National Committee for Space & Radio Sciences
Australia in Sapce: Space-based PNT

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Vision

By 2030, Australia will be seen as a sophisticated user of space-based positioning, navigation and timing (PNT) technology. Our sovereign PNT infrastructure and skilled workforce are world class, underpinning and stimulating the growth of the broader economy. We have the ability to deliver and use superior PNT information to make intelligent decisions and make sense of the complexity of the world we inhabit, which are supported by resilient access to timely, reliable and accurate PNT information.

Space-based positioning, navigation and timing (PNT) technology is *critical infrastructure that* underpins many scientific, commercial and personal user applications (see https://www.gps.gov/applications/, https://www.ga.gov.au/scientific-topics/positioning-navigation/positioning-australia). Furthermore, it is expected that society's reliance on accurate, available and reliable PNT information will continue to expand rapidly over the coming decade. This increased *reliance* on PNT as critical infrastructure underpinning many economic-, social-, scientific- and security-related activities brings into sharp focus a number of issues related to *vulnerabilities*, and *shortcomings*, of space-based PNT technologies and services. This is of particular concern for Australia due to its unique characteristics – large area, important primary industry, location, small and concentrated population, PNT space technologies are operated by other countries. Hence Australia must invest in PNT systems that address Australia's diverse PNT requirements as well as building resilience in the event of space-based PNT capabilities are compromised.

The NCSRS has an interest in space-based PNT with respect to the *science priorities* for both the upstream and downstream components of the value chain in Australia. These include the development of satellite and augmentation systems, the user-end and system-level hardware and software components, the user-end signal and measurement processing algorithms and methods, the infrastructure and services for improving PNT capability, and specific user application scenarios both in the civilian space and defence that require input or investment by Australian space science researchers, industry and other organisations.

In this brief note it is not possible to mention (let alone detail) all of the PNT activities being undertaken in Australia, or to make a complete list of recommendations with regards to a PNT R&D agenda. What are listed are some of the science challenges that are associated with ensuring the delivery of a national space-based PNT capability that addresses today's, and future, requirements for accurate, reliable and resilient PNT information in the Australian region – its maritime areas as well as New Zealand and other neighbouring island states.

GNSS Today

Global Navigation Satellite Systems (GNSS) are at present the sole means of delivering a global PNT capability to users, with suitably equipped receiving equipment, to a *base-level* positioning accuracy of a few metres and timing accuracy of tens of nanoseconds.

The term GNSS refers to the various constellations of satellites that broadcast signals in predominantly the L-band frequency of the electromagnetic spectrum. When these signals are tracked by GNSS receivers, base-level PNT capabilities are available to all users 24/7 anywhere in the world. However with advances in receiver technology, operational procedures and measurement processing, GNSS positioning information can be *substantially improved* – to the sub-centimetre-level positioning accuracy, instantaneously, even when the user receiver is moving. Calculation of the Coordinated Universal Time (UTC) and time dissemination services using GNSS at better than the nanosecond-level is achievable. This *enhanced* PNT performance is extremely important for a number of user communities.

Today's GNSS receiver may track signals from most (if not all) of the following satellite constellations: the U.S.'s GPS, the Russian Federation's GLONASS, the E.U.'s Galileo GNSS, China's BeiDou GNSS, and region-based augmentation systems such as the Australian and New Zealand Space-based Augmentation System (SBAS), Japan's Quasi-Zenith Satellite System (QZSS), India's Regional Navigation Satellite System (NavIC). Over 140 satellites are broadcasting GNSS signals. With society's increasing reliance on GNSS-derived PNT, the myriad issues associated with the *accuracy*[1], *availability*[2], *continuity*[3] and *integrity*[4] of PNT information become paramount.

GNSS Market

The global GNSS downstream market continues to grow rapidly. Based on the report of the European Global Navigation Satellite Systems Agency (GSA) 2019 GNSS Market Report, the global installed base of GNSS devices in use is forecast to increase from 6.4 billion in 2019 to 9.6 billion in 2029, while global GNSS downstream market revenues from both devices and services are set to grow from €150 billion in 2019 to €325 billion in 2029. The GNSS market growth will be further stimulated by *global mega-trends* such as digitalisation, big data, the sharing economy and Artificial Intelligence applications that use GNSS for PNT. From the perspective of science, GNSS technology can also contribute towards tackling socio-economic challenges by supporting environmentally friendly transport solutions, natural hazards disaster risk mitigation and response, sustainable agriculture, meteorological and climate monitoring, as a tool of the geosciences, and others.

