Ensuring PNT resilience:

A global review of navigation policies and roadmaps

PNTの "Resilience"を高めるには？

～各国のPNT政策とロードマップについて～

Joshua Critchley-Marrows

School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney

Graduate School of Aeronautics and Astronautics, The University of Tokyo

Quentin Verspieren

Graduate School of Public Policy, The University of Tokyo

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For More Information

Joshua Critchley-Marrows, School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, joshua.critchley-marrows@sydney.edu.au

Quentin Verspieren, STIG Education Programme, Graduate School of Public Policy, The University of Tokyo. q.verspieren@pp.u-tokyo.ac.jp

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DISCLAIMER

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List of Abbreviations

BKZS	Bölgesel Konumlama ve Zamanlama Sistemi
CCP	Chinese Communist Party
CIS	Commonwealth of Independent States
EC	European Commission
eLORAN	Evolved Long Range Navigation
ESA	European Space Agency
GEO	Geosynchronous Orbit
GLAC	GNSS and Location-Based Service (LBS) Association of China
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ISS	International Space Station
KARI	Korean Aerospace Research Institute
KPS	Korean Positioning System
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
PNT	Positioning, Navigation and Timing
PPP	Public-Private Partnership
QZSS	Quasi-Zenith Satellite System
R&D	Research and Development
SBAS	Satellite-Based Augmentation System
SBPP	Space-Based PNT Programme
UN	United Nations
WAAS	Wide-Area Augmentation System

1. INTRODUCTION

Positioning, Navigation and Timing (PNT) services have become the backbone of numerous vital infrastructures: banking and financial networks rely on space-based timing, various transportation services are fully dependent on satellite positioning, and so on. Any disruption of space-based PNT services, whether intentional or accidental, could have dramatic consequences for national security, public safety and economic security. In consequence, states owning and operating Global Navigation Satellite Systems (GNSS) have grown extremely concerned with the reliance of their infrastructure and its ability to provide stable and trustworthy PNT signals.

How did these concerns manifest themselves? What are the resilience considerations included in the PNT policies and roadmaps that have been adopted by major operators of GNSS and other spacefaring countries in recent years? This work proposes a review and comparative analysis of the main navigation policies and strategy documents in the United States, Canada, the European Union, Russia, the United Kingdom, India, Japan, Australia, Türkiye, China and South Korea, to ensure the resilience of PNT services.

An important aspect to this work is use of the word ensure, which implies action. This is contrary to assure, where only a verbal confirmation is given, or insure, which means failure is followed by consequences or compensation. The differences between each are illustrated in Figure 1.

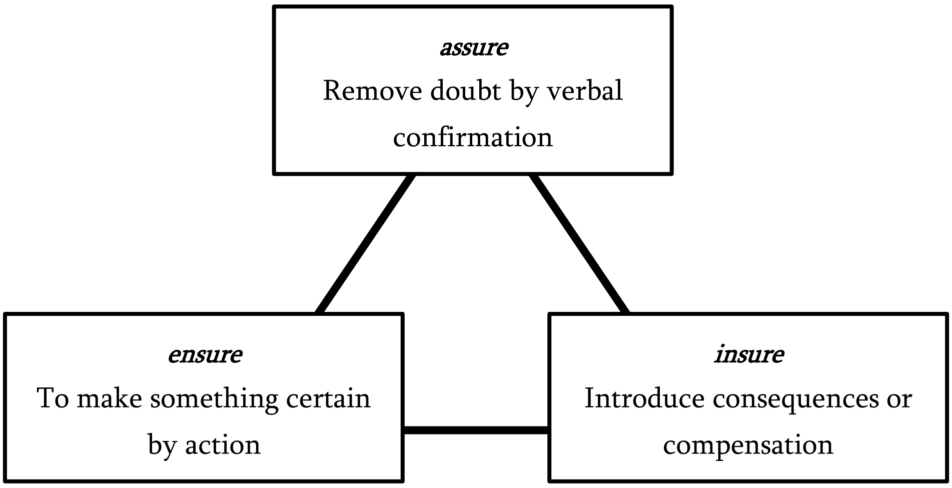

Figure 1. Differences of definition between common words assure, ensure and insure.

There is however little clarity on the exact meaning of each of these terms in the context of policy documents and in the PNT-related literature, those being often used interchangeably, in particular in the expressions of 'ensuring PNT resilience' and 'assured PNT'. The authors do not intend here to provide authoritative definitions of these terms, but rather to use common dictionary definitions to show that both the concept of resilience and the means to achieve it are not fully understood in policymaking circles, therefore hampering the adoption of clear and actionable PNT resilience policies.

It should be noted that while this article emphasises the dangerous reliance of numerous critical infrastructures on GNSS, it does not only focus on the resilience of GNSS but more generally on PNT resilience, which can be realised through alternative infrastructures, such as terrestrial networks (e.g.

eLORAN, 5G). Accordingly, some of the countries analysed in the article do not – yet – operate their own space-based PNT infrastructure, such as Australia, Canada and South Korea.

The article is organised as follows. After reminding the reader of the historical development of PNT infrastructure and of the threats and vulnerabilities it is exposed to in section 2, section 3 introduces the concept of resilience and the terminology adopted across various sectors. The core of this work, the detailed review and comparative analysis of existing PNT policies and roadmaps of major spacefaring countries, with an emphasis on resilient PNT, are presented in section 4. Finally, section 5 introduces and analyses themes and trends in PNT resilience, based on particular topics identified in section 4.

2. PNT SERVICES: HISTORY, THREATS AND VULNERABILITIES

Long before the ubiquity of satellite-based PNT services, radio waves were used for positioning and navigation. In 1888, two years after having demonstrated the existence of electromagnetic waves, Heinrich Hertz conducted the first experiments on radio direction finding . Using a rudimentary loop antenna, he was able to determine the direction of the radio signal (but not its sense) as the one displaying the maximum gain. By reproducing this approach with a second radio signal, it became possible to triangulate one's position. This basic though efficient method was employed for most of the early 20th century. Photographs of planes in the 1930s clearly show large hand-rotating loop antennas above the cockpits. Radio direction finding systems became the foundation of the larger field of radio navigation for which a variety of other methods were invented such as the emission of a narrow beam in which the user - typically aircraft - manages to remain, or the use of transponders. Overall, radio navigation relies on the use of reference electrical beacons emitting signals used to calculate angular directions, distances, and, in some cases, velocities.

The game-changer in the provision of navigation services was the development and launch of the Transit satellite constellation (also known as NAVSAT) by the United States from 1959. Funded by the Navy, it provided the world's first operational space-based radio navigation and timing services (with 50 ms accuracy) from 1964 to 1996. The user's location was obtained by measuring the Doppler shift of the satellite's signal. After the testing of numerous satellite technologies in support of PNT services, the Transit system was made obsolete by the development and deployment of the Navstar-GPS constellation by the US Air Force, now simply known as the GPS.

GPS employs time difference of arrival, where satellite time information is provided directly to the user for position calculation, and is a significant performance improvement compared to the Doppler-based TRANSIT system. Initially reserved for military uses, the GPS was progressively opened to civilian use by President Ronald Reagan following the KL007 incident of 1983. However, it is only in 2000 that President Bill Clinton revoked the Selective Availability policy, from which civilian users had only access to a degraded GPS signal.

Since then, space-based PNT signals have been integrated in almost every part of our societies. All modes of transportation are partially or fully reliant on satellite navigation, timestamps at the heart of the global financial system and of any other synchronised system (e.g. telecommunication, energy grids) are provided by satellite timing services, modern military forces are operating in the assumption of assured access to PNT services, etc. Overall, our society has grown over-reliant on space-based PNT services, which explains the proliferation of sovereign GNSS around the world: GLONASS in Russia, Beidou in China, Galileo in Europe, QZSS in Japan, and NavIC in India.

This over-reliance poses huge risks for our societies considering, beyond cases of internal GNSS failure, the number of hazards and threats facing the uninterrupted provision of space-based PNT services. For instance, the proliferation of space debris and extreme space weather events have the potential to disrupt the functioning of GNSS. But, most importantly, the advancement of counterspace capabilities worldwide has increased the pressure over the need to ensure stable PNT services. Following the classification established by the Center of Strategic and International Studies, counterspace threats can be divided into four main categories: kinetic physical (e.g. direct-ascent anti-satellite or co-orbital anti-satellite weapons), non-kinetic physical (e.g. directed energy weapons), electronic (e.g. jamming, spoofing) and cyber (e.g. data interception, seizure of control) [1]. In 2021, General David Thompson, then-Vice Chief of Space Operations declared that US satellites were the targets of daily reversible attacks [2].

