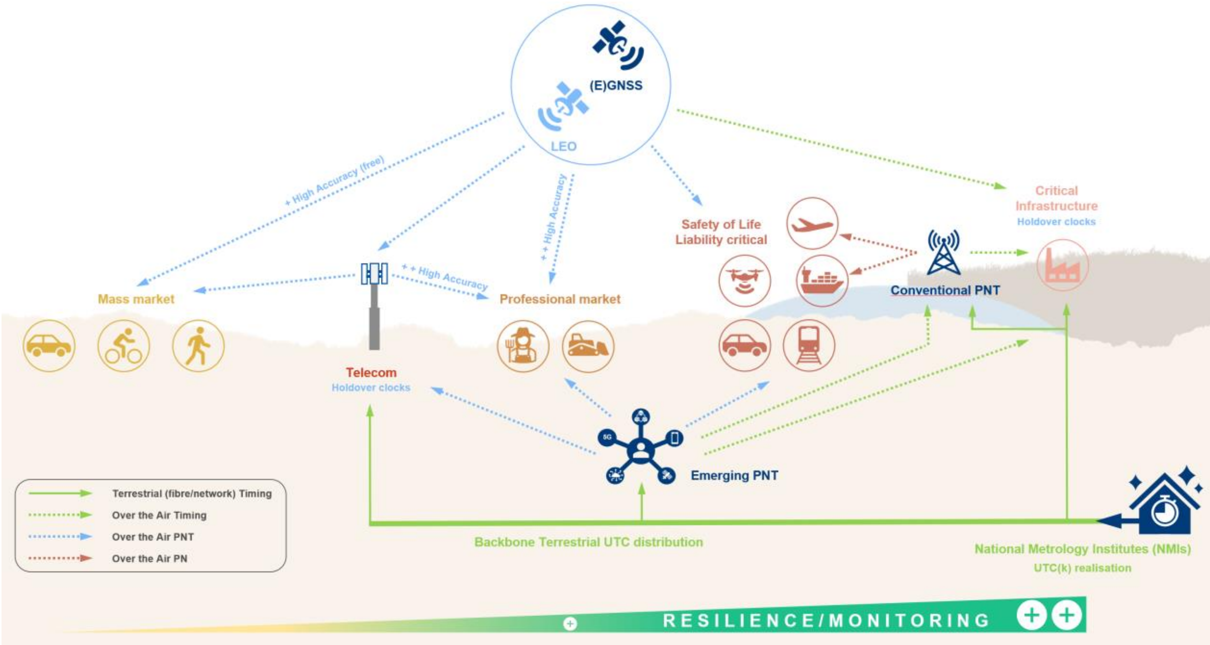

Figure 1. EU PNT vision, following [RD. 1]

This concept is presented in Figure 1 from [RD. 1]. Proposed EU PNT is a combination of the space and terrestrial systems, which allows for flexible and resilient ecosystem. An enhanced PNT provision supports the European Green Deal, reducing the energy use and increasing the efficiency of energy transfer. This also addresses the challenges of an increased level of sophistication in hybrid threats [RD. 38]. In this way, it is possible to provide the support for the future industrial needs of smart grid, smart mobility and other future technologies, leading to a stronger Europe in the world, fit for the digital age[1].

A substantial upgrade to the current GNSS limitations and vulnerabilities will be introduced with the Galileo 2nd Generation (G2G), whose mission requirements are mostly addressing those issues. As such, it is essential to consider the modernisation of GNSS, and of Galileo in particular, given its critical underpinning of a new PNT ecosystem in Europe. Within this concept, **the non-GNSS components would be best referred to as Complementary (Continuous) PNT (C-PNT)**, given their objective to provide resilience, extend PNT to specific environments that cannot be served by GNSS, and act as limited spatial and temporal backup supporting existing infrastructure. This concept supersedes previously reported activity on backup/alternative PNT (A-PNT) as fully independent system was identified as not optimal for the proposed ecosystem.