A recent economic study by Ernst and Young (EY) has found that *improved PNT capability* for Australia and New Zealand through an SBAS technology is expected to

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Based on the required navigation performance (RNP) specifications:

[1] Definition of Accuracy: The accuracy of an estimated or measured position at a given time is the degree of conformance of that position with the true position, velocity and time.

[2] Definition of Availability: Availability is the percentage of time that the services of the system are usable by the user.

[3] Definition of Continuity: The continuity of a system is the ability of the total system (comprising all elements necessary to maintain user position within the defined area) to perform its function without interruption during the intended operation.

[4] Definition of Integrity: Integrity is the measure of trust that can be placed in the correctness of the information supplied by the system.

deliver more than $6.2 billion in benefits for Australia, and more than $1.4 billion in benefits for New Zealand, over the next 30 years. General benefits of an operational SBAS include wider coverage, enhanced accuracy, signal integrity and reduced commercial costs and infrastructure investment.

Assured GNSS-PNT

Assured GNSS-PNT is in many respects a form of augmented GNSS. *Augmentation* refers to improvements at the system or user level that enables suitably equipped users to derive PNT information at the level of accuracy, availability, continuity and integrity appropriate for their application, and in general at higher levels than GNSS base-level specifications. *Assured PNT* protects the users, ensuring that trustworthy PNT information is available to critical user applications. The science and research community has a significant role to play in the coming years in enhancing GNSS performance, e.g., by contributing to the development of assured and resilient PNT systems.

The quest for high accuracy (e.g., over long periods of time) GNSS has been a long-term emphasis of the GNSS R&D community for supporting science and user PNT applications. For example, Geoscience Australia is able to utilise GNSS data measured from the *Continuous Operating Reference Stations* (CORS), to estimate the relative locations of points up to several thousand kilometres apart with an accuracy of several millimetres. Today, enhanced GNSS performance is required by demanding *safety-of-life and mission-critical applications*, such as those relating to deployment of fully automated and connected land vehicles. For these applications, high availability, continuity and reliability of services, in addition to high accuracy, are critical to ensure *safe and reliable navigation*. Hostile cyber operations such as *jamming*[5] and *spoofing*[6] of GNSS signals are a growing concern due to the serious disruption to society that they may cause. Developing PNT technology able to address other GNSS shortcomings, such as its unsuitability for providing PNT information in *indoor environments*, is an additional challenge.

GNSS Priorities and Challenges for Australia

Geoscience Australia

Geoscience Australia (GA) is primarily responsible for the (civil) *Australian National GNSS infrastructure* to deliver augmented GNSS services. It will do this via several strategic initiatives:

- Deliver a SBAS capability to enable accurate positioning to the decimetre-level across Australia and New Zealand, and surrounding maritime regions, as well as improving the integrity of GNSS for civil aviation applications.
- Develop a robust, open, real-time national GNSS tracking network. This state-of-the-art ground infrastructure to track, verify and optimise data for high accuracy positioning (3-5cm accuracy) across the Australasian region of operations.

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[5] Jamming refers to the interruption of a receiver's receiving electromagnetic signals from a satellite by using a signal with the same frequency but with significantly higher power. The aim is to overpower the extremely weak GNSS signals so that the GNSS receiver cannot track them. Jamming is a synonym for intentional interference.

[6] Spoofing refers to transmission of fake signals, i.e., mimicking of the characteristics of a true signal, so that the user receives the spoofed signal instead of the real one. The aim of spoofing is to mislead a GNSS receiver.

- Develop an open source software toolkit for the real-time analysis of space geodetic observations to, e.g., estimate precise satellite orbit and clock behaviour as well as other bias parameters.
- Deliver augmented GNSS correction message streams to enable real-time precise positioning across the Australasian region of operations.
- Continue to develop and maintain the *Australian Geospatial Reference System* (AGRS) – Australia's 3D coordinate system that underpins all spatial and mapping data.
- Contribute to the maintenance of the *International Terrestrial Reference Frame* (ITRF), through GA's extensive geodetic infrastructure: Australia's GNSS tracking network, Australia's Satellite Laser Ranging (SLR) network, and (in partnership with the University of Tasmania) Australia's Very Long Baseline Interferometry (VLBI) network.