Most of the recorded counterspace activities against GNSS fall under the category of electronic interference. For instance, Russia has been particularly active in GPS jamming and spoofing activities. According to the Secure World Foundation's annual counterspace threats open-source review, Russia has been prioritising electronic warfare capabilities in the overall modernisation of its counterspace apparatus, a focus which has been placed under the spotlight since the beginning of the conflict with Ukraine. It has officially been deploying 250,000 GPS jammers to protect facilities across its territory and mobile systems have been spotted along its forces in Ukraine and Syria [3]. Even away from conflict zones, it is not uncommon for Russia to spoof GPS signals to disguise movements of President Putin [4]. Similar examples are plentiful such as, on the other side of the Eurasian continent, the constant jamming of GPS signals by North Korea on its Southern border [5]. More examples are listed in Table 1.

Table 1. Examples of threats and vulnerabilities to GNSS.

Target	Region	Source
Russia GPS spoofing and jamming in Ukraine war and neighbouring regions	Russia, Ukraine, Syria	*Forbes* (2023)
Jamming of GPS signal on the borders of North and South Korea	South Korea	*BBC News* (2016)
Russia performs anti-satellite missile test capable of impacting GPS	Russia	*Inside GNSS* (2021)
GPS jamming attack off the coast of Cyprus	Cyprus	*Fortune* (2020)
Iran jams GPS on ships in Strait of Hormuz	Persian Gulf	*GPS World* (2019)
GPS jamming and spoofing attacks creating circular patterns in the Port of Shanghai	China Sea	*The Maritime Executive* (2019)
Australian Qantas pilots subject to GPS jamming from supposed Chinese warships	China Sea	*Australian Aviation* (2023)
Truck driver with GPS jammer accidentally jams Newark airport	New York	*CNET* (2013)

Target	Region	Source
GPS jammer on nearby warship disrupt GPS signals along Danish coast	Denmark	*TV2ØST* (2023)
Nine Galileo satellite clocks have stopped working	Europe	*BBC* (2017)
Multiple timing issues have been experience with GLONASS satellites	Russia	*ICONCOX* (2013)
Three atomic clocks fail on Indian regional GNSS NAVIC	India	*GPS World* (2017)

The combined risks posed by the aforementioned hazards and threats is pushing GNSS owners and operators to work towards ensuring the resilience of their services and more generally, has prompted governments to evaluate and strengthen the overall resilience of their country's PNT service provision infrastructure, including, but not restricted to, GNSS.

3. DEFINING 'RESILIENCE'

'Resilience' is a word with an extended history, with roots traced to the 1620s where it meant an 'act of rebounding or springing back', often used for immaterial things. In engineering, the word was first used in the context of material science in the 1830s, meaning 'elasticity, power of returning to original shape after compression'. This definition can be linked to the modulus of resilience or elasticity measure, a popular property in the civil engineering domain to describe the ability of a material to distort temporarily and return to its original shape [6].

Other scientific and technical disciplines have also associated resilience within their field. In ecology, resilience of an ecosystem is the ability to absorb changes and still exist, maintaining stability [7]. For psychology, resilience is often used in the context of describing the human response to traumatic stress. In this field, it is often criticised that resilience lacks precise definition, adopting definitions ranging from 'symptom-free functioning following trauma exposure' to 'positive adaptation despite adversity' [8].

Business management and leadership research has readily adopted the term in the 21st century, especially in recent turbulent economic conditions as well as high-risk startup ventures. Often referred to in the context of the 'organisation', 'resilience can be defined as the ability to deal with challenging conditions by ensuring the existence and prosperity of the organization' [9], or 'the capacity for companies to survive, adapt and grow in the face of turbulent change' [10].

A common theme across disciplines is the reference to the 'system', be it an organisation, an ecosystem or the human mind. This system is then said to be 'resilient'. However, it might be noted by the reader that the definition of resilience is not clarified, where some authors have highlighted the lack of consensus has been problematic when dealing with the issue [8]. This deficiency might also be noted in the topic of PNT resilience.

GNSS resilience is typically associated with a broader case for the resilience of a nation's critical infrastructure. The daily operations of the State are highly reliant on utilities such as energy, waste disposal, and water, where any loss or degradation could lead to severe consequences. GNSS is either referred to as an enabler of critical infrastructures, or as a critical infrastructure in itself.

Attempts to quantify resilience, in order to understand if it has been achieved, has led to an abstraction from the material science 'modulus of resilience' [11], [12]. Originating from a more general definition of system resilience [13], it is formulated as a ratio of system recovery and loss as a function of time. To restrict the definition to only a factor of time might be an oversimplification, and appears to be more reflective of system stability than resilience.

Other measures include the degradation in quality of infrastructure during a recovery period, or more comprehensive structural based modelling of a network's vulnerability and recoverability following a disruption [12], [14]. However, such metrics can only be clarified once the engineering solution has been proposed and potentially implemented, rather than on the policy itself, and so is not helpful in the context of this paper. Current systems could be quantified as such, however.

PNT resilience typically takes the form of system resilience. It is argued by Proctor that a system is resilient if it continues to carry out its 'mission' in the face of adversity or threat [15]. To exhibit this quality, it must incorporate three primary functions, the 'ability to detect threats', 'respond appropriately', and 'rapidly recover'. As an approach, the 'system-of-systems' is presented as a common methodology also adopted within the aviation domain [16], [17].

Other authors define resilient PNT as integrating PNT information from multiple sensors and sources, adapting to different environments and adjusting based on appropriate functional and stochastic modelling [18]. This definition is especially presented in the case of maritime and e-navigation concepts [19]–[21]. However, this is seen by the authors as an approach, akin to the system-of-systems, rather than a definition.

For the case of PNT policy, the theme of resilience is commonly referred to and reflected. The policy contents are the topic of section 4. From a technical perspective, resilience is treated as a figure of merit of a PNT system alongside accuracy, availability, security and integrity. However, the policies themselves do not attempt to define the term. In the framework of this article, the definition adopted is *the ability to recover from and/or continue operations, with some acceptable degradation to satisfy critical needs, in the face of adversity*, being reflective of historical definitions in other fields, and also representative of the literature.

It has been introduced in section 1 the use of the word 'assure' in the frame of PNT, where 'assured PNT' is often adopted in military circles. 'Alternative PNT' is another common term. Both appear to refer to the suite of technologies that seek to safeguard PNT users against the threats and vulnerabilities highlighted in section 2, adopting the proposed system-of-systems approach. The suite of technologies may include adoption of inertial sensors, vision-based navigation instruments, terrestrial radio navigation and a new form of satellite-based navigation. Each of these have been highlighted in resilient PNT policy roadmaps by various governments, as described in Section 4. It is treated by the authors that the umbrella term should be resilient PNT, inclusive of all policy and technical development that address the threats and vulnerabilities mentioned in section 2.

Other terms that are often treated in the context of resilient PNT are augmentation and robustness. Augmented PNT refers to technologies that improve the performance of GNSS, and are dependent on existing space-based PNT services. Given the discussion in this article, the authors suggest that robust PNT refers to the suite of technologies that will ensure PNT for the user. It is not linked to the actions that will deliver resilient PNT, but merely to a specific action that has confirmation that this meets resilient PNT objectives. Again, each term is treated underneath resilient PNT, and is defined in Figure 2.

Credit should be given to the IEEE P1952 – Resilient Positioning, Navigation and Timing User Equipment Working Group that are also seeking to unify terminology. We wish to complement these efforts to develop definitions, proposing a policy perspective and interpretation based on the consultations made as part of this study.

Resilient PNT
Ensures the ability the PNT service will recover and/or continue operation, with some acceptable degradation to satisfy critical needs, in the face of adversity.

Assured PNT
Remove doubt that PNT services will be continuous and available by verbal and/or written confirmation.

Robust PNT
The use of a suite of technology that ensures PNT services will recover and/or continue, with some acceptable degradation to satisfy critical needs, in the face of adversity.

Augmented PNT
The use of technology that is dependent on GNSS to improve performance metrics such as accuracy, precision, availability, continuity and integrity.

Alternative PNT
The use of a technology that is independent of GNSS to calculate PNT information that meets the same critical application needs.

Figure 2. Definition of terms commonly used or quoted under the umbrella of resilient PNT.

4. Global Review of PNT Policies, Roadmaps and Original Research

Considering the crucial importance of PNT services for national safety and security, most major space powers have issued strategy documents for the development, sustainment, or improvement of resilient national PNT capabilities. These documents can take various forms based on the usual practices of each government, namely policies, plans, roadmaps, etc. In addition, while some are focussing specifically on improving PNT resilience, others have a more general scope. This section reviews relevant and comparable national PNT strategy documents in the United States, Canada, the European Union, Russia, the United Kingdom, India, Japan, Australia, Türkiye, China and South Korea.

To complement limited or unavailable policy documents, this review also incorporates the perspective of leading experts, gathered through interviews or email exchanges. Special mention is made when a policy characteristic is received by a viewpoint of an interviewee, and not attributable to an official policy document.

4.1. Government PNT Policies, Roadmaps and Original Research

This subsection introduces published government and closely-tied organisation articles and policy statements with regard to PNT, assuring resilience and future plans of development. Some documents refer explicitly to PNT, and treat both GNSS and terrestrial-based infrastructure, whilst others focus solely on satellite-derived navigation and timing. For some governments, space-based infrastructure is treated and will in future be relied upon for PNT services. However, each perspective at least suggests that a PNT source should be secured.

