Somerset House, New Wing, Strand,
London, WC2R 1LA, United Kingdom
info@londoneconomics.co.uk
londoneconomics.co.uk
@LondonEconomics
+44 (0)20 3701 7700

Economic benefits of resilient PNT in the UK

Concept Paper for the Royal Institute of Navigation UK PNT Leadership Seminar

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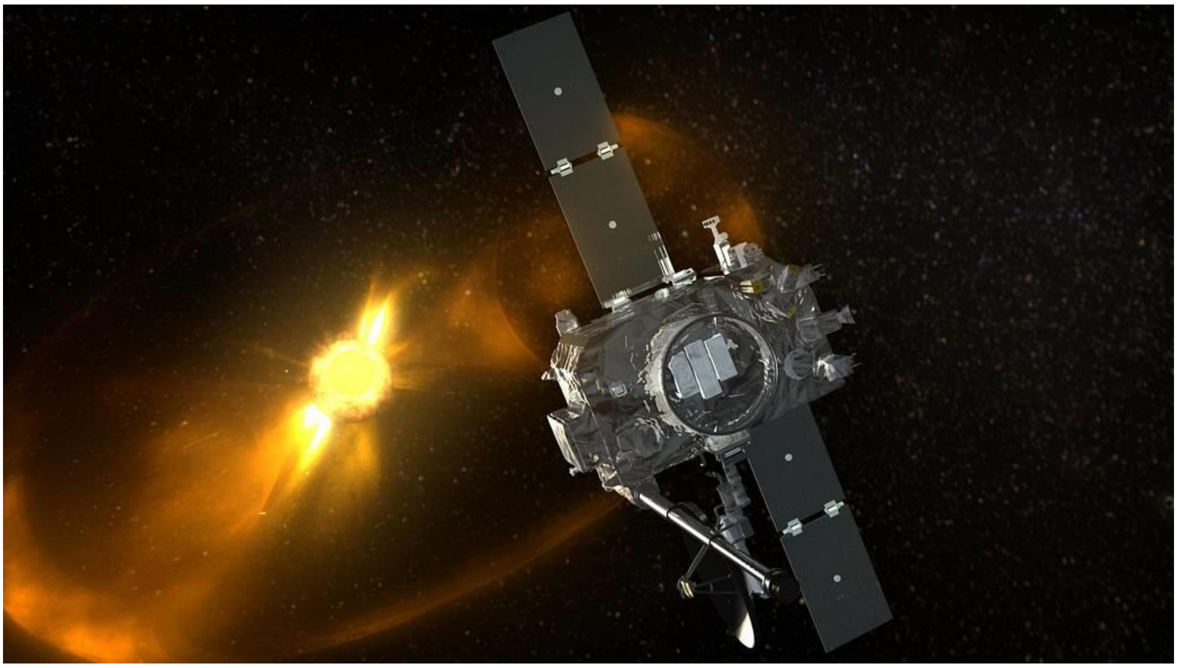
Abstract

Position, Navigation, and Timing (PNT) information is a crucial input into many technologies that underpin the modern economy. The most widespread source of this information is satellites in space, generically referred to as 'GNSS', or Global Navigation Satellite System – GPS is one example. The proliferation of GNSS as a source of PNT is usually attributed to its global availability and zero cost – but as reliance on GNSS has increased, so too has the exposure to its weaknesses. These weaknesses are increasingly apparent as the scale and sophistication of attacks on existing PNT systems grows.

The UK is well placed to capture a greater share of the growing market for resilient PNT and could, with sufficient public and private effort, reap the rewards of moving early to address the issue of resilience in PNT. This concept paper seeks to test the hypothesis that 'the UK can generate value and sustainable leadership from investing in resilient PNT, benefiting government, academia, industry and, ultimately, individuals'.



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As a team, we have been pioneering innovative analytical techniques and advising decision-makers across the space industry, space agencies and international governments since 2008. Drawing on our solid understanding of the economics of space, expertise in economic analysis and industry knowledge, we use our expertise to reduce uncertainty and guide decision-makers. Our consultants are highly-qualified economists with extensive experience in applying a wide variety of best practice analytical techniques to the space sector, including:

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Head Office: Somerset House, New Wing, Strand, London, WC2R 1LA, United Kingdom.

w: londoneconomics.co.uk
e: space@londoneconomics.co.uk
: @LE_Aerospace
t: +44 (0)20 3701 7700
f: +44 (0)20 3701 7701

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Responsibility for the contents of this report remains with London Economics.

Authors

Rasmus Flytkjaer, Divisional Director, Head of Space
rflytkjaer@londoneconomics.co.uk
+44 (0)20 3701 7717

Tom Goulding, Economic Consultant
tgoulding@londoneconomics.co.uk
+44 (0)20 3701 7564

1 Introduction

Could the UK, as a modern, developed economy, survive in a disrupted or denied PNT environment?

Position, Navigation, and Timing (PNT) information is a fundamental input into many technologies and services that underpin modern life. Today, the most widespread source of PNT information is satellite systems in space, generically referred to as 'GNSS'. Cars, planes, trains, and ships all use GNSS as a matter of course for navigation, resulting in travel efficiencies and improved safety in adverse weather conditions. Farmers and logistics companies rely on GNSS to improve productivity and support modern society. Power and utilities company rely on the systems to synchronise and manage their services, as do internet and other telecommunications service providers. Other sectors including meteorology, the emergency services and finance industry have come to rely on GNSS signals as a key source of PNT to enable efficiencies.

Figure 1 Reliance on GNSS across the UK economy

The proliferation of GNSS as a source of PNT is impressive, and often surprising, though its global coverage, low implementation cost, and usually high availability and reliability perhaps mean the proliferation is only to be expected. As the reliance on GNSS has increased, so too has the exposure to the weaknesses of the system of infrastructure that is fundamental to modern life. The heavy reliance on GNSS across the economy has historically been raised by government and civilian commentators, and their calls are increasing in frequency and strength as the scale and sophistication of attacks on existing PNT systems increases. While these take different forms depending on the sector and specific implementation of GNSS in question, the sectors where the UK has the most value at risk from a loss of GNSS-provided PNT are precisely the sectors that lack adequately resilient backup options.