Science Priorities

Science underpins all GNSS technologies and applications. These range from fundamental physics (time, relativity, quantum technologies, electromagnetic propagation, surface reflections, etc), Earth observation, geoscience and space weather applications, through to space engineering, signal processing, hardware and software development, robotics and automated systems, consumer devices, etc. Several science priorities arising from space-based PNT are listed below:

- Operationalising continuous, real-time, high fidelity *Earth and climate change monitoring*, and for geoscience research and activities in general.
- Generating an accurate record of the absolute and relative sea level in Australia as well as countries throughout the Pacific.
- Facilitating the use of GNSS receivers aboard satellites, in all orbits, and even on missions beyond Earth orbit, for so-called *space service volume navigation*.
- Continued development of GNSS receivers for *CubeSats*, to support more applications of small satellites for communications, Earth observation and PNT.
- GNSS *meteorology* can measure moisture, temperature and pressure using ground receiver networks and/or space systems for real-time monitoring of the atmosphere.
- GNSS *reflectometry* uses reflected GNSS signals from land, ice and water surfaces, tracked by modified ground or spaceborne GNSS receivers to measure soil moisture, surface wind speed and direction, detect ships and oil spills, and more.
- Answering fundamental unresolved Earth science questions. *Improvements in GNSS precise positioning techniques will enable a shift in geodetic science focus from observing secular steady state processes to observing dynamic time-varying transient processes*. Delivering this capability to monitor the Earth's ever-changing shape on a second by second basis with millimetre accuracy make tractable a range of important questions such as:
    - How are ice sheets, oceans, and the solid Earth coupled in space and time?
    - How is the terrestrial storage and the global water cycle changing with time?
    - How do fault mechanics and Earth rheology interact to influence the occurrence of earthquakes and the earthquake cycle?
    - How do solid Earth's material properties vary in space and time?

- What can observations of surface deformation reveal about magmatic processes and volcanic hazard?
- What is the connection between solid Earth processes and surface and landscape evolution?
- What do real-time approaches promise for geohazard forecasting, warning, and rapid response?

National Priorities, Challenges and Opportunities
Additional priorities, challenges and opportunities can be identified:

- Exploring unique opportunities offered by Australia's early deployment of *next generation SBAS capabilities*, such as Dual-Frequency Multi-Constellation (DFMC) and Precise Point Positioning (PPP).
- Delivering GNSS products that contribute to our understanding of the atmosphere for weather forecasting, climatological studies, and the behaviour of the ionosphere and space weather.
- Encouraging the adoption of GNSS-PNT capabilities that contribute to the UN SDGs.
- Monitoring of satellite navigation system performance across the Australian region for all users.
- Augmenting the GNSS space segment, e.g. using low earth-orbiting satellites.
- Developing products and services essential for ensuring *assured* PNT information for mission-critical and safety-critical PNT applications such as automated industrial machines, driverless vehicles, etc.
- Design and implementation of sub-metre (and even decimetre-level) accuracy GNSS systems based on low-cost mass-market GNSS receivers, enhanced via *5G telecommunications* infrastructure delivering augmentation information for enhanced accuracy and integrity.
- Collaborating on national and international GNSS *interoperability* and *compatibility* of all GNSS signals and services, as well as *industry, spectrum and geodetic standards*, including continued engagement with international forums such as the UN's GGIM and ICG, ISO, ITU, RTCM, RTCA, and others.
- Developing an industry strategy to facilitate development of high-tech GNSS-related products and services by local companies and organisations.
- Investing in training and education so that Australia will have the workforce able to take advantage of the opportunities of assured PNT.
- Supporting GNSS-related research in universities and other research organisations, including translation of research into products and services.
- Encouraging research, development, and commercialisation of PNT technologies that complement GNSS. These include new inertia sensors, terrestrial ranging systems, vision and imaging sensors, signals-of-opportunity, and others.
- Embracing digital transformation to fuel innovation in a data-driven society. This innovation will be underpinned by technological advances in the areas of Artificial Intelligence, the Internet of Things, digital connectivity (such as 5G), cloud computing, data analytics, and access to PNT and geospatial information.

Concerns and Threats
Cybersecurity

Interference (intentional or otherwise) and *spoofing* of GNSS signals is a topic of growing concern, globally as well as in Australia. The denial of PNT (or provision of falsified PNT) information is a significant concern. If unmitigated, these threats have the potential to undermine societal use of PNT technology and impact dependent science activities[7]. Cybersecurity is therefore one of the most critical threats to GNSS-PNT availability, integrity and resilience. A number of strategies will need to be implemented in order to detect and mitigate sources of denial of GNSS-PNT capabilities. Some will be organisational, though many will be technical. The need to develop and incorporate safeguards into GNSS-PNT reliant infrastructure and services requires significant work. Considerable work is underway, e.g., GA is liaising with ACMA, the Department of Home Affairs, Department of Defence and relevant security agencies on appropriate regulatory and enforcement responses.