Key documents and sources are summarised in Table 2, chosen as the most current reflection of resilient PNT policymaking and activities. Further detail of the document origin and contexts are provided in the following sections. Some documents are translated using the free version of the internet-based machine translation tool, DeepL, as indicated in the table. When a document has been translated, any interpretation will be justified with further English language references, opinions of policy experts and/or native speaker interpretations. This will be explicitly mentioned in the text.

Table 2. Key PNT policy, roadmap or original research from each country.

PNT Policy, Roadmap or Original Research	Country	Language (Translator)
An update on the Australian Space Agency's Positioning, Navigation and Timing Roadmap (Presentation)	Australia (AUS)	English
Positioning, Navigation and Timing (PNT) Canadian Risk Assessment and Risk Mitigation Assessment Project	Canada (CAN)	English
China Satellite Navigation and Location Service Industry Development White Paper (中国卫星导航与位置服务 产业发展白皮书)	China (PRC)	Chinese (DeepL). Verified by Xiaofeng Wu (The University of Sydney).
European Union Space Strategy for Security and Defence	European Union (EU)	English
Indian Satellite Navigation Policy-2021 (SATNAV-2021)	India (IN)	English
Policy on Satellite Positioning (衛星測位に関する取組方針)	Japan (JP)	Japanese (DeepL). Verified by native speaker.

PNT Policy, Roadmap or Original Research	Country	Language (Translator)
Not publicly available	South Korea (ROK)	-
Main Directions for the Development of Radio Navigation Systems of the CIS Member States for 2019-2024	Russia / CIS (CIS)	Russian (DeepL). Verified by Eldar Rubinov (FrontierSI).
National Space Program Strategy Document	Türkiye (TUK)	English
Satellite-derived time and position: a study of critical dependencies	United Kingdom (UK)	English
National Research and Development Plan for Positioning, Navigation and Timing Resilience	United States (US)	English

4.1.1 Australia

Australia is located in a highly advantageous geographical position when it comes to GNSS. Its proximity to regional space powers, as well as large continental area, provides the country with near full coverage of all four GNSS and both regional navigation satellite constellations. This provides the country with a strong position of resilience, where all GNSS constellation services must be denied for Australia to lose position and timing capabilities. It should however be mentioned that systems like QZSS are developed to be complementary with GPS, and if GPS were lost, the system performance would also be downgraded. This may change though given recent developments in Japan, as discussed in Section 4.1.6 Japan.

Having said this, Australia, like most countries in the present geopolitical landscape, seeks sovereignty and national capability. According to experts, the form that sovereignty takes is not the ability to manufacture satellites nor deployment, but a level of control and system capability that allows the country to be 'self-sufficient'. An example of this development is the recent procurement of SouthPAN, a Satellite-Based Augmentation System (SBAS) for Australia and New Zealand. Unlike other developed SBAS, this system is delivered as part of a service subscription to the American aerospace company Lockheed Martin and Spanish aerospace subcontractor GMV. As part of the agreement, some degree of knowledge-sharing as well as operation must be located in Australia.

The drive for resilience was also instrumental in the recent development of the Australian Space Agency. Australia's small population but large size has led to a significant dependence on satellite services. However, the country has only emerging local spacecraft development nor does it have a serving launch capability. The space agency seeks to develop this sovereign manufacturing capability and an ability of self-reliance. Australia is fortunate to contain a significant portion of the globe's highly demanded resources, an asset that the country also seeks to tap into.

Thus, when it comes to the development of PNT resilience, the nation's agenda seeks for a solution that allows it to claim sovereignty. The Australian Space Agency PNT roadmap makes plans to achieve this through the research and development of key technologies and capabilities. A draft was publicly disclosed at the International GNSS Conference in Sydney, Australia on the 8th December 2022 [22]. Such developments include establishing an Australian GNSS monitoring centre, developing PNT service authentication and encryption, designing more accurate and stable atomic clocks, and working towards the miniaturisation of inertial navigation in space. The roadmap is ambitious and comprehensive, displaying Australia's commitment to be a leader in PNT.

The roadmap involves numerous stakeholders across the national ecosystem, including the Department of Defence, the Department of Home Affairs and Geoscience Australia. Some responders highlight a lack of awareness and internal knowledge on the topic. There is also uncertainty to which organisation is the owner of this issue, where leadership is required to deliver solutions for resilient PNT. Their contributions though were invaluable to the roadmap development, and will also be fundamental to its execution.

Additional pathways towards resilient PNT have also been highlighted in [23], [24], as part of industry and science growth plans. However, the most comprehensive assessment and cross-sector capture is presented by the Australian Space Agency roadmap. Geoscience Australia serves as the ultimate authority on PNT, where it chairs the Resilient PNT committee, which is governed by the Australian Space Coordination committee. The view is held that any PNT solution for Australia will be a space solution, as terrestrial solutions alone are impractical considering Australian geography.

A recent change of government administration in Australia has led to a significant shift in general space technology development, where the civil space budget has been cut by approximately two-thirds in May 2023 [25], which may impact the country's PNT ambitions.

Another key part of Australia's resilience response is the Critical Infrastructure Act [26]. The act explicitly includes space technology, and places a mandate on the operator or owner to ensure that the system is protected in national interest. Particular concern remains to a national timing capability, where many isolated and remote regions of the country depend entirely on timing from satellites. However, there is at present no Australian-owned or operated timing spacecraft.

4.1.2 Canada

Canada shares the longest land border in the world with its neighbour, the United States of America. With a shared history and culture, Canadian defence and civilian policies are complementary with their neighbour. When it comes to aerospace, Canada is a partner to the US in the North American Aerospace Defense Command, an active participant in the International Space Station (ISS), and a major player in the NASA-led, Artemis programme.

Concerning GNSS and PNT, the Government of Canada is contributing search and rescue receivers to the GPS Block IIIF satellites, as part of COSPAS-SARSAT [27], as well as participating in the US SBAS Wide Area Augmentation Service (WAAS) infrastructure, hosting several ground stations. It also provides infrastructure to augment and facilitate access to PNT information from both private and public entities, using a variety of multi-GNSS sources. Canada however has no PNT policy, responding only to present national needs, and has no ownership of a regional or global GNSS.

No single Government of Canada department or agency has an overall mandate for PNT issues, applications or policy development. Nevertheless, given the growing importance of PNT services, a number of Government of Canada departments came together in 2011 to form the Canadian PNT Board (then known as the Federal GNSS Coordination Board) for the coordination of federal civilian PNT activities and international liaison. This initiative also established the supporting Canadian PNT Office to consolidate and coordinate PNT related topics. Since its inception, the PNT Board has had three terms, the most recent mandate being renewed to 2027. The current sponsors are from the following government departments and agencies: the Canadian Space Agency; National Defence (as represented by Defence Research and Development Canada); Fisheries and Oceans Canada (as represented by the Canadian Coast Guard); Natural Resources Canada; Innovation, Science and Economic Development Canada; Public Safety Canada; and Transport Canada. According to government experts, the Canadian Space Agency mandate currently does not include PNT in the broadest sense (to encompass both terrestrial and space-based), contrary to other countries being reviewed as part of this study.

A number of studies have been commissioned by the Office, and consolidated from different departments, including an *Economic Value of GNSS based PNT* [28] and an *Analysis of Canadian GNSS Interference Detector Data* [29]. For what concerns resilience, a report was developed to reflect the findings of a project titled: *Positioning, Navigation and Timing (PNT) Canadian Risk Assessment and Risk Mitigation Assessment Project* [30]. The project considered Canada's 10 critical infrastructure sectors, and a risk assessment was made based on a standard approach. Experts provided the following feedback from the study:

- Respondents considered themselves able to maintain their operation for a short disruption using their existing mitigation measures. However, respondents were concerned with the possibility of sustained disruptions for which they had no means to maintain operations, and corrupted or erroneous data which can be difficult to detect.
- Respondents understood how their current risk mitigation efforts assist to protect their systems and how additional mitigation would contribute to further reducing their risks. However, several respondents indicated their reliance on equipment manufacturers to incorporate the proper PNT resiliency within their receivers. In these situations, respondents had minimal insight into how their equipment could detect, respond to, or recover from a threat.
- Many considered the risks to their current PNT uses and applications as being acceptable, thus not requiring any actions on their part. Specifically, investments in risk mitigation measures were viewed to provide a low return given the low threat likelihood, the lack of historical PNT disruptions, and the adequacy of their existing mitigation measures.

The outcomes of the study were consolidated into three core recommendations, (1) to encourage Canadian Governments and critical infrastructure sector organisations to include PNT in their risk management programs and activities; (2) to encourage awareness raising, information sharing and collaboration-related initiatives; and (3) to establish communities of interest. The study and future activities are driven by the needs and requirements of the user community, and not by other factors.

PNT and timing-only information desired by user groups are explicitly separated in the study. Timing-only users include financial and energy sectors, which are heavily regulated and have mature risk management procedures.