The UK is well placed to capture a greater share of the growing resilient PNT market, and indeed can play a vital role in increasing the global pace of growth. Home to world-leading research and development clusters, academic centres of excellence, and an existing strong high-tech manufacturing base, the UK could, with sufficient public and private effort, reap the rewards of moving early to address the issue of resilience in PNT.

Where there is value at risk, both in the UK and abroad, there is an opportunity to provide value by mitigating that risk. This concept paper seeks to test the hypothesis that 'the UK can generate value and sustainable leadership from investing in resilient PNT, benefiting government, academia, industry and, ultimately, individuals'.

1.1 Resilience of UK Critical National Infrastructure

The Cabinet Office requires the UK's 13 Critical National Infrastructures (CNIs) to produce annual Sector Security and Resilience Plans[1], including descriptions of security approaches, risk assessments, and planned risk-mitigating and risk-response actions. There is public acknowledgement of the threats and hazards facing the UK's CNI, ranging from terrorist attacks and cybercrime to natural hazards such as pandemics or severe weather. In addition to these, new and existing infrastructure must be prepared to handle longer term issues including hostile states, the effects of climate change, and a population due to continue growing until 2050[2].

To this end, the UK Critical Infrastructure Resilience Programme[3] was begun in 2010 to address vulnerabilities. The Blackett Review[4] into critical dependencies on GNSS in 2018 recognised that in recent years both the threats to the UK and the infrastructure upon which modern life depends have evolved. Nascent digital infrastructure including 5G, electricity system management, autonomous vehicles, and the Internet of Things will contribute to an increasingly interconnected, and hence interdependent, set of national infrastructures[5].

Global satellite navigation systems (GNSS) provide time and position information underpinning the UK CNIs, largely due to their excellent accuracy, reliability, geographical coverage, and low cost. Alternatives to GNSS do exist, but for most modern use-cases GNSS has been widely seen as the ideal solution for low-cost inputs into Position, Navigation, and Timing (PNT) applications of all types. This results in such an attractive package that many aspects of the UK economy, supported by CNI, have become entirely dependent on GNSS signals, integral to innumerable systems and applications. The reality is that crucial services and infrastructures have taken advantage of the opportunities presented by GNSS without adequately considering the vulnerabilities in the system and hence risks of this reliance.

Sector	GNSS dependence
Agriculture	Precision farming, variable rate application, crop monitoring
Aviation	Routing, landing and takeoff, efficiency of flight corridors
Emergency services	Emergency call location, resource dispatch and tracking, navigation, security and surveillance
Finance	Time stamping
Rail	Train positioning, automatic door systems, passenger information
Maritime	Navigation and safety, cargo handling, Automatic Identification Systems, environmental and sustainability monitoring

[1] UK Cabinet Office. (2017). 'Public Summary of Sector Security and Resilience Plans'
[2] United Nations. (2022). 'UK Population to 2100'. Available at: https://ourworldindata.org/grapher/population-past-future?time=2000..2100&country=~GBR
[3] Cabinet Office. (2010). 'Strategic Framework and Policy Statement on improving the resilience of Critical Infrastructure to disruption from natural hazards'
[4] Government Office for Science. (2018). 'Blackett Review – Satellite-derived Time and Position: A study of critical dependencies'
[5] Government Office for Science. (2018). 'Blackett Review – Satellite-derived Time and Position: A study of critical dependencies'

Sector	GNSS dependence
Road	Navigation, telematics and fleet management
Offender tracking	Movement tracking of recently released offenders
Surveying	Cadastral surveying, mapping, mining, civil engineering, marine surveying, infrastructure monitoring
Location-based consumer services	Fitness wearables, location-based smartphone applications, Augmented Reality
Energy	Timing and synchronisation of energy grid
Telecommunications	Satellite-based communications, terrestrial wired and wireless telecoms
Meteorology	Weather forecasting, lightning detection
Health	Transport of patients and medical supplies, vulnerable people tracking and support, lone worker tracking and security

Both satellites and their signals are exposed to space weather: geomagnetic storms, solar flares, and ionospheric perturbations can introduce delays, frequency shifts, and loss of signal. Each of these can result in degraded GNSS PNT accuracy or integrity failure, i.e., can cause harm to PNT systems. Furthermore, the radio signals travel distances of around 20,000km from the satellites to earth, meaning they are innately weak and hence easy to interfere with. Environmental issues such as signal blocking in cities and reflection/refraction of signals cause performance degradation including outages and significant position errors. Aside from these environmental issues, malicious interference from criminals[6] and accidental collateral damage[7] are continuously evolving and increasing in quantity. To give a sense of magnitude, the 2016-19 STRIKE3 project identified 59,000 deliberate jamming signal interferences with GNSS in their monitoring sample of 23 countries and 3 years[8].

Considering the current threat level reveals uncomfortable levels of exposure to disruption in most Critical National Infrastructures. PNT Systems that exhibit resilience to the disruption or harm caused by the factors above are therefore of critical importance for the continued function of most CNIs. While the default choice for much of the modern UK society is space-based GNSS-provided PNT, alternatives and augmentation systems have been explored within the UK and overseas in search of much-needed resilience. The significant benefits of space-based solutions should not be ignored, so the key to providing resilience is not to replace it but to implement a combination of PNT technologies, working together.

2 Economic impact of a loss of PNT

There can be no doubt that the reliance of the UK, and indeed much of the modern world, on PNT information is significant. GNSS satellites are the primary source of information by which other PNT sources are conditioned, and hence underpin the UK's PNT capability. System design has, for years, come to over-rely on GNSS while threats have increased. This imbalance creates a serious risk to the UK and other nations' wellbeing. On the other hand, this means that the UK may be able to generate value and sustainable leadership from investing in resilient PNT, benefiting government, industry and, ultimately, individuals. This chapter explores the available literature on the estimated impacts of even a temporary loss of GNSS – and hence the loss of most PNT capability – to quantify the magnitude of this risk – and hence the potential value of resilience.