Resilient PNT
Ensuring the resilience of critical infrastructure such as PNT to respond to emerging challenges and threats is critical challenge. *Resilient* PNT is the convergence of traditional PNT technology with non-traditional and emerging technology to improve the reliability, performance and safety of critical applications. Resilience offers assured PNT information by protecting, authenticating and offering alternatives sources to the dominant GNSS-PNT technology. There are currently some investigations underway regarding risks to infrastructure and supply chains.

It is acknowledged that reliance on GNSS alone for many applications (especially those in urban environments where buildings block GNSS signals and therefore significantly reduce PNT availability) is not possible. PNT will have to be provided by multi-sensor systems, requiring ongoing R&D as well as investment in “testbeds” for promising non-GNSS technologies, e.g. Locata positioning technology. Furthermore DST has established the Science, Technology and Research (STaR) Shots program to focus strategic research and proactively develop new leap-ahead Defence capabilities. One of the strategic priority is explore the use of quantum technologies and demonstrate a prototype quantum-assured PNT system independent of GNSS. It is intended to address assured PNT requirements in all domains.

Sovereignty
The issue of *sovereignty* when using unencrypted broadcast GNSS signals from foreign-owned and operated satellite constellations is intrinsically tied up with the two issues mentioned earlier: (1) GNSS vulnerability to interference and spoofing, and (2) limits to GNSS availability in indoor or urban environments. Sovereignty is therefore is related to PNT resilience. Resilience can be increased when the PNT infrastructure (signals, message broadcast channels, etc) are under state control. Non-GNSS PNT technologies are ground-based technologies that are better able to be “protected” than satellite systems. Furthermore they are not just complementary to GNSS (able to be used when GNSS is unavailable), but may also be alternatives to GNSS for PNT under certain scenarios. Hence addressing the challenge of indoor positioning (which is not possible using GNSS) so as to ensure a *seamless* transition

[7] The impact on Timing (as it provides necessary synchronisation electrical power networks, mobile telecommunications, computer and financial systems, civilian time transfer, science applications, etc) is even more insidious than in the case of Positioning.

from outdoor positioning using GNSS to indoor PNT will also increase PNT resilience and the degree of sovereign control.

Research, Education and Training
An insufficiently skilled workforce is a clear and present threat to PNT research, development, commercialisation and systems operation. Australia's critical space-based PNT infrastructure and systems relies heavily on access to a highly skilled and trained workforce. Without an increase in resources allocated to STEM education and training of the next generation PNT scientists and engineers, Australia runs the risk of limiting its ability to take full advantage of emerging opportunities being afforded by the rapid growth in PNT technology and its many downstream applications. Hence addressing the workforce challenges will go some way to addressing both the resilience and sovereignty issues mentioned above.

Recommendations
The WG proposes three recommendations.

Recommendation 1: PNT Resilience

Insight	Aspiration	Actions	Impacts	Metrics
Australia's increasing reliance on PNT in critical applications will require increased resilience in associated infrastructure and services. The research community has a significant role to play in improving PNT resilience.	Australia has improved the security and resilience of our space-based PNT infrastructure to protect and ensure continuity of services to businesses, governments and the community at large.	1. Build resilient GNSS-PNT infrastructure able to detect and mitigate vulnerabilities such as signal interference and spoofing and cybersecurity attacks. 2. Promote the development of alternative (non-GNSS) PNT technology. 3. Invest in R&D in academia, government and industry. 4. Promote the development and commercialisation of resilient PNT products and services.	1. PNT that can be relied upon for safety-critical and mission-critical user applications. 2. Impact of denial of PNT service (either intentionally or unintentionally) is minimised. 3. Australian science, industry, and society in general, benefits from access to fit-for-purpose PNT information	1. Minimum disruption of critical science and societal activities due to denial of access to assured PNT. 2. Increased sales of Australian-developed PNT products and services. 3. Increased skilled PNT educated workforce.

Australia's increasing reliance on PNT for critical applications will require increased resilience in associated infrastructure and services. It is therefore necessary to implement measures that build PNT resilience. These include: monitoring the performance of GNSS systems; protecting PNT infrastructure against cyber attacks; understanding the impact of PNT service denial on different user communities; and encouraging the development, testing and implementation of back-up or alternative PNT technologies, including those not based on GNSS. In seeking solutions, the defence and security agencies should cooperate with the civilian industry sectors and universities.