4.1.3 China

The space strategy of the Chinese government is known to be more private with their space policy intentions. However, when it comes to overarching goals and ambitions, the Chinese Communist Party (CCP) has been highly vocal. PNT and GNSS has been directly referenced as part of the most recently published 14th China

Five-Year Plan, the guiding document for policy of the CCP over the years 2021-2026. Using a translated version of the document by the Stanford Cyber Policy Center [31], the central theme is written as 'National Informatization', quoted that 'without informatization, there is no modernization'.

Direct references to the Beidou system as part of overarching goals of the CCP include, 'Commercial applications of the Beidou system and satellite communication network should continue to expand', 'port' and 'aerospace information infrastructure based on the Beidou system', 'Beidou system-based nationwide uniform train operating timing and dispatching command system', and 'construction of an international road transportation management and service system based on the Beidou system.' It is clear that the Beidou system seeks to be adopted across critical transportation infrastructure, as well as other general applications.

The five-year plan is deeply linked to the Belt-and-Road initiative, where Beidou is essential to the delivery of this key policy initiative of the CCP [32]. However, for such embedded dependence, an assurance of Beidou availability and accuracy is essential. Mentions of cybersecurity are included as part of the text, such as 'Establish a scientific cybersecurity vision' and 'enhance information security development levels and cybersecurity protection capabilities.' However, key reference to assuring Beidou is less so explicitly referred.

Beidou and satellite governance is centralised within the CCP. The China Satellite Navigation Committee, made up by members of the CCP, is the central decision maker. The China Satellite Navigation Office then operates below the committee, and the China National Administration of GNSS and Applications acts as the functional department for application management, promotion and adoption [33].

The voice of the Chinese industry in PNT policymaking is strong, consolidated under the GNSS and Location-Based Service (LBS) Association of China (GLAC). Their contributions include development of Chinese policy white papers to the CCP, as with their 2022 version, the *China Satellite Navigation and Location Service Industry Development White Paper* [34]. A translation was made using DeepL, and was independently verified by Dr. Xiaofeng Wu of the University of Sydney. The authors view this document to be the most detailed description of China's PNT ambitions and policy approach.

An important observation of the Chinese approach is to carefully consider the progress of other space faring nations, that usually also have access, or intends to, develop an independent PNT system. The white paper consolidates both policy development and technological progress, highlighting key milestones and meetings in Chapter 1.2 [34].

The white paper's policy recommendation stresses the importance of maintaining Beidou integrity, but also positions Beidou as the ultimate solution to PNT. A significant portion of the document, within Chapter 2 , discusses in detail the adoption of Beidou within China. Experts interviewed by the authors of this article have often quoted Beidou as the most developed and ambitious PNT system, which can be credited to its three-tier orbital arrangement (LEO, MEO and GEO), as well as to the number of services that it provides.

The white paper does highlight the security measures regarding Beidou in Chapter 3.3.1. It mentions the need to study internal forms of navigation, i.e. inertial measurement units, as well as quantum technology. It also raises the importance of user equipment being interchangeable between alternative sources of PNT, especially in areas where GNSS is not available. China is also deploying eLORAN services to support highly accurate timing provision for 5G service provision [34]. However, it clearly presents advancing Beidou's technical systems as the best methodology to achieve resilience, arguing that no alternative would be able to achieve spatial and temporal services with such integrity, reliability, trustworthiness and accuracy. Specific policy contributions are illustrated in Table 3, as well as discussion in Section 4.2.

4.1.4 European Union

The European Union (EU) owns a GNSS, Galileo, and an SBAS, the European Geostationary Navigation Overlay Service (EGNOS), and is now considering the development of alternative PNT systems. Most of the European progress towards navigation has been directed by the *European Radio Navigation Plan*, which provides a pathway for European GNSS adoption across multiple market sectors, as well as potential complementary PNT systems [35].

Started in 2001, the initial phases of the Galileo program were conducted by the European Space Agency (ESA) with joint funding from the EU. After the success of the in-orbit validation phase with ESA's GIOVE-A (launched in 2005) and GIOVE-B (2008) satellites, the phases leading to operational services were fully funded by the EU, with ESA entrusted with design and procurement via a delegation agreement. Initial services started on 15 December 2016, but have experienced significant challenges using advanced but temperamental clock technology. Now fully owned by the EU, Galileo is managed by the European Commission (EC) with the EU Agency for the Space Program (EUSPA) - formerly European GNSS Agency (GSA) as operator. To this day, ESA retains its role of principal architect and procurement organisation, including for the incoming Galileo Second Generation (G2G).

EGNOS became fully operational in 2011 as a joint project of the EU, ESA and the European Organisation for the Safety of Air Navigation (Eurocontrol), providing augmentation services for GPS and Galileo. It is expected to serve for Galileo augmentation in the future. It consists of payloads onboard commercial satellites, such as SES's or Eutelsat's, and is operated by private company European Satellite Service Provider on behalf of EUSPA.

The recent *EU Space Strategy for Security and Defence* reiterated the recognition by the EU of space as a critical domain and expressed that the EC is considering proposing an EU Space Law that 'could provide the framework to collectively enhance the level of resilience of space systems and services in the EU', in addition to existing measures taken in *Directive (EU) 2022/2557 on the resilience of critical entities* and *Directive (EU) 2022/2555 on measures for a high common level of cybersecurity across the Union*. Concerning PNT resilience, the strategy indicates the importance of Galileo's Public Regulated Service, and the need for both its 'continuous evolution', and the operations of 'complementary payloads in orbit'. It also mentions important projects to ensure PNT resilience such as 'EU Radio Navigation Solution (EURAS) or future defence Navigation Warfare (NAVWAR)' [36].

Concerning non-GNSS PNT resilience, although it is not a policy or strategy document of the EU, one could look at the recent report published by Joint Research Centre, titled *Assessing Alternative Positioning, Navigation and Timing Technologies for Potential Deployment in the EU* that provides interesting considerations on the possibilities offered to the EU in terms of alternative PNT, including LEO PNT and ground-based solutions [37]. It is however unclear how this report's suggestion will be taken into account by the EC in future policy formulation.

4.1.5 India

India is one of the world's major players in the provision of space-based PNT services, thanks to its regional GNSS, NavIC, and its SBAS, the GPS-aided GEO Augmented Navigation (GAGAN) system. NavIC is a GNSS constellation composed of eight satellites launched from 2013 to 2018, which provides PNT services over India and neighbouring areas. Approved in 2006 in reaction to the US denial of GPS services over the Kargil region in 1999, NavIC was developed and is operated by the India Space Research Organisation (ISRO). GAGAN is a regional SBAS developed by the Airport Authority of India in collaboration with ISRO to provide augmentation services for aeroplanes in the Indian and neighbouring airspaces. Its services are provided by three GEO satellites.

The draft *Indian Satellite Navigation Policy-2021 (SATNAV Policy-2021)* was issued by the Indian Department of Space online for public consultation . Although it was taken down after the deadline for comment passed on 29 August 2021, it remains available at the time of writing on a specialised website [38]. Although it cannot be considered an official policy of the Government of India, the draft remains the most recent communication on Indian PNT policy intentions, with reference to resilience-related themes and a number of statements on assuring the system integrity of NavIC.

The draft's opening 'policy statement' highlights within one short sentence two elements which are the centre of this paper's focus: (1) the need to achieve 'self-reliance' in space-based PNT and augmentation services, with an emphasis on (2) 'assuring availability and quality'. To these, the subsequent list of objectives adds the requirement to work towards the 'compatibility and interoperability' of NavIC and GAGAN with other existing GNSS and SBAS. The rest of the documents then presents concrete measures which, if taken, will help India advance towards greater PNT resilience such as devising 'a mechanism to assist strategic users in development of specific techniques to ensure protection against and to mitigate the possible threats on usage of secured navigation signals of NavIC', and preparing 'risk mitigation plan shall be devised and implemented to protect the infrastructure (*note: GAGAN*) from any security threats'. Interesting statements in a technical nature from the draft policy include the government will work towards 'expanding the coverage (of NavIC) from regional to global', as well as moving to a terrestrial system that can operate without relying on GNSS.

Due to unsuccessful requests for interviews at ISRO and other relevant government entities, it was impossible for the authors to confirm the approval process stage of the draft policy. However, it is clear from the draft that the Government of India has seriously recognized the importance of both PNT and augmentation services resilience, to 'ensure guaranteed and continuous availability' of services.

4.1.6 Japan

Japan possesses its own regional GNSS, the Quasi-Zenith Satellite System (QZSS) - also known as Michibiki, providing GPS complementary PNT, augmentation, and messaging services. Owned by the Cabinet Office, developed by MELCO and operated by the Quasi-Zenith Satellite System Services Inc., QZSS is composed of four satellites, three on an inclined GSO and one in GEO. The trial phase started in January 2018, with operational services officially launched in November of the same year. Three additional satellites will be launched in 2024 in GEO, inclined GSO and quasi-GEO, providing a service fully independent of GPS. Previously, SBAS were provided by the MTSAT Satellite Augmentation System, operated by the Ministry of Land, Infrastructure, Transport and Tourism, and which operational services started in late 2007.