[6] NBC News. (2016). 'GPS under attack as crooks, rogue workers wage electronic war'
[7] Resilient Navigation and Timing Foundation. (2020). 'Thousands of GNSS jamming and spoofing incidents reported in 2020'
[8] EUSPA. (2019). 'STRIKE3 Project'. Available at: http://gnss-strike3.eu/ [Accessed October 2022]

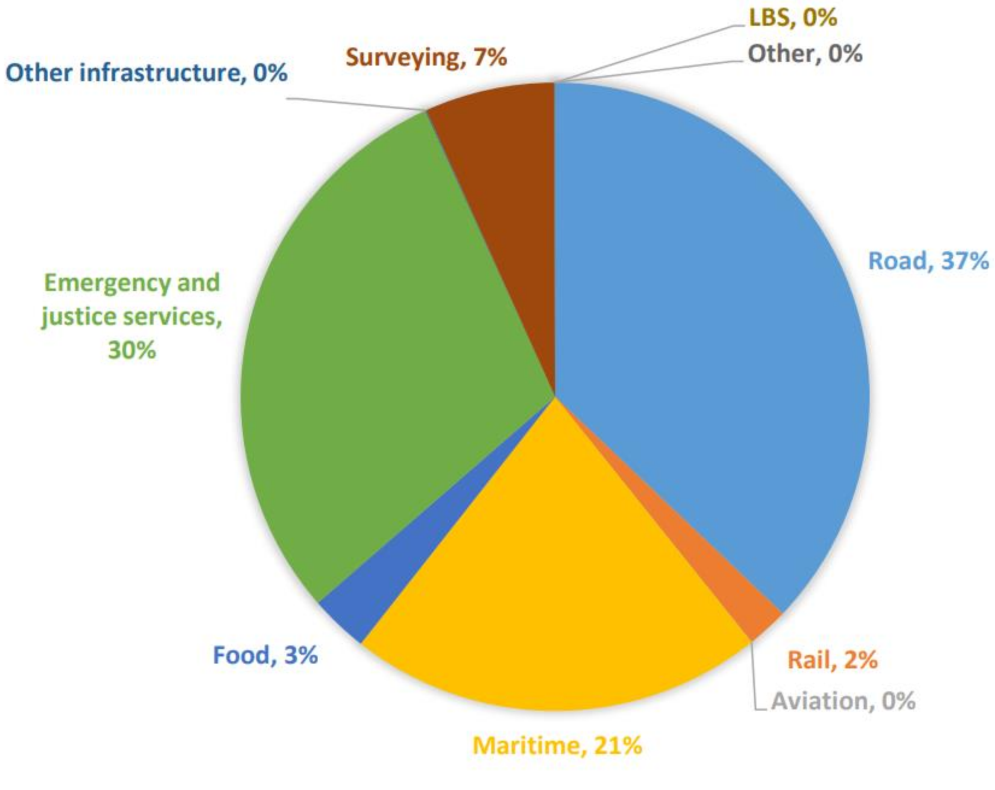
2.1 The economic impact of a loss of GNSS

2.1.1 United Kingdom (London Economics)

In a 2017 report[9] commissioned by Innovate UK, the UK Space Agency, and the Royal Institute of Navigation, desk-based research and 35 expert consultations formed the evidence base for analysis of 10 applications domains. These domains were Road, Rail, Aviation, Maritime, Food, Emergency and Justice Services, Surveying, Location-Based Services (LBS), Other Infrastructure (including applications such as telecoms, dangerous goods monitoring, and the timing and synchronisation of the National Power Grid), and Other Applications (including Finance, weather forecasting, and tracking vulnerable individuals). Notably, defence applications were not included within the analysis.

The report found that an estimated £5.2 billion of value would be lost over a five-day period. The Road, Maritime, and Emergency and Justice Services account for 67% of all impacts.

Figure 2 Economic impact to the UK of a five-day loss of GNSS (in 2017)



Source: London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'

Benefits and losses in some sectors and applications important to the UK economy, such as financial services, were not quantified. The impact of loss was claimed in interviews with stakeholders from the finance industry to be negligible owing to well-developed redundancy systems. A further important finding was that the UK power grid is considered to have a more resilient design than most power grids. The UK National Grid has also developed contingency plans for the case of severe

[9] Innovate UK. (2017). 'The economic impact on the UK of a disruption to GNSS'

space weather events, including the availability of spare transformers in the case of damage[10]. In addition, the UK Government is updating assessments of the impact of these severe space weather events[11] [12].

Note that the measurement of economic losses is estimated in relation to the (actual real-world) baseline in which GNSS is the chosen technology. This means that the relevant counterfactual in each application is the technology that is available for immediate deployment in the event of an outage. This means that the (non)existence of redundancy or backup sources of PNT information in each sector directly impacts the losses estimated.

The UK Space Agency intends to publish an updated version of this 2017 report[13].

2.1.2 USA (RTI International)

In 2019, the National Institute of Standards and Technology commissioned a report[14] to estimate the potential economic impacts of a GPS outage on the US private sector. The report found that the US economy would lose an estimated $30.3 billion over a 30-day outage of GNSS. Notably they provide a further aggregate estimate of $45.4 billion in the case where the outage occurred during the Spring peak planting season for US Agriculture, which is heavily dependent on GPS for precision agriculture techniques.

Importantly, the impact of a GPS outage was only considered for those industries that derive marginal service improvements from GPS. This means that the analysis of economic loss excludes industries that use GPS today but do not necessarily require the extra precision delivered by GPS. As explicitly noted in the report, this means that the loss estimates presented “should be interpreted as an underestimate of likely impacts”.

Another important methodological point is that economic impacts were measured relative to a counterfactual that specified that pre-existing positioning, navigation, and timing (PNT) systems continued to be available in the absence of GPS. Thus, the relative benefit for some sectors is negligible but substantial for those with applications that have a requirement for GPS’s accuracy and precision. For most sectors, the counterfactual assumption is that “*in the absence of GPS a Loran-based network… likely would have received more investment to fully cover the US*”.