This proposed SOSA ecosystem, also offers resilience, multiple sources of information, local augmentation of GNSS, enhanced error detection and more precise accuracy estimation. This complexity require both expert knowledge (requiring support to higher and technical education) and fostering of general PNT awareness and education.

4.3.1 Implementing the vision

The System of Systems combines multiple C-PNT technologies, supported by a modernised GNSS (i.e. G2G), to provide optimal PNT service in diversified environments. The expected infrastructural (OPEX/CAPEX) and user

[1] *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024_en*

segment costs should be considered both in the light of the benefits of an enhanced EU PNT as well as the economic and social cost of a possible PNT outage, especially if combined with hybrid treats [RD. 38].

Arguably, such an approach should be also supported by further infrastructure developments, addressing the EU skill shortage (i.e. by investing into centres of excellence and higher education institutes) and enhancing the EU entrepreneurial spirit (by providing the culture, developing markets and sources of funding). This should also include market based regulations supporting and encouraging commercial investment in resilient PNT. Alongside this, a careful market driven policy would also play an important role (for example towards a harmonised market for the EU high accuracy atomic clocks).

The main **actions** recommended at the **EU level** could include:

1. **The creation of a resilient, terrestrial time backbone** operating at the nanosecond accuracy level $(10^{-9}s)$
   - The standard of the current industry accuracy is millisecond (1e-3s) to microsecond (1e-6s). However, future applications in various industrial sectors (5G, multimode transport, self-driving cars, massive data centres) will require a nanosecond accuracy. While some sectors (banks, data centres) are moving ahead on their own, a standardised approach would be easier to maintain and more resilient. Critically, it would enable future, network-based PNT, some of which (5G, two ways WiFi) was already tested/demonstrated within the EU;
   - Discussion with **stakeholders**, such as EURAMET (European Association of National Metrology Institutes) and WELMEC (European Cooperation in Legal Metrology), should focus **on the requirements, time-scale and funding required to create a timing backbone**, by interconnecting European NMIs, at nanosecond level with fibre-based time transfer. In this context it is worth mentioning a recent relevant action directly involving the JRC in Ispra. Following discussions with InRIM, the Italian Metrological Institute, **JRC considers integration into the Italian Quantum Backbone (IQB)** combined with the direct nanosecond access to the UTC(IT). This represents an opportunity for relevant R&D and to demonstrate the value of the approach discussed above;
   - The initial focus should be on **critical infrastructures** (telecommunication, aviation and maritime), which expressed interest in independent time sources, although further encouragement and funding are needed;
   - The proposed interconnections would create large, across-Europe assembly of atomic clocks. This would extend EU's learning opportunities in the field, allowing for example, to test interference on more advanced clocks and to learn more about possible modes of failure or behaviours. This could lead to **enhanced knowledge opportunities with possible advances for the clocks manufacturing sector**, which is highly strategic for the EU.
2. **Provide the necessary capillarity** by introducing and enhancing both new and already existing C-PNT technologies
   - The capillarity between backbone and end-users mostly depends on the actual user needs and some of the existing technologies and connections are very likely to be re-used, hence reducing the cost;
   - The current situation of the **ground atomic clocks** has to be analysed, in discussion with the relevant stakeholders, including those considering dual-use for security and defence applications;
   - Approaches that offer LEO based UTC time distribution (Satelles-like) should be recommended for remote locations or as a secondary backup;