The Cabinet Office have always been very secretive about its resilience and security policy with regard to QZSS, and so there is no publicly available detailed document on the matter. However, both the Policy on Satellite Positioning issued by the Cabinet Office in April 2021 and officials contacted by the authors did mention the importance of space mission assurance in the overall resilience strategy of the Government of Japan. It is hence likely that the main principles of resilience as outlined in the US Department of Defence's Space Mission Assurance doctrine would be part of Japan's approach. In terms of sovereignty, a senior advisor to the Cabinet Office explained to the authors that the Government of Japan was aiming to develop a 'fully Japanese' QZSS, in particular by stopping the reliance on American atomic clocks [39]. Consultations with universities and the industry are underway for the provision of Japan-made atomic clocks by 10 to 15 years.

As for considerations on PNT resilience as-a-whole, i.e. beyond GNSS, there is no dedicated strategy in Japan. As such, the resilience of PNT infrastructures would likely be dealt with via existing policy on cybersecurity [40] or economic security. It was announced in early 2023, following the release of the new National Security Strategy of Japan that a National Space Security Strategy was under preparation, to be released the same year. It is therefore possible that Japan's PNT resilience policy gets clarified in the short-term. Concerning technological development, the same senior advisor at the Cabinet Office explained that no discussion has taken place on eLORAN, and that the development of a LEO PNT constellation was ruled out considering the difficulty to secure frequency allocations. It would be too costly 'for a country of Japan's rank' to possess two distinct space-based PNT systems. For the Cabinet Office, having access to two different GNSS, QZSS and the GPS, is enough to guarantee Japan's access to PNT services.

4.1.7 South Korea

The Government of the Republic of Korea announced in 2018 its plan to build a domestic regional GNSS, called the Korea Positioning System (KPS). Similar to Japan's QZSS, KPS will consist of a constellation of eight satellites (three in GEO and four in inclined GSO), with the first one launched in 2027, for a full operational service achieved in 2035 [41]. Under the responsibility of the Ministry of Science and ICT, the GNSS will be developed and built by the Korea Aerospace Research Institute (KARI). In complement to KPS, Korea is developing a terrestrial system-of-systems PNT, being driven by the maritime sector. The system will incorporate eLORAN, differential GNSS and the new VHF Data Exchange System, a new communication standard developed by the International Association of Lighthouse Authorities. Services would be accessible not only to marine vessels, but also aviation, defence, automotive and critical infrastructure operators [42]. This may be in response to repeated jamming by North Korea of GPS signals [5].

Korea's policies related to PNT and the KPS are developed in three main documents: the Korean Strategy for Fostering the Space Industry (found by the authors in Korean), the KPS Development Project Plan (only available partially as a press release) and the National Space Council Operational Plan (unavailable publicly). While the first one focuses on the potential of KPS for the advancement of the Korean industry and future promotional efforts to be conducted along those lines, the second one is providing precise directions on the development of KPS. However, the available press release does not make any mention of measures taken to ensure the future resilience of KPS or the role of KPS in the overall resilience of PNT services in South Korea, again emphasising its economic and industrial impacts.

Discussions with Korean aerospace engineers associated with KARI, as well as policy articles relating to Korean Research and Development (R&D) [43], suggest that the approach of Korea is to develop sovereign capability, with regard to competitiveness on global markets treated as a secondary consideration. This is largely linked to Korea's modern history, where foreign technology access cannot be regarded as assured. This trend can also be associated with Korea's general space strategy in launch, small satellites, and as is treated here, the KPS, where it has taken a centralised approach. The concern with PNT for Korea is to have a sovereign capability, taking precedent over the general resilient PNT theme as is sought by other nations treated in this work.

4.1.8 Russia / Commonwealth of Independent States (CIS)

Since the Cold War, Russia has continued to provide satellite navigation leadership through the GLONASS system. The constellation is still widely used today, with most receivers, including in smartphones, capable of receiving the GLONASS signal [44]. Traditionally, the satellite employs a frequency division scheme to distinguish satellites, but a recent technical and policy change will see GLONASS converge more towards the GPS signal standard that uses code division [45]. This is connected to a general strategy towards multi-GNSS, a philosophy that embodies using multiple systems that follow the same standards to diversify risk.

The governance of GLONASS is part of a broader framework of PNT policy. The satellite system was established as a key component, alongside a comprehensive legal and regulatory framework involving many stakeholders across government ministries, departments and agencies, as well as industry contractors and user equipment manufacturers [46]. Given Russia's historic and current role as a space and defence power, effective PNT systems are crucial for the country's role in the world to be maintained.

However, in 2019, a new policy plan was developed and signed by the Russian Federation and some members of the Commonwealth of Independent States (CIS), translated as the *Main directions (plan) of the development of radio navigation* [47]. The interpreted content and conclusions have been verified by Dr. Eldar Rubinov of FrontierSI. Some countries listed in the document appear to have not yet signed, or have abstained, including the Republic of Azerbaijan, Turkmenistan, Ukraine and Moldova. The plan covers the years from 2019-2024. The document is viewed by the authors as the most representative of current PNT policy plans of Russia and the registered signatories, including Armenia, Tajikistan, Belarus, Kazakhstan, Uzbekistan and the Kyrgyz Republic.

The document hints a step away from GLONASS as the core component to providing PNT services, stressing the importance of integrated solutions. This includes both inertial forms of navigation, and the growth of a highly distributed eLORAN service, known as Chayka. This is motivated by highlighting the importance of the large northern geographic area covered by the regions. It is argued that using eLORAN and inertial navigation would enhance shipping between transport hubs in polar regions, an area that MEO GNSS systems are limited in reaching. GNSS vulnerabilities in hostile environments have also encouraged the use of Chayka over GLONASS, as is the case in the Ukraine conflict [48].

A majority of Russia's intentions when it comes to ensuring resilience is within Section 5.6 of the plan [47]. Through highlighting system vulnerabilities, such as geomagnetic storms from space weather, cyber threats, system failures and both unintentional and intentional interference, the plan includes the integration of alternative forms of radio navigation, as well as internal forms of navigation, the monitoring of threats in the electromagnetic environment, training, the expansion of signals employed by GLONASS and the improved robustness of the detection and mitigation of vulnerabilities within user equipment.

International collaboration is also a key component, presented in Section 6 [47], including between CIS member states, as well as neighbouring European and Asian countries. Participation in radio navigation related international organisations under the United Nations (UN) such as the Intergovernmental Committee on GNSS, International Civil Aviation Organisation and International Maritime Organisation are stressed. Policy points are summarised in Table 3.

4.1.9 Türkiye

As an aspiring space power, Türkiye has in recent years intensified its investments and efforts in the space sector. Led by the Turkish Space Agency (TSA), Türkiye's national space programme covers a wide range of topics, including the development of a regional GNSS and negotiated extension of EGNOS SBAS coverage.

The *National Space Program Strategy Document 2022-2030* released in 2022 includes a section on the development of the Regional Positioning and Timing System (in Turkish *Bölgesel Konumlama ve Zamanlama Sistemi*, in short BKZS) [49], motivated by the potential impact that the disruption of foreign GNSS could have on the country. The BKZS program is at its feasibility study phase, and so specific technical details cannot be shared. Türkiye aims to be able to domestically produce critical components of the future BKZS, such as atomic clocks, planned to be tested in a CubeSat by 2026.

The first BKZS satellite is planned to be used for SBAS and operational PNT services are expected from the launch of the fourth satellite onwards (no final number of intended satellites are yet disclosed). At the moment, Türkiye does not possess its own SBAS and is only partially covered by EGNOS. So, until sovereign SBAS is secured by BKZS, negotiations with the EU to extend SBAS to the whole Turkish territory will be conducted. Additional reference stations will be deployed. The TSA will continue to 'support' existing ground-based augmentation system TUSAGA-Aktif, and 'upgrade it to be compatible with BKZS' when deployed. Finally, Türkiye will plan on 'performing signal distribution from space'. An expert interviewed by the authors explained that the BKZS program was likely to be developed as a public-private partnership, rather than government-only.

Türkiye's national strategy does not include any reference to PNT resilience, instead preferring the use of PNT robustness that it plans to achieve through two dimensions: (1) critical receivers should be compatible with at least two GNSS and (2) the development of 'alternative systems' fusing ground and space-based data using 'artificial intelligence, sensors, artificial vision, Internet of Things'.

It should be noted that while using the term of 'alternative positioning, timing and navigation systems', the Turkish national strategy merely refers to a national alternative to foreign GNSS, rather than alternative technologies or approaches as discussed in section 5.3. An expert familiar with the matter however told the authors that alternative PNT solutions (e.g. LEO PNT) could be considered in the feasibility study.