2.1.3 USA (RAND Corporation)

A further study[15] from the US noted how considerations of the modern PNT ecosystem ‘often shifts rapidly to the GPS constellation of satellites’ due to its comprehensiveness, cost, and high degree of integration into many technologies. Despite this, the study notes that supplementary sources of PNT information do exist, ranging from precision clocks to wired transmissions.

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[10] UK Cabinet Office. (2015). ‘Space Weather Preparedness Strategy’

[11] UKRI led SWIMMR Programme (https://www.ralspace.stfc.ac.uk/Pages/SWIMMR.aspx)

[12] UKRI awards Rhea Group a contract up update Space Weather impacts (https://www.rheagroup.com/rhea-group-to-update-key-space-weather-impact-report/)

[13] UK Space Agency response to FOI 2206/002 5th July 2022

[14] RTI International. (2019). ‘Economic Benefits of the Global Positioning System (GPS)’

[15] Homeland Security Operational Analysis Center. (2021). ‘Analyzing a More Resilient National Positioning, Navigation, and Timing Capability’. Note that this study includes a comprehensive literature review and hence draws on many other economic benefits studies of GNSS, largely within the USA. These include ACIL Allen Consulting (2013); Carroll and Montgomery (2008); European Global Navigation Satellite Systems Agency (2016, 2017); Grisso, Alley, and Groover (2005); John A. Volpe National Transportation Systems Center (2009); John Deere (2018); Leveson (2015); Martin et al. (2005); Oxera Consulting (2013); Pham (2011); Schimmelpfennig (2016); Technical Strategy Leadership Group (2012); U.K. Government Office for Science (2018); and Young, Rogawski, and Verhulst (2016).

Building on the work of RTI International (Section 2.1.2), the researchers perform sector-by-sector microeconomic analyses that consider the ability of attackers to interfere with GPS signals, the economic impact of these attacks, and likely mitigating technologies to reduce these impacts. Their estimated range of potential losses from a nationwide GPS disruption is between $785-1,318m per day – though they argue that existing complementary PNT and backup technologies, when coupled with 'reasonable assumptions about law enforcement's ability to identify and apprehend' perpetrators, make for 'surprisingly low' estimates of economic impact from attacks.

While the study is not in favour of extensive public funding of alternate PNT systems, it does note that having 'time-proven, robust fallbacks' available is highly desirable, and calls for 'prudent system design' that avoids creating yet further dependencies on GNSS as a source of PNT. Such alternate systems, it is argued, cannot fully prevent all the estimated damages and hence the resulting cost benefiting analyses are not favourable for such public funding for the purpose of damage mitigation alone. The report thus recommends a private sector-led approach to PNT system resilience.

2.2 Sectoral findings and factors unique to the UK

The UK study identifies a number of sectors where resilience in PNT is highly valuable, as the estimated economic impact of a loss of GNSS-provided PNT is very high. Notably in 2017 an estimated 67% of economic impact would be felt in just three sectors: road transport, emergency and justice services, and maritime (including port logistics). The rail system and surveying sector are further key sectors in terms of magnitude of impact from a loss of GNSS (9% in total). Detail on how these losses are estimated can be found in the UK study[16].

In each sector, the most widely adopted PNT and backup systems (or lack thereof) play a vital role in generating the estimates of economic impacts. In cases where a redundant system is readily available the magnitude of losses are far smaller. It is logically the case, then, that **the sectors where the UK has the most value at risk from a loss of GNSS-provided PNT are precisely the sectors that lack adequate resilient backup options.**

The sectors of interest identified in the UK study broadly align with the US studies, which also found high impacts in road transportation and maritime (including port logistics). There were also significant estimated losses in emergency services. Importantly, despite different technical implementations, the report comes to similar conclusions as the UK report in that sufficient holdover capacity in telecoms exists to maintain timing synchronisation throughout outage periods.

The figures presented in Section 2.1 suggest that large economic consequences await if the resilience of PNT in the UK is not addressed to cope with even a temporary loss of GNSS. This section has highlighted that broad similarities across the UK, US, and presumably other geographies exist, with differences in the economic losses estimated are driven by factors including:

- **Geographical differences** such as population density;
- **Cultural differences** reflected in attitudes and legal frameworks;
- **Study methodology differences** such as scope of analysis (i.e. economic sectors considered, or satellite constellations included in analysis) and choice of counterfactuals;
- **Time period differences** that impact estimated total impacts and averaged 'daily' values;
- **Differences in technologies and systems in use** with implications for resilience or available technology.

[16] London Economics. (2017). 'The economic impact on the UK of a disruption to GNSS'

The last of these, the technologies and systems in use, are of particular importance as they are both tangible (that is, not artefacts of the research methodology) and directly impactable. In recognition of this, efforts are underway to understand and bolster the quality of alternative options to GNSS as a source of PNT[17].

2.3 Economic demand for resilient PNT

The earlier parts of this section demonstrated the large (and growing) range of use cases for PNT, many of which have historically preferred GNSS as a primary source. Each of these use cases comes with their own particular implementation and hence unique vulnerabilities. These in turn give rise to different mitigation strategies, with the cost and effectiveness of each strategy varying enormously by use case and business sector. In many cases research is still ongoing, with significant innovation potential still remaining.

For example, the criticality of timing (in communications, power transmission, and financial transactions, to name but a few sectors) means that large investments have been made on hold-over technology. This technology aims to ensure continuity of service during outages of the primary timing source – generally space based PNT. Very expensive solutions can withstand long GNSS outages; GNSS is, in fact, often used merely to condition the clocks of these solutions.

This utilisation of GNSS as part of a larger system rather than the sole input is an important defence against disruption. The resulting solution is often more sophisticated than simply adding one back-up source of timing information, hence the growing use of the term ‘system of systems’. In these systems of systems various sources are often blended together by sensor-fusion algorithms to provide improved PNT performance. Such solutions are relatively immature and widely-accepted standards are yet to emerge. As research and development of such system of systems continues, the threats faced are increasing. This presents not only a risk, but also an opportunity for research, innovation, and industry leadership as the economic demand for successful implementations grows in line with the value at risk.