3. Promote the **use of expertise inside the EU**, by creating centres of excellence and downstream commercial applications.
   - While the first step foresees the development inside the EU, further stages should include the export of the knowledge, both as individual solutions and as a complete commercial solutions;
   - New infrastructures, such as 5G, should be encouraged to deploy C-PNT, also through standardisation or regulatory initiatives, as this will bring benefits both to them and their customers;
   - Adequate consideration should be given to **establishing an industry-based EU PNT forum, including industry and education stakeholders**. The US PNT Executive Committee and the US PNT Advisory Board are examples of governmental and industry/academia direct feedback loops. While some of such mechanisms exist in EU (for example, through DEFIS and EUSPA user forums) a winder (and earlier) industry participation would be recommended. Feedbacks from industry would suggest the creation of a non-political focus group to address the needs for consistent management of the PNT for the benefit of EU Member States, balanced for large and small industrials players (ETSI balanced approach was presented as a good example that could be followed). Such a forum would allow for direct and early discussion on R&D activities as well as to establish a channel for discussion with senior representatives of industry. The forum should operate on fix schedule, ensuring consistency.
4. **Encourage and simplify the PNT development** by:
   - Developing C-PNT testing standards. This could be done in a broader context, enhancing the *IEEE P1952 Resilient PNT User Equipment* standard and creating specific EU based recommendations. In this context the JRC itself could provide valuable inputs, considering the relevant experience in testing activities and the in the definition of testing standards and procedures, as well as the unique testing facilities;
   - Supporting an industrial supply chain (atomic clocks, subcomponents) and a continuous provision of expertise (higher education) to create a dynamic ecosystem;
   - Promoting specific R&D (industries, research centres, universities) funding: the approach of the Defence Advanced Research Projects Agency (DARPA) incremental funding (testing technologies and funding only those that work) and that of ESA of maintaining funding only if the keystone requirements are meet are very relevant example to be considered. This should also include the pipeline of funding, with progressively increased requirements of TRL, to encourage long term industry investments;
   - Further developing the PNT market by a mix of regulations and market driven forces. The focus should be on market segments that either utilise or directly support EU technologies or that are particularly critical (such as energy, telecommunication and data centres);
   - Investigating the possibility of identifying a dedicated spectral allocation for EU terrestrial C-PNT services and how it could be integrated/standardised in devices.

In addition, specific actions can be defined **for the supporting legislature**:

5. **Mandate A-PNT backups for Critical Infrastructure**. A good starting point could be represented by mandating independent time provisions to CI, possibly including the Galileo Time Generation Facility (TGF). In this context, it would be relevant to understand whether
   - Common standards and/or legal base for NMIs to act as UTC providers can be established in EU;
   - There is a need for specific industrial and the mid-term Horizon Europe actions on optical clocks. Precise Clocks Requirements within the EU, given the current geopolitical situation are being defined pretty much in isolation. A broader approach would benefit the overall EU

resilience (though given the different requirements, ground and space clocks should be separated).

6. Expand the PNT provision and **identify if there is an economic benefit in the support of further implementation of C-PNT**.
   - Identify market segments that would benefit the most from C-PNT and draft minimal standards;
   - Encourage MSs to adopt similar stance and identify the market areas that would need specific support;
   - Consider the potential size of the market and focus only on the most promising ones. In this context, the synergies with IRIS[2] should be considered;
   - Define industry standards to ensure the interoperability, as a minimum to UTC and ETRF. Commercial companies would be expected to pick up those standards voluntary, following the publication of EU C-PNT guidance and recommendations. Combining this with an international efforts such as IEEE P1952 or WELMEC/EURAMET could address both the EU needs and its global standing. One outcome within reach could be the publication of testing guidelines by the JRC.

   Those actions are intended to establish and nourish the EU C-PNT ecosystem players as well as to shape the EU market accordingly. The aim is to create a virtuous circle, further fuelled by market forces, improving the adoption of C-PNT solutions, increasing the overall PNT resilience and creating synergies with GNSSs. The EC objective would be to monitor and control with regulations/recommendations if and where required. Given the importance of this, international players should be also considered, as long as they can directly benefit from the EU growing competences.
7. Continue the work started with the European Radio Navigation Plan (ERNP)[2] on **PNT Awareness**.

To support all the actions listed above, Table 3 aims to identify the best technologies and actions required for different geographical scenarios. The table lists:

- The optimal PNT and the time only technologies for the different EU geographical scenarios;
- The actions required to enable the development of the PNT technology, for the EC in regulatory domain. Please note that it requires terrestrial time backbone infrastructure.