Recommendation 2: Sovereignty

Insight	Aspiration	Actions	Impacts	Metrics
The sovereignty of PNT infrastructure is an increasingly critical issue. PNT that is accurate enough available where needed, and trustworthy requires that all aspects of PNT technology and services are able to be monitored, and ideally be under the control of an Australian entity (or entities).	Australia will have improved sovereign access to PNT infrastructure and services through: 1. Improved understanding of the impacts of PNT capability denial on all user sectors. 2. More development and implementation of the fundamental GNSS technology is developed and/or implemented by Australian agencies. 3. Development and deployment non-GNSS PNT products and services be developed, tested and deployed in "hotspot" mode to support safety- and mission-critical applications.	1. Scrutinise the degree of vulnerability of scientific, industrial and personal PNT applications to disruption. 2. Engage with the R&D communities (academic, government, industry) to develop more local PNT infrastructure, products and services. 3. Monitor overseas developments in this area. 4. Coordinate implementation of GNSS and non-GNSS technologies, products and services across states and industry sectors to ensure interoperability of PNT systems.	1. PNT information can support safety-critical and mission-critical user applications. 2. Impact of denial of PNT service (either intentionally or unintentionally) is minimised. 3. Australian science, industry, and society in general, benefits from access to fit-for-purpose PNT information. 4. Affordable, trustworthy, PNT information of a suitable quality and assurance is also available indoors.	1. Increased levels of R&D across all PNT systems including increased focus on non-GNSS PNT. 2. Growth in the Australian PNT industry. 3. Increased value of Australian-produced PNT products and services. 4. Increased sophistication of PNT use in critical environments (that are not easily serviced by GNSS, such as urban and indoors) through use of appropriate non-GNSS PNT systems.

The sovereignty of PNT infrastructure is an increasingly critical issue. Little of the PNT infrastructure is under the control of Australian entities. Addressing this weakness requires a multi-faceted response. The Australian SBAS is one of the few examples of GNSS infrastructure that is an exception to the above. Australia should support the development of PNT products and services (based on GNSS and non-GNSS PNT technologies). This would require strategies for, e.g., industry development; increased R&D by universities and other research organisations; improved cooperation between different agencies and industry sectors; as well as addressing some of the issues raised by Recommendation 1.

Recommendation 3: Workforce Capacity

Insight	Aspiration	Actions	Impacts	Metrics

An insufficiently skilled and trained Australian workforce is a threat to PNT research, development, commercialisation and system operation.	Australia has a highly skilled workforce of PNT scientists and engineers. Australia is able to take full advantage of emerging opportunities being afforded by the rapid growth in PNT technology, and its many downstream applications.	1. Ensuring STEM education and training of a PNT-literate workforce with the knowledge, skills, and creative problem-solving capabilities and digital literacy to meet the demands of the industry, government and academic sectors. 2. Engaging with peak bodies to identify skill and capability gaps. 3. Fundamental R&D in geodesy, space science, and spatial skills, and others. 4. Equipping science graduates with new skills, e.g. in business, entrepreneurship, finance, law, etc. 5. Enhancing collaborative partnerships strategies between government, universities and industry sectors to stimulate broader socio-economic growth. 6. Supporting and promoting diversity and inclusive STEM education.	1. A knowledge-based economy - Australia is able to capitalise on scientific discoveries, basic and applied research. 2. A vibrant space-based R&D and PNT industry in Australia. 3. Leveraging Australia's unique position to create new innovations in PNT products and services. 4. Knowledge and technology transfer - Australia to be known as a key sector leader in PNT and space science in the region.	1. Skills needs and gaps in PNT and space science are understood by policy makers, peak bodies and education providers; and addressed through targeted strategies. 2. There is a long-term stable pipeline of investment in PNT research and education. 3. Australians working in PNT R&D are equipped with relevant skills, knowledge and training to drive and thrive in Australia's PNT industries. 4. Recruitment of home grown highly skilled and trained STEM workforce. 5. An integrated national space science PNT innovation and education strategy with co-partnership with government, universities and industry sectors.

An insufficiently skilled and trained Australian workforce is a threat to PNT research, development, commercialisation and system operation. Such a threat will prevent Australian companies and agencies from taking advantage of the many emerging opportunities being afforded by the rapid growth in PNT technologies and the many downstream applications. Furthermore, in order to address Recommendations 1 and 2, an integrated national space science PNT innovation and education strategy with co-partnership with government, universities and industry sectors will be required.