Another source of economic demand is in supporting the efficiency of transportation of all types and in the accuracy of positioning data. Many studies have found that all sections of UK supply chains are dependent on precisely the ‘accurate and real-time information’ that risks to PNT put at jeopardy.[18]

The broad alignment of the UK and other nations’ vulnerabilities to PNT outages creates a strong economic incentive to develop solutions, as domestic resilience can be achieved alongside developing valuable international opportunities. It is also clear that those sectors with the largest value dependence upon GNSS are able to create positive business cases and return on investment if resilient PNT techniques and systems are implemented, as potential losses (financially and reputationally) are mitigated. Another avenue is the development of legislation, regulation, and standards – which are currently relatively immature. Appropriately designed, these could be a stimulus for innovation, while at the same time addressing the risks described.

[17] In the UK see the MoD Defence Equipment & Support’s contracts totalling £3.8m (https://des.mod.uk/des-alternative-navigation-technologies-gps/) and in the US work by the Position, Navigation, and Timing Research and Development Interagency Working Group (https://www.whitehouse.gov/wp-content/uploads/2021/08/Position_Navigation_Timing_RD_Plan-August-2021.pdf)
[18] National space Partnership. (2022). ‘Strategic Case for Intervention: Intelligent Supply Chains’

3 The market for resilient PNT

3.1 Value chain

Research and Development

As awareness of the value reliant on resilient PNT grows, so too will the demand for new research and development of technical and system designs. Improving the stock of knowledge, applying existing technology in novel ways, and otherwise increasing capacity all begins with the research portion of the value chain.

Given the UK's long and continued track record as a hub for cutting-edge scientific research, there is a unique but time-limited opportunity for UK engineers, researchers, and investors to move quickly and achieve much in the resilient PNT space. This has been seen many times before in the PNT space, with examples including multi-frequency receiver design, multi-GNSS systems, antenna technology, signal innovation, deeper understanding of propagation effects, inertial systems design and integration, test and simulation systems, and interference detection.

PNT infrastructure provision

This value chain segment is concerned with the manufacture and delivery of the physical infrastructure required for a PNT system to function, and the operation of this infrastructure. This infrastructure varies across different technological solutions, of course, but as a general rule involve high-specification manufacturing capabilities in order to take advantage of cutting-edge research inputs. Organisations carrying out the operations role may be public or private depending on the eventual market structure of the technology: GNSS are ultimately funded by governments, although some are industrially operated, while other satellite derived PNT systems are funded and operated by private companies.

The UK hosts a number of experienced players and ambitious startups that manufacture infrastructure for a range of sectors – whether home grown or local sites for international companies. With a strong supply of skilled science and engineering workers and development support from the strong R&D sector this is an area of potential national strength. With the right conditions for investment, UK companies are willing to invest in PNT resilience and this also attracts Foreign Direct Investment (FDI) opportunities. Operations are generally conducted by the same entities that own the system infrastructure, and the UK has previously expressed interest in owning and operating its own infrastructure. The UK has drawn up plans for a UK-operated GNSS[19] and an eLoran implementation reached Initial Operational Capability in 2014[20].

PNT module manufacturing

These manufacturers produce the basic building blocks for PNT systems. These modules include receivers, which receive signals from GNSS or other PNT information sources, or inertial units that detect force and map this to movement.

[19] UK Space Agency. (2018). 'Space sector to benefit from multi-million-pound work on UK alternative to Galileo'
[20] Inside GNSS. (2014).'UK eLoran Now In Operation to Back Up GPS'

System integrators

Entities in this portion of the value chain are responsible for the technical implementation of the PNT solution, often as part of complex interconnected systems. These system integrators include the important manufacturers producing user equipment, which facilitates the delivery of PNT information to users and combines PNT technologies such as receiver chips and modules, antennas, and atomic clocks into user-friendly products that allow use of PNT information. They therefore enable the final step in delivering the value of the system and are at the heart of PNT system resilience. User equipment could be available through either a purchase model (where users own the equipment) or through an increasingly popular service/lease model with service-level agreements (SLAs).

Another key part of system integration is the research, development, and implementation of key enabling features such as systems design, necessary software, analytics, and ultimately the creation of PNT system-of-systems architecture. These connect the various physical components of a PNT system, and work in tandem with consulting and advisory services. Consulting and advisory services are often required to bridge the gap between technical capabilities, manufacturers, operations, and sources of funding. While generalised consulting players with knowledge of the sector are widely available, specialised consultants to the resilient PNT industry are an emerging group.

Application providers

These entities provide end-users with final products and services that utilise the other segments of the value chain. These applications can be extremely broad and varied, as they are the final interface between the market's demands for PNT services and the sector's ability to provide the technical inputs underpinning these.

The skills required to develop and provide these applications are regularly data-analytics heavy, favouring expertise in rapidly growing areas such as Artificial Intelligence and Machine Learning.

3.2 Technologies within scope

It is important to note that there is no single PNT system or technology that can fully replace or back up GNSS. There are overlapping sets of strengths, weaknesses, and dissimilar vulnerability vectors to each possible technological option. It is therefore the case that to achieve PNT system resilience several technology options must be considered for each use case in order to ensure threats are mitigated and the PNT information is not harmed. This "system-of-systems" approach[21][22] combines different technologies with dissimilar failure modes which when managed strategically, can provide information to users without any single points or common modes of failure. See Table 1, adapted from the 2021 US paper[23], which summarises alternatives to GNSS and their respective strengths and vulnerabilities.