Geographical Scenario	Enabling actions	Time services suggested	PNT services suggested	Additional benefits
EU-wide	Regulations for the grid and telecommunication networks, development of standards, mandate testing and release testing guidance, definition of the need for CI backup	LEO and (possibly) eLoran	LEO-PNT complementing GNSS	Limited additional cost for end user
MS/Province	Development of standards, mandate testing and release testing guidance	Fibre and (possibly) eLoran, with capillarity provided by pseudolite (time only) and FTN	Pseudolites complementing GNSS	Interference detection and enhanced

[2] https://joint-research-centre.ec.europa.eu/scientific-activities-z/alternative-pnt_en#the-european-radio-navigation-plan-ernp

<table>
<tr><th>Geographical Scenario</th><th>Enabling actions</th><th>Time services suggested</th><th>PNT services suggested</th><th>Additional benefits</th></tr>
<tr><td>Local</td><td>Infrastructure regulations, A-PNT technology regulations</td><td colspan="2">Pseudolite, fibre or FTN (depending on accuracy and user cases), local augmentation</td><td rowspan="2">performance monitoring</td></tr>
<tr><td>Remote locations</td><td>Regulations</td><td colspan="2">LEO-PNT, Pseudolite and (if in range) eLoran complementing GNSS</td></tr>
</table>

Table 3. Suggested PNT technologies vs geographical scenarios.

PNT technologies are vital to the functioning of many CIs sectors such as energy, transport, banking, financial market infrastructure and digital infrastructure. With the ever-increasing interconnection between CIs, the risk of cascading effects and spill-over from a disruption to other sectors is becoming crucial [RD. 38]. The Directive on the Resilience of Critical Entities (CER)[3] aims to ensure the provision of essential services and, in this context, it is important to understand how PNTs are used across all sectors of the directive and how the critical infrastructures that depend on PNT services can increase their resilience.

The Joint Research Centre (JRC) will support the implementation of the CER directive by:

1) Developing non-binding guidelines and recommendations to help Member States to identify critical entities and determine the significance of disruptive effects. In this task the dimension of PNT services should be included in order to understand the dependencies with the identified critical entities.
2) Developing guidelines to specify the technical, security and organisational measures that critical entities need to undertake. Such guidelines may include alternative robust PNT technologies to reduce the reliance on a single system, enhancing the overall security and resilience of critical entities.
3) Developing of best practices, guidance materials and methodologies, and cross-border training activities to test the resilience of critical entities. In this context the use of PNT and C-PNT should be considered by taking into account the input from the experts in the field.
4) Providing scientific advice on an ad-hoc basis to the CER group: the CER group will support the Commission and facilitate cooperation among Member States and the exchange of information on issues relating to the CER Directive. In this regard, JRC can inform the representatives of the MSs and call the experts on PNT and C-PNT to present their work during the CER group meetings.

In this context, the implementation of the CER directive, including its focus on dual-purpose technology and security aspects of critical infrastructures, is of utmost importance. It will help ensure that essential services continue to function effectively in the face of potential threats or disruptions.

[3] https://eur-lex.europa.eu/eli/dir/2022/2557/oj

5 Conclusions and Recommendations

Global Navigation Satellite Systems (GNSS), such as the European Galileo and the U.S. Global Positioning System (GPS), is the ubiquitous underpinning of the EU economy and its critical sectors, as energy, transport, telecommunication and financial, to name just a few, by providing positioning, navigation and timing (PNT) services. For this reason is must be a priority to enhance, harden and protect this asset. While important actions are undergoing to modernize GNSS (Galileo is developing its 2nd Generation, while GPS is launching its 3rd generation satellites), it is considered necessary to complement the GNSS services with Alternative PNT (A-PNT) systems. A-PNT is an umbrella term describing the PNT technologies not dependent on GNSS.