4.1.10 United Kingdom

The *Satellite-derived time and position: a study of critical dependencies* was a critical review on the UK's dependency on GNSS, commissioned by the UK Government Office for Science [50]. Popularly known as the 'Blackett' review, it was published in 2018 and is still accessible online. The study remains a landmark and has been quoted by experts to be a template for similar reviews by other nations. This report gives the most impartial perspective, and so will form the basis of the policy analysis of the UK in this work.

The report incorporates viewpoints from both British and US-based GNSS experts. These experts may come from academia, industry or government, however it might be noted that even though specialists are sought across the sector, it is unclear whether a variety of departments across government have been appropriately involved, even though invited to contribute. Experts consulted as part of this study have commented that the relevant knowledge within British departments and agencies was insufficient, where representation was typically by generalist civil servants. Selection of an authority is also required to support any new GNSS or PNT programme, which is presently not the case.

The recommendations to the UK government and industry suggest a range of strategies to ensure that the UK continues to receive PNT information in the scenario of any disruption. Content includes monitoring and mitigation of threats, testing and validation of GNSS equipment, promotion of the use of alternative PNT technology, including inertial and terrestrial systems, introduction of standards and international collaboration. The outcomes are summarised in Table 3, as part of Section 4.2.

In complement to this review, further studies have been completed by industry groups on behalf of various public institutions for the benefit of the UK. They have been a recipient of high praise, and so some are treated in this analysis. The first of these is by the consultancy company London Economics, titled 'The economic impact on the UK of a disruption to GNSS' [51]. It was commissioned by Innovate UK, the UK Space Agency and the Royal Institute of Navigation.

The assessment considered ten domains across the economy that were treated as dependent on GNSS, and provided a comprehensive value impact if GNSS was disrupted. A highly notable finding was that an estimated £5.2 billion (approximately US$6.2 billion) would be lost to the economy over a five-day period if GNSS were to disappear. Road, maritime and emergency and justice services account for 67% of the impact.

The second study highlighted here is a contracted project by the Navigation Directorate of the European Space Agency titled MarRINav [52], initiated and led by the UK, driven by the conclusions identified in [50]. Focusing on the maritime sector, the project explored risks, dependencies and requirements to deliver an alternative PNT for the British coastline. A notable conclusion of the study highlighted that there was no cohesive definition of system resilience, encouraging the topic to be explored in greater detail. Both terrestrial and space-based PNT solutions were assessed, considered across multiple market sectors.

As a consequence of Brexit negotiations with the European Union, the UK chose to no longer seek access to Galileo, following EU restrictions on participation. To ensure UK sovereignty in PNT, the Government formed the UK GNSS programme, which after internal review and government committee decisions, the programme was renamed to the Space-Based PNT Programme (SBPP) and remit revised [53]. The removal of GNSS from the title suggested a Galileo-like system was no longer being considered. According to statements on the SBPP webpage, terrestrial and space-based solutions were treated, adopting a system-of-systems approach [54].

Media outlets have suggested that UK Government-owned LEO satellite communication company OneWeb may be able to deliver a service signal for positioning and timing. However, experts have indicated that the price tag may largely exceed the development cost of a fully-fledged MEO constellation. Ambitious targets for a sovereign GNSS system are alluded to in text from the UK National Space Strategy [55] and Defence Space Strategy [56], adopting terms like resilience, robust, assured and alternative capabilities. It is not clear what form these may take.

The Space-Based PNT programme was closed in 2022. A recent House of Commons debate has indicated that the government was stalled on the commencement of such a programme, calling for a strategy to act on the original Blackett report [57], and further verified by written evidence of Proctor [53]. Thus, the timeline for the delivery of a UK PNT alternative is uncertain. However, the extensive actions through numerous studies have indicated that some objectives have been achieved. There are also reports of a cross-government PNT office being established, but it is yet to be announced publicly [58]. Most developments towards Resilient PNT for the UK indicated in Section 4.2. PNT Policy Comparative Analysis are not part of a coherent approach formulated by a current policy position, but steps made by the encouragement of industry.

4.1.11 United States of America

As the original developer of radio navigation services, through TRANSIT and later the GPS, the USA is often viewed as the leader of GNSS technology and policy. GPS is the most common and sometimes primary and sole form of PNT information for military and civil users. However, the GPS is and remains an asset of the US Department of Defense, which, according to experts, provides little avenue for conversations on civilian needs. Thus, system capabilities are often predominantly developed with defence interests in mind.

By law the 'Secretary of Defense shall provide for the sustainment and operation of the GPS Standard Positioning Service for peaceful civil, commercial, and scientific uses on a continuous worldwide basis free of direct user fees' [59]. This law assigns coordination duties to assure that both Transportation and Commerce, as well as other departments, continue to receive PNT services of GPS.

Recent concerns over the GPS with regard to cybersecurity, jamming and spoofing, space weather and others have raised the importance of securing alternatives. The recent Trump Administration Executive Order 13905 on Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services, of 12 February 2020, seeks to address these concerns [60].

As a complement to this policy, the *National Research and Development Plan for Positioning, Navigation and Timing Resilience* was released by the White House's Office of Science and Technology Policy (OSTP) in August 2021 [61]. This R&D plan is viewed by the authors as the latest and more detailed PNT roadmap to date, with a strong emphasis on resilience.

The plan includes the most comprehensive list of government agencies and departments involved in its development, incorporating the Departments of Commerce, Defense, Energy, Homeland Security, Interior and Transportation, as well as NASA, the National Security Council and the Office of Management and Budget. Additional agencies are also included as supporting arms to the achievement of R&D objectives. The numerous perspectives consolidated into key areas of development have led to accommodation of far-reaching objectives compared to other nations.

The objectives of the plans are categorised into three stages, but appear to be implemented concurrently. Each stage includes characterisation and modelling, improvement and expansion, and integration and deployment. They seek to review existing infrastructures and the surrounding environment, improve on what is present, as well as to develop new technology. The list of goals is the most comprehensive found in available policy documents worldwide, and so is used as the basis for comparing the different objectives of each country treated in this study. Most have been paraphrased to a form that best reflects the countries treated.

Critically, what is not specifically referred to in the strategy of the USA is to develop national sovereignty of PNT. However, it is easy to argue that this is already achieved as the parent of GNSS and the home of the GPS. The *National R&D Plan* does explicitly refer to international collaboration on achieving resilient PNT with foreign governments and organisations [61]. All nations appear to also be considered within this context.

4.2. PNT Policy Comparative Analysis

In order to conduct a comparative analysis of the various policies and roadmaps listed in Table 1, the authors have extracted from them broad categories of actions or measures that can be taken to advance towards more resilient PNT services, such as developing a better understanding of PNT services and associated infrastructures, or fostering international collaboration on PNT utilisation. Then, within these categories, general action items were found across reviewed policies and strategies. These categories and action items are described below, followed by the comparison of all policies and roadmaps in Table 3.

As a baseline to this study, the USA's development plan categories are used as a baseline [61]. It is concluded by the authors that the objectives encapsulate the most common themes of resilient PNT policy documents from other nations. Having said this, several items have been added, or title adjusted, to include all relevant items to delivering resilient PNT.

The ticks in Table 3 indicate intention or progress towards completion of each listed component, as is disclosed in relevant public documents. Information that is not provided in any publicly released document, but is confirmed through interviews with experts, is denoted by a red tick. Some resilient PNT policies are more limited in their publicly distributed content, and include national administrations from China, Japan, Korea and Türkiye. However, this should not indicate that the policy is not well-developed, as it may be more developed internally. Every effort has been made by the authors to understand all aspects of the policy by speaking to experts.

Each theme and component are presented in italics below, A to C providing an increasing measure of advancement. O is a complementary field, providing indication of internal and external collaboration, and also the desire to be independent of other states or regions. A description is provided in normal text:

A. *Characterise and Evaluate*

   An initial step to a PNT policy must encapsulate at least some of these items.

   a. *Perform an economic assessment to the cost of disruption to PNT*
      To understand consequences of loss to PNT across various critical sectors for the support of policy implementation.
   b. *Characterise PNT needs and requirements of relevant market sectors*
      Usually by full market assessment, with objectives to understand the stakeholders, identify critical assets, and assess appreciation for protecting against PNT disruption.
   c. *Evaluate threats and vulnerabilities to current PNT systems*
      A general evaluation of the nation's threat landscape, by surveys, testing campaigns as well as assessment of the threats and vulnerabilities facing other nations and regions.
   d. *Understand existing technologies available that deliver PNT*
      Each technology reviewed would need to be sovereign to the nation. Roadmaps are established to assure that these technologies would be developed and deployed if not the case.

e. *Appraise test capabilities and test protocols for assessing PNT infrastructure, equipment and services*
   This is usually an internal procedure of the assessing agency.
f. *Assess tools to qualify performance of PNT equipment and services, both individually and as an integrated system*
   May include acquiring technical instruments for testing and development of methodologies and procedures.