[21] Andy Proctor, Developing a PNT Architecture Framework, Navigation 2021 Conference, Edinburgh 2021

[22] Andy Proctor, A structured approach to achieving System Resilience in PNT systems, RethinkPNT, 2022, www.rethinkpnt.com

[23] Homeland Security Operational Analysis Center. (2021). 'Analyzing a More Resilient National Positioning, Navigation, and Timing Capability'

Table 1 Alternative options for PNT resilience

Group of alternatives	Example alternatives	Common features	UK interest
Wireless PNT signals	eLoran LEO-provided PNT Space-based augmentation Pseudolites	RF signals from transmitters of known location. User computers time and location from pseudorange. Maintains user anonymity.	UK General Lighthouse Authority operated eLoran stations in the mid-2010s, and one functional station remains in Cumbria. Various UK-based commercial interests.
Signals of opportunity	WiFi/WLAN LTE/4G Cellular 5G Cellular DVB-T DAB LEO comms constellations MF DGNSS AIS UWB Bluetooth	Existing RF signals not primarily intended for navigation. User computers location from triangulation and ranging. User may or may not get time from signal.	
Wireless time signals	NPL DCF77	Usable by remote users. Maintains user anonymity. Provides time only.	NPL Time funded by BEIS and operated by Babcock International from Anthorn Radio Station. Serves as UK's national time reference.
Wired time signals	NTP PTP Optical Fibre White Rabbit	Variations on two-way communications to measure time-transfer delays. Provides time only.	
User equipment based	Holdover clock Chip-scale atomic clock Inertial Navigation System Simultaneous location and mapping (SLAM) Audio and/or visual based systems LIDAR	No new signals. Relies only on modification to user equipment. Typically sensors and technologies. May maintain user anonymity.	INS of interest to UK Quantum Technology Hub Sensors and Timing
PNT resilience technologies	Nulling antennas Direction finders Jamming or signal degradation detection systems	Enables continued use of GPS signals and/or existing user equipment. Maintains nominal PNT performance of benign environment.	

Source: Homeland Security Operational Analysis Center. (2021). 'Analyzing a More Resilient National Positioning, Navigation, and Timing Capability'

3.3 Projected market size and evolution

The cybersecurity market encompasses all the products and services that maintain privacy, availability, and integrity in the cyber domain. The continued expansion of the market is near-inevitable given the trend of increasingly connected devices and general digitisation across the economy, despite market maturity still being some way off.

Reliable PNT information, as a crucial input into most modern digital devices and processes, is therefore a key part of cybersecurity and many parallels exist between cyber system resilience and PNT system resilience. Importantly, data on the current spend in the cybersecurity market is observable and available today, making it a useful proxy for the growth in spending on resilient PNT and other conceptually similar solutions.

Of course, there are opportunities for the growth of resilient PNT spending elsewhere. One example likely to generate much investment in the coming decade is Autonomous Vehicles. To be functional and safe on real-world roads these self-driving vehicles will have strict resilience and integrity requirements of their PNT information. More than half a billion road-based GNSS devices will need to be replaced with a system capable of delivering resilient PNT to achieve the projected trajectory of Autonomous Vehicle uptake over the next decade.

The actual size of the opportunity created in theorised or nascent technologies of the future, of which Autonomous Vehicles is but one example, is difficult to assess with any degree of certainty. One market forecast suggests the UK market for Connected and Autonomous Vehicles will reach 23% of all vehicle sales (almost 1.5 million units) by 2035[24] – each of which will come with high requirements for resilience in their PNT information. Despite this, it is clear that any estimates of the growth in spending on resilient PNT based on current spending only represent the tip of the proverbial iceberg due to their ignorance of yet-to-emerge sources of demand.

With these important caveats noted, we turn to the available data that can be used to proxy current and future growth in demand for resilient PNT systems. First, data on the evolution of the cybersecurity market supports a view of an expansionary trajectory, as total spend on critical infrastructure cybersecurity between 2012-2021 shows. The total global cybersecurity spend grew at a compound annual growth rate (CAGR) of almost 12% over the period 2012-16, followed by an uptick in growth that resulted in a CAGR per year of 14.8% from 2016-21. By 2021 this resulted in a global spend of almost £100bn.

The global annual spend on GNSS devices for Timing and Synchronisation purposes is projected to be slightly more than £1bn per year throughout the 2020s[25]. This equates to approximately 1.25% of the total cybersecurity spend. If this spend on GNSS devices can be considered to be from consumers seeking timing and synchronisation services that are agnostic to the source, this can be taken to be indicative of the size of the market today for resilient PNT among critical infrastructure. At the observed 2016-21 cybersecurity market growth rate this market could be in excess of £4bn within 10 years.

Another interesting market is the timestamping market, which can be seen as another proxy market for the demand for resilient PNT. This is due to its position as a source of timing and synchronisation services, and hence its use as a backup for other PNT sources. This highlights how alternative PNT

[24] Connected Places Catapult. (2020). 'Market Forecast For Connected and Autonomous Vehicles'
[25] EUSPA. (2019). 'GNSS Market Report Issue 6'

sources are used to mitigate against risks of other sources, though they usually come with their own vulnerabilities. One approach to estimate potential market size for resilience is to begin by estimating the required number of timestamps per year per organisation in the Energy, Telecoms, and Finance industries. It should be noted that this resilience is either currently provided by other means or inadequate – the value estimated is therefore theoretical. These three sectors are assumed to represent the vast majority of demand for always-available timestamping. It is assumed that the Energy and Telecoms industries require timestamping every second of the year. In Finance, however, timestamping is only relevant for the days markets are open and trading – this means only approximately 25% of the year is relevant for Finance. Using the number of seconds in a year the total number of required timestamps by an organisation is calculable.

Publicly available pricing quotes are not available for timestamping services, and so this study turns to price data from Digistamp, a provider of verified time stamps. Digistamp charges a variable rate per timestamp, with lower prices per timestamp when customers purchase greater volumes. The available datapoints were used to reconstruct their pricing function. This was used to calculate the cost to provide the required number of timestamps to organisations in each industry, with costs per timestamp growing over time at the projected inflation rate. The number of organisations was used to arrive at a theoretical total value of approximately £3.5bn per year across Europe alone (so the total market is assumed to be approximately £10bn). This is included here as a rough indication of the market size that resilient timestamping could underpin with the introduction of resilient PNT.

The global monetised market for currently available resilient PNT proxies, then, amounts to around £1bn today – as estimated by the global annual spend on GNSS devices for Timing and Synchronisation purposes. This figure is grown at the growth rate of the total global cybersecurity spend, so as to maintain the share of this value as a percent of total cybersecurity spend. The £1bn amount is thus projected to more than quadruple within the next 10 years. Additionally, based on the timestamping market, there is a further £10bn global market for current spending on time stamping services in addition to GNSS that indicates a potential additional market size for resilience in time stamping. The following sections will consider how much of this market is potentially addressable by UK industry.