Within this we report an assessment of the implications and costs of deploying A-PNT infrastructures in EU is provided. In order to understand the full potential of those A-PNT technologies, the report assessed both the technologies that were subject to the JRC tests demonstration [AD. 2] and some other that are considered of particular interest in this context. The results of the test campaign showed that, while mature A-PNT technologies exist, they cannot fully replace GNSS, especially related to UTC provision. As such, it is very clear that A-PNT should act as local augmentation for mission specific requirements or limited time backup.

This report demonstrated that **alternative PNT technologies should be implemented as part of a broaden EU PNT strategy, underpinned by the flagship GNSS Programmes Galileo and EGNOS and possibly further supported in future by IRIS².** This would represent an economically optimal way to create resilient and ubiquitous PNT. In this context, the cost should be considered against the possible loss of economic benefit, estimated at €69bn annually (see section 4.1).

Within the proposed "**system of systems**", the non-GNSS components would be best referred to as **Complementary (Continuous) PNT (C-PNT)**, given their objective to provide resilience, to extend PNT to specific environments that cannot be served by GNSS, and to act as limited spatial and temporal backup supporting the existing infrastructure.

The proposed EU PNT ecosystem would consist of space assets and a terrestrial timing backbone, providing global PNT coverage and resilient timing. This in turn would enable mission specific C-PNT services, allowing for increased availability, accuracy and resilience. While both space and timing backbone should be supported by public funding, **the C-PNT services should be commercially driven while being supported by relevant regulatory actions**. In this way, the deployment of A-PNT systems would fit within a wider EU PNT system able to strengthen its resilience and performance, creating C-PNT system of systems approach. Additional discussions with public and private stakeholders should be encouraged in order to understand if, and to what extent, further investments are needed to foster the A-PNT implementation.

The importance of **interconnecting the European NMIs** was highlighted in [AD. 2], with option of local atomic clocks backups. This is expanded in this report, discussing how this could enable UTC resilience. In this context, and to further enhance EU PNT resilience, it could be strategic to investigate the possibility of dedicated spectral allocation for EU terrestrial PNT services, beyond those currently used by GNSS.

The System of Systems concept presented in the report would combine multiple C-PNT systems, underpinned by the GNSS, to provide the optimal PNT coverage. Comparing to GNSS, it is an expensive scenario, both from infrastructure (OPEX/CAPEX) and user costs perspective. However, such an investment should be considered against the economic and social cost of a PNT outage, especially in the light of hybrid treats [RD. 38].

Following the analysis performed in the report, the following actions are suggested:

- Create a **resilient terrestrial time backbone** operating with the nanosecond accuracy. This should be possibly complemented by actions to foster an adequate EU atomic clock market.

- **Provide the necessary capillarity**, connecting the backbone with the end users. This could be a combination of existing and future C-PNT technologies, depending on the user needs and longer term prospects.

- Consider the set-up of an **EU industry based PNT forum**, encompassing wider industry and education stakeholders, allowing for the earlier feedback. While some of this mechanism exist in EU (through DEFIS and EUSPA user forums) it does not include them in the earlier service discussions and does not address non directly downstream users such as, for example, traditional timing companies or upcoming PNT services

- **Develop C-PNT testing standards**, ideally in the broader international context. This would lead and consolidate any previous effort done by European and non-European countries.

- Encourage the further development of C-PNT technologies in EU, by creating coherent policy and a vibrant market of skills (including interventions on the high education). Both **strict funding requirements** (allowing to drop unsuccessful projects early) **and a long term pipeline of funding** should be considered, with progressively increased requirements of TRL to encourage further investments.

- Continue the general **PNT awareness** started with the ERNP**.**

Building on the legacy of the ubiquitous and accurate PNT systems (GNSS), we need to develop systems and technologies capable of supporting the new emerging automated systems that need to operate in hostile environments and requiring resilient, reliable and accurate PNT information.

The evidence of policy and regulatory actions, supported by adequate budget commitments and longer term plans, would be an important element to encourage the industry to invest. A wider forum to engage with the PNT downstream industry, including the various industrial and R&D players, would provide a further push to the actual implementation, leading the EU to the new era of resilient and reliable PNT.

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