B. *Improve and Expand*
Implementation of A., acting on internally addressed needs.

a. *Develop and improve internally-derived capabilities of PNT*
   Either government driven or sponsored. Refers to inertial sensor suites, such as inertial measurement units, atomic clocks and potential quantum technology, as well as benefits from state modelling and propagation.
b. *Develop and improve external sources of PNT, both man-made and natural*
   Either government driven or sponsored. Refers to existing and new space and terrestrial-based RF navigation, as well as employment of traditional celestial-derived PNT, such as sextants, pulsar observations and magnetometers.
c. *Establish quality assurance measures for a wide range of end users*
   Deployment of the internal tools evaluated and characterised in A.b. and A.d.
d. *Improve and expand disruption detection and mitigation methods*
   Jamming and spoofing tools, as well as mitigation algorithms, are encapsulated under this component.
e. *Prototype and demonstrate consumer equipment to adopt new PNT services*
   A general component to seek adoption of the newly developed items of components B.a.-B.d.

C. *Integrate and Deploy*
Seeks to integrate the multiple components to achieve resilient PNT for the nation.

a. *Determine concepts and techniques for securely integrating multiple sources of PNT services*
   Either government driven or sponsored. Development towards sensor fusion and selection of sources that are reliable and authentic.
b. *Development of common hardware platforms and signal standards, if appropriate, for multiple sources of PNT information*
   Either government driven or sponsored. GNSS is highly standardised - similar approaches should be developed for other PNT information sources.
c. *Develop resilient PNT system architectures and frameworks*
   Either government driven or sponsored. Defining and developing what is required to declare resilient PNT has been achieved.
d. *Investigate using internal sources as primary sources of PNT service*
   Either government driven or sponsored. Presently, internal sources are treated as a secondary source, and so is not a source of PNT certainty. A rigorous assessment is required to determine if this declaration can be modified.
e. *Develop cybersecurity standards, best practices, and other guidance to achieving resilient PNT*
   Cybersecurity concerns are increasing in recent years, and new calls have been made for their assessment.

D. *Collaborate and Coordinate*
As with previous efforts for GNSS through UN ICG, similar collaboration and coordination attempts should be made for new PNT information sources and achieving resilient PNT, a common problem facing nations and regions.

a. *Internal coordination and collaboration between government actors*
   Internal coordination through a relevant office or department to collaborate between relevant government actors that hold concern for resilient PNT.

b. *International cooperation and adoption of resilient PNT systems*
   Seeking partnerships between nations on these topics, to develop universal standards.
c. *Develop national / regional sovereignty in PNT*
   Sovereignty concerns given the criticality of this technology for the functioning of society. The nature of when sovereignty is achieved is unclear.

Table 3. Comparison of policies and roadmaps. Ticks in red indicate that not all information has been released in public documents.

PNT Resilience Policies/Plans Components		AUS	CAN	PRC	EU	IN	JP	CIS	ROK	TU	UK	US
Theme	Component											
Characterise Evaluate	Perform an economic assessment to the cost of disruption to PNT		✓								✓	✓
	Characterise PNT needs and requirements of relevant market sectors	✓	✓	✓	✓	✓		✓			✓	✓
	Evaluate threats and vulnerabilities to current PNT systems	✓ (red)	✓		✓	✓	✓	✓			✓	✓
	Understand existing technologies available that deliver PNT	✓	✓ (red)		✓			✓		✓	✓	✓
	Appraise test capabilities and test protocols for assessing PNT infrastructure, equipment and services	✓ (red)			✓		✓	✓			✓	✓
	Assess tools to qualify performance of PNT equipment and services, both individually and as an integrated system	✓ (red)		✓				✓			✓	✓
Improve Expand	Develop and improve internally-derived capabilities of PNT	✓		✓				✓			✓	✓
	Develop and improve external sources of PNT, both artificial and natural	✓		✓	✓			✓	✓		✓	✓
	Establish quality assurance measures for a wide range of end users	✓ (red)						✓			✓	✓
	Improve and expand disruption detection and mitigation methods	✓ (red)	✓		✓	✓	✓	✓			✓	✓
	Prototype and demonstrate consumer equipment to adopt new PNT services	✓ (red)		✓	✓	✓		✓			✓	✓
Integrate Deploy	Determine concepts and techniques for securely integrating multiple sources of PNT services	✓		✓		✓		✓		✓		✓
	Development of common hardware platforms and signal standards, if appropriate, for multiple sources of PNT information	✓		✓		✓		✓		✓		✓
	Develop resilient PNT system architectures and frameworks	✓		✓	✓			✓		✓	✓	✓
	Investigate using internal sources as primary sources of PNT service	✓		✓	✓							✓
	Develop cybersecurity standards, best practices, and other guidance to achieving resilient PNT	✓ (red)		✓		✓	✓	✓			✓ (red)	✓
Collaborate Coordinate	Internal coordination and collaboration between government actors	✓	✓	✓	✓		✓				✓	✓
	International cooperation and adoption of resilient PNT systems	✓		✓			✓		✓		✓	✓
	Develop national / regional sovereignty in PNT	✓		✓	✓	✓	✓ (red)		✓	✓	✓	✓

5. Common Themes and Issues

5.1 Public-Private Partnerships for PNT

As provided in Sections 1 and 4 of this work, GNSS has primarily been developed as a government, public or militarily owned system. The private industry might be contracted to deliver systems or operations to GNSS, but the service itself is developed for the public and/or the military. As has been highlighted by various state actors however, to achieve resiliency, new models of delivering GNSS for society may be required.

The concept of Public-Private Partnerships (PPP) have been increasingly popularised in recent decades worldwide, where industrial actors are invited and encouraged to become more involved in the delivery of public services. The participation may involve the inclusion of private financing to develop social infrastructure, where a return is expected in the form of taxes or service fees, contracted services, or the privatisation of public infrastructure or industries. The view is that these initiatives will enhance social infrastructure and be more cost-efficient with public money [62]. The concept and modalities of PPPs vary strongly from country to country, and even within one country, being an umbrella term encompassing different public-private interactions for the delivery of a service, including long-known arrangements such franchises, concessions and *affermage* [63].

In the space sector, PPPs have become popularised by NASA and the USA, especially in regard to space exploration. The extension of ISS operations to 2030 has encouraged private space actors to explore commercial research and development. The Moon-to-Mars roadmap has led to a number of programmes where NASA will partly contract private companies to develop spacecraft for lunar operations, the rest being funded by privately acquired investment. Other examples also exist for communication and Earth observation - the question is if such PPP are possible for PNT?

PPPs were initially discussed as the preferred approach to deliver the European GNSS, Galileo, a constellation developed for civilian use and with requirements that are not primarily driven by defence stakeholders. However, future profit making was not clear from industry, nor did EU countries have the necessary legal and procedural frameworks to realise PPP for Galileo [64].

Government administration of PPPs is a hurdle that could be overcome by sufficient planning, however, the issue of financing PNT through service fees is more significant. Studies and policy reviews by Canada, the USA and Australia, as discussed in Section 4, have highlighted that the private industry is aware of issues regarding resilience, but the issue is often regarded as 'out of sight, out of mind'. Stakeholders would not be prepared to allocate budget to meet resilient conditions.

PPP must primarily be driven by the government for PNT. Such courses to remedy issues in PPP include:

- Development of codes and laws that require industry to utilise resilient PNT. This would then encourage industry to meet their responsibilities, to be delivered as part of a PPP. However, this state required investment may lead to fierce opposition by industry.
- Implementation of an R&D programme to develop resilient PNT technologies. PPP methodologies are implemented as part of the programme. Future export potential to satisfy policy objectives of other countries in terms of PNT resilience and sovereignty, a topic discussed in Section 5.4.

Overall, the case for the development of PNT services through PPP remains to be made. In the absence of clear benefits from service provision by commercial actors, private PNT systems may need to be subsidised for instance through a contract for delegation of services (e.g. garbage disposal).

5.2 Clarifying Government Responsibilities

A theme in the development of PNT policies, especially in terms of resilience, is the high variability in government responsibility. Many leading actors in the development of PNT policy among state governments are aware of the necessity for engagement across departments, however they are often met with barriers. These may be due to a lack of expertise in their respective departments, or to the consideration that the issue is not of sufficient importance to allocate resources. There is also confusion at national level on who should bear the responsibility, often redirecting it between departments and agencies.

The various roles of different departments are addressed in Table 4. Only those agencies and departments that are quoted by the national plans or policies, or that have been officially identified as part of the domestic coordination process are used in the table. As different governments have different ministries or departments, the authors have not directly compared institutions but rather whether relevant entities in charge of specific areas of governmental action were consulted (e.g. ministry/agency in charge of transports, economy, science or space).

Comparing Table 4 with the developed policy positions signified in Table 3 and strategies discussed in Section 4.1, it might be concluded that a more cohesive plan has been developed by increasing the stakeholder base. However, this will also need to be strengthened through expertise within each department. It is also highly dependent on existing relations between departments and administrative bodies. A strategy and plan is only developed when a relevant party has been created and developed. The Canadian PNT Board, as an internal federal government collaboration initiative, is regarded by the authors' as one of the most rigorous and comprehensive, owing to the dedicated unit for bringing the government stakeholders and PNT initiatives together. Some of the relevant departments have also contributed funding to its creation.