3.4 Market opportunities and the value chain

The markets outlined in Section 3.3 are those that have readily available revenues that can be used to proxy the potential market for resilient PNT services. Those services as they exist today largely fall in the later sections of the value chain described in Section 3.1, where companies utilise and integrate existing technologies and infrastructure into their products and services.

These approximations of the potential market do not include the economic value generated by the other value chain segments. In particular, significant public funding for R&D and infrastructure provision in the PNT industry and the science and engineering domain more generally may follow newly announced strategies and policies. For example, a proposal for a UK PNT Strategy was previously drafted[26] with the stated aim of bringing cohesion to disparate projects including UK GNSS, RETSI, MarRINav, RGNS, and many S&T low TRL innovations. This public support is mirrored in the United States, where, as a result of the growing vulnerability of GPS to jamming and spoofing, the U.S. Senate Armed Services Committee (SASC) has ordered the Pentagon to provide an alternative to GPS within two years. Outside the scope of national governments, the IEEE are

[26] UK Parliament. (2022). 'MPs request clarity on Government's approach to Position, Navigation and Timing'

currently working to develop a PNT standard for measuring resilience, and the 'Open Industry Alliance' was recently launched to strengthen PNT resilience[27].

The UK is well-placed to capture some of the benefits of such public interest, and potentially public funding, that these examples strongly imply. It is first important to note that the nation is excellently placed to benefit from increased research funding for resilient PNT. The output of the UK's internationally impressive academic sector is world-leading, with all major engineering and technology departments at UK universities being engaged at some level with PNT. Key- examples in the PNT space include:

- University of Nottingham, which is host to the world-leading GNSS Research Academic Centre of Excellence,
- University College London's Space Geodesy and Navigation Laboratory,
- Imperial College London's PNT research group, and
- Warwick University where 90% of engineering research is recognised as world-leading[28].

In the private sector, major multinational companies such as Airbus Defence and Space are well-represented within the UK, with teams routinely work on the design (and manufacture) of advanced technologies for telecommunications and navigation.

Increased research funding generally leads to improved manufacturing capabilities. As technologies are developed and integrated into systems, the researchers working on these problems are uniquely well-placed to advise the development of the engineering processes that result in finished products. The UK has a long history of precision engineering excellence, and to this day hosts manufacturing sites for companies both small and large that produce high-tech components for uses across the entire global economy. Specific examples within the PNT space include Spirent, Focal Point Positioning, Racelogic, OXTS, Omnisense. Increased manufacturing capability inevitably generates value for the manufacturers who can produce and sell novel items as first-movers in the domestic and global market.

Further value is likely to accrue in the domestic UK market, as having direct access to new, more resilient, PNT services lowers the barriers to their integration into the economy. In this way, the UK can expect improved mitigation to economic loss as a direct result of the implementation of resilient PNT research. Of course, the domestic value creation from this mitigation of economic loss can be exported. New export opportunities created by the domestic development of resilient PNT in turn create new markets and growth opportunities for the companies selling and developing these products.

The estimation of the potential economic benefits generated by the entire resilient PNT value chain (as discussed in this section) is outside the scope of this study – though research into comparable value chains in different sectors indicates the direct return on investment is likely to be in the range

[27] This alliance currently comprises ten companies — infiniDome, Iridium Communications, Jackson Labs Technologies, NAVSYS Corporation, NextNav, OPNT, Orolia, Qulsar, Satelles, and Seven Solutions.

[28] Research Excellence Framework. (2021). Reported at: https://warwick.ac.uk/fac/sci/eng/news/over_90_of/ . Warwick's Manufacturing Group faculty offers PhD roles on topics such as Assured PNT for Remote Robots (https://warwick.ac.uk/fac/sci/wmg/education/researchdegrees/vacancies/phd-in-assured-positioning-navigation-and-timing-pnt-for-remote-robots/)

of £2-£7 per £1 invested with further spillovers of £4-£14.[29] This makes for an aggregate return on investment of between £6-£21 per £1 invested.

In the business-as-usual case, with UK-focused funding of research and development remaining at currently-announced levels, we expect around 2% of the global resilient PNT market to be captured by UK businesses. This is a direct implication of the expected R&D conversion rate into marketable products where the UK has a technological or economic advantage. This is broadly in line with the UK's share of the global GNSS market, a technology that is presumed to share many features with the nascent resilient PNT market, including the sensitive nature of applications and consequent limitation on market accessibility. Of course, this also commits the UK to following the business-as-usual development path of resilience in PNT options, which leaves it to others to ensure the development timelines stay ahead of increasingly sophisticated attacks.

With this development speed in mind, the later parts of this section aimed to illustrate the potential for this share to be greater if greater investment in the resilient PNT value chain were carried out. In particular, it is highly likely that UK investment in skills and R&D for system integration could generate market-leading intellectual property and hence convert into marketable products and services. As the complexity of the resilient PNT industry increases over time, intellectual property and human capital in the form of skills will form a key opportunity for the UK. Intellectual property and human capital are considered among the hardest inputs to replicate, and hence can potentially provide a sustainable competitive advantage. A successful portfolio of government interventions could include training and targeted R&D projects alongside work on infrastructure, legislation, and regulation.

3.5 Projected UK Investment impact

Taking action to create economic conditions conducive to investment in resilient PNT, as well as directly making these investments, could take many different forms, outlined below:

- **Domestic PNT infrastructure** to mitigate against current and future threats, mitigate dependency and vulnerability, protecting the value at risk from a loss of GNSS. The impact of such investment would likely be unseen and limited in normal times, but significant in the event of harm to GNSS services. However, it would also give economic agents a reliable infrastructure to include in their PNT-dependent processes. Additionally, complementary infrastructure could enable the use of automated PNT-based processes in sectors that may have held off out of fear of signing up to a single point of failure.
- **Academic research and development** to build on the existing knowledge base and develop UK PNT skills and capabilities. In time such capabilities would lead to formation of new companies or knowledge spillovers into industry, for example through recruitment.
- **Industrial research and development** to build on existing capabilities, grow skills and create new products or services in the resilient PNT domain potentially resulting in export opportunities.
- **Testbeds or other infrastructure further downstream** to allow UK organisations to test and refine their offering and improve their competitive position.
- **Government as an anchor customer** could give UK industry a foothold in the market and referenceable experience leading to capacity building and a strengthened competitive position.