Table 4. Organisations consulted as part of Resilient PNT policy creation.

Country	Coordinating Administration	Administration responsible for:						
		Agriculture / Fishery	Security and Defence	Natural Resources	Transport (incl. aviation and maritime)	Economy, Industry and Business	Science, Research and Innovation	Space
AUS	Geoscience Australia		✓	✓		✓	✓	✓
CAN	Innovation, Science and Economic Development	✓	✓	✓	✓	✓	✓	✓
EU	Joint Research Centre							✓
IN	Department for Space	Undefined domestic coordination process						✓
JP	Cabinet Office	?	✓		✓	✓	✓	✓
ROK	Ministry of Science and ICT	Undefined domestic coordination process					✓	✓
UK	Department of Science Innovation and Technology		✓			✓	✓	✓
US	National Science and Technology Council		✓	✓	✓	✓	✓	✓

5.3 PNT beyond MEO GNSS

Given PNT resilience is of strong importance to many world governments, R&D is often seen as one of the next steps to deliver action. However, it has been pointed out by experts that solutions have already been developed and exist. A concept presented is a 'system-of-systems' approach to delivering PNT resilience [15], utilising existing and implementing new systems to augment and back-up a primary PNT system (which often is GNSS).

To highlight one of these, terrestrial radio navigation systems, primarily eLORAN, but also maritime VDES and 5G network towers, have been highlighted by some governments. Countries with large geographical distances and sparsely spread populations, such as Russia, are one of the strongest proponents of this approach. A similar nation in geographical area and populated in small areas is Australia, but space has been suggested to be much more firm to their strategy.

A more pioneering solution to solving challenges of resilience is the creation of new types of space-based navigation beyond the traditional MEO-based GNSS. The concept is commonly referred to as LEO PNT, and incorporate a variety of approaches:

- Dedicated constellations providing only PNT services (e.g. Xona Space Systems).
- Signals of opportunity from existing LEO communication constellations (e.g. StarNav).
- Hybrid solutions where the LEO constellation may host an additional payload or share signal bandwidth to deliver a ranging signal (e.g. as studied for OneWeb).

Systems boast advantages such as improved orbit diversity, greater signal power, strong Doppler tracking by faster orbital velocities, these systems still rely on GNSS signals and frequencies, as well as MEO-based infrastructure. Some of these delivered systems may operate independently of GNSS infrastructure, signal structure and/or frequency, and may not be open to the public. Their dependence and likeness to GNSS will decide if they could act as an alternative or back-up system. Otherwise, they could only serve as an augmentation. Their system classification would depend on the sector they are adopted in, with maritime [65] and aviation [66] markets adopting separate radionavigation standards, for example. Xona Space intends to utilise GNSS receivers on board the satellite, and so would still be inoperable if a cyber-attack targeted GNSS, as well as any form of space-based attack.

Out of these various factors, two clear decisions are being treated by governments, to either adopt a space-based or terrestrial-based technology adoption, and if adopting a space-based approach, whether to develop traditional MEO GNSS in an elliptical orbit or to develop new PNT systems. The first decision should be an argument encouraged by two factors, geospatial, in terms of geography and population distribution, and space utilisation heritage. The second decision lies in the technological roadmap of LEO PNT, which is yet to be realised.

It is highlighted by the authors that developments in LEO PNT should be considered in parallel to new PNT infrastructure for the Moon [67], [68]. Similar technology would need to be developed for both scenarios, and both applications can be treated as test grounds for the other. However, this topic has not been treated by the literature.

5.4 Sovereignty

The analysis of Section 4 frequently refers to a nation's desire for independence, control, self-sufficiency or 'sovereignty' over GNSS. As discussed, GPS remains an asset of the US Air Force, and so as the importance of GNSS was realised by both defence and commercial sectors, many countries did not wish to depend on the USA for delivery of PNT. This has since prompted governments to explore and develop their own systems. However, to what degree does a nation seek sovereignty over GNSS and PNT? What is sovereignty?

The term 'sovereignty' has been under frequent study and debate since the 17th century, when the concept of the nation state was also starting to develop. Philosophers John Locke, Thomas Hobbes and Jean-Jacques Rousseau have written lengths on the topic, forming part of theory to the social contract that citizens of a state subscribe to, entrusting power to a government for common protection and societal development. Sovereignty has since formed part of constitutions in the USA, France and China, amongst many other nations, forming what is known as popular sovereignty, where power rests with the people and to the nation's leadership and government.

In international law, sovereignty is the essential quality that all states should have supreme control over their internal affairs. It is subject though to the agreed, but perhaps not ratified, limitations imposed by international law, such as rules for forbidding the use of force or the international law of human rights. The concept of state sovereignty has been outlined in the Declaration on the Principles of International Law (Resolution 2625). A specific aspect of interest to technological sovereignty is that no state or international organisation may intervene in matters that fall within the domestic jurisdiction of another state.

So, for the context of GNSS, and what sovereignty might mean, it would mean supreme control and authority over the system, and that no other state should interfere with its use. This can then be interpreted to mean that a state desires the system capability, but not also the ability to develop. Resilient PNT roadmaps include R&D of the technology internally, however, in the interest of sovereignty, this would not be necessary.

Sovereignty might mean control over ground stations and terminals, choice of signal format or content, the ability to manufacture space-based PNT satellites, or merely the fact that a government is agreed to be the primary stakeholder. Each form would require some degree of knowledge dissemination from those that develop the system, but this might be all that is sufficient for the nation. The terms are then under negotiation and for the authority to which it lies.

Some nations have acquired through commercial procurement from other nations different systems of PNT, such as the Australian and New Zealand SBAS system SouthPAN from the American Lockheed Martin and the Spanish GMV, and the Korean satellite navigation system KASS from the European Thales Alenia Space. This might suggest that this interpretation of sovereignty carries some weight, as long as some degree of authority over the system is delivered by these acquisitions. The UK Ministry of Defence uses a concept known as 'Assured Capability' to govern their acquisition of new technology.

The interesting aspect of PNT sovereignty raised in this review is to act as a means to achieving PNT resilience, the main overarching goal of the policy. By governments achieving the desired control and authority of the system, they look to deliver resilience. However, achieving resilience does not necessitate sovereignty, nor vice versa. The authors consider sovereignty to be distracting from the goals and ambitions of achieving resilient PNT, especially given recent procurement activities of some nations treated in this review.

6. Conclusions

It appears in this article that the issue of PNT resilience has yet to appear on the political agenda of numerous countries. Even for the most advanced space nations, it remains a topic of lesser importance in discussions related to national security and critical infrastructure protection, despite a consensus within expert circles and the availability of mature technologies for the provision of resilient PNT services. This issue did not permeate at the highest levels of decision-making, nor at government departments or agencies where the extreme reliance of PNT services is generally understood. Numerous factors can explain the dissonance between the importance of this issue and its lack of existence in policymaking.

First, even within expert circles, there is no general agreement on the definition of the concept of resilience and *a fortiori* PNT resilience. As described in section 3, numerous terms (e.g. resilient PNT, robust PNT, assured PNT, augmented PNT) not only coexist but are used interchangeably in policy and programmatic documents. As such, knowledge exchange and benchmarking among countries is made extremely difficult. It is also challenging for government officials and politicians to introduce ambitious and costly policies on concepts that are not well understood and defined. Although it does not have the ambition of carving the authors' definition of PNT resilience into stone, this paper however tries to contribute to clarifying the understanding of and approach to PNT resilience of major space powers, acknowledging other efforts by professional bodies such as IEEE to achieve harmony and unification.

Second, a hurdle faced by the promoters of PNT resilience lies in the functioning of the government. PNT resilience is inherently a cross-governmental issue: PNT services can be provided by a wide range of space-based and ground-based technologies and are used by all types of sectors, virtually involving all possible ministries. Therefore, comes the question of who would pay for research and implementation of solutions for PNT resilience. The entity responsible for space affairs? Numerous capabilities and infrastructure are ground-based. Users? They span across the whole of government. National security authorities? Most PNT services are used for civil and economic activities. PNT resilience is a typical hot potato issue which gets tossed around in government, unless taken over by the highest level of decision-making like in the US.

Third and last, PNT services remain too strongly associated with space. For most decision-makers and officials in the government, PNT services are only provided by GNSS, and it is perceived as sufficient for national and economic security to have a functioning and fairly resilient GNSS, including the possibility to rely on PNT services provided by allied or partner GNSS. Alternative PNT systems - the term itself confirming the pre-eminence of space-based PNT - are often seen as secondary, if not superfluous. Very little studies have been conducted by governments to assess whether space-based PNT is the best approach for the nation or at least if it is sufficient.

The three points above do not constitute an exhaustive list of issues hampering the development of serious considerations on PNT resilience by the governments of major powers, including the can of worms that is 'sovereignty', but are considered by the authors to be those of highest complexity and importance.

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