[29] London Economics (2015), *Return from Public Space Investments*

Additionally, all the different modes of public investment would help raise awareness and promote resilient PNT in a wider context, potentially leading other countries to intervene in the resilient PNT space. The world's leading economies have previously looked to the UK as a leader and paradigm-setter in resilient PNT, as evidenced by the investments in Galileo's control segment and security. The UK Government could act as a catalyst to promote UK resilient PNT technological capital and industrial leadership.

Resilient PNT solutions would likely be implemented through a combination of various interventions as there is no single substitute for GNSS. Each use of PNT can be considered to have its own challenges and specific requirements (quality or resilience requirements[30]). But all interventions would have the same overall properties and implications: research intensive, export-oriented, ubiquitous, and integral enabler of everyday services, cutting edge manufacturing and science, spillover benefits.

At the theoretical level, investments in space have been estimated to result in direct returns of £2-£7 per £1 invested and spillovers of £4-£14.[31] The wide range reflects the differences in the space domain, where public goods (such as GNSS and Earth Observation) are harder to monetise for the innovator, while satcoms with its exclusive usage is more likely to be monetised. Hence there is a strong theoretical case for investment in the area.

The UK has historically seen strong returns on its investments into PNT architecture.

- National Physics Laboratory developed the first accurate atomic clock, distributes NPL time
- Galileo: UK companies such as SSTL and Airbus Defence & Space captured more (approximately 24%) than the UK's input funding share (approximately 14%) in commercial upstream contracts and UK companies secured significant commercial advantages. Growth, scale and capabilities, reputation, and spillovers to other business units were all cited as direct benefits of participation. Indirect benefits include multiplier impacts that generate additional economic output in the UK supply chain and knowledge spillovers through heightened home-grown scientific excellence.
- InnovateUK investments, many of which have developed PNT products and services in the construction, agritech, aerospace, and space sectors have delivered an overall return of 7:1[32]
- UK Space Agency investment in the European Space Agency Navigation Innovation and Support Programme (NAVISP) has enabled several new innovations and companies to introduce new products and services. (DDK Positioning, Helix Geotech, Collins Aerospace, Cobham technologies, Envisage Space, CGI and more). Recent impact analysis shows the total return on UK investment in ESA will be 11.8:1 in Gross Value-Added terms[33]

Beyond the UK, data points exist that point to huge potential successes (Figure 3):

[30] Andy Proctor, A structured approach to achieving System Resilience in PNT systems, RethinkPNT, 2022, www.rethinkpnt.com

[31] London Economics (2015), *Return from Public Space Investments*

[32] UK Department for Business, Energy & Industrial Strategy. (2021). 'UK Innovation Strategy: Leading the future by creating it'

[33] UK Space Agency. (2022). 'Impact evaluation of UK investment in ESA'

Figure 3 Academic data points

The Impact of Public R&D Funding
Ebersberger, B. (2005)

- Public funding increases private innovation effort of funded firms. The largest effects are from collaborative innovation activities.
- An increased private innovation effort increases innovation output on average.

Value for money? New microeconometric evidence on public R&D grants in Flanders
Czarnitzki, D. & Lopes-Bento, C. (2012)

- Public funding of R&D does not fully crowd out private investment, meaning public funding increases the overall level of investment in innovation.

The effect of public support on investment and R&D: An empirical evaluation on European manufacturing firms
Carboni, O. (2017)

- On average, public funding increases the private innovation effort of funded firms, in both nominal and real terms. The largest effects are when it is stimulating collaborative innovation activities.
- An increased private innovation effort increases innovation output on average

Finland and the mobile phone industry: A case study of the return on investment from government-funded research and development
Walwyn, D. (2007)

- The Finnish government achieved a multiplier effect of ~66x on their initial R&D expenditure on the mobile phone manufacturing industry

So, with a strong UK track-record in PNT and over-performance in Galileo contracts, could resilient PNT be an opportunity for the UK's that mirrors Finland's mobile phone manufacturing? As Walwyn notes, the timely identification of a 'major growth opportunity' coupled with 'a sustained commitment to R&D' resulted in a runaway success with 'extraordinarily high' impacts on national GDP and many private sector businesses[34].

3.5.1 Growth of the UK's share of this market

A successful UK investment in resilient PNT would see UK companies' share of the overall resilient PNT market grow over time. From a starting point on the order of 2% of the total market (proxied by UK share of the GNSS market)[35] a very successful intervention would see UK industry capture up to 4%, equivalent to additional UK turnover of £220m. Strong growth in the resilient PNT market, as supported by evidence from the cybersecurity industry, suggests that this figure could increase over the coming decade – with targeted investments in R&D, infrastructure, skills, regulation, and standards all raising the medium term growth rate.

It is worth highlighting here that the potential prize discussed above pertains only to the slice of the PNT market that is deemed to be aware of resilience issues and concerns at present. It remains to be seen what proportion of the more than 500m road PNT devices currently in use (reported in the EUSPA Market Report) will realise they require improved resilience – especially with the transition towards autonomy.

With increased focus on resilience, other segments of the PNT market may follow, opening the possibility for the UK to access a market for GNSS devices and augmentation services worth more than €100bn globally.

[34] Walwyn, D. (2007). 'Finland and the mobile phone industry: A case study of the return on investment from government-funded research and development'

[35] UK Space Agency (2021), *Size and Health of the UK Space Industry 2021* and European Union Agency for the Space Programme (2022), *Market Report* considering device and augmentation service revenue only.

3.5.2 The UK stakeholders most likely to benefit

The growth of the UK's share of the resilient PNT market, under both the business-as-usual and the in the targeted public investment cases, has thus far been discussed at the aggregate level. Much of the UK growth resulting from the development of resilient PNT is likely to be seen in an interconnected ecosystem. As investors gain confidence in the space due to policy and other support from the government, R&D budgets and hence the rate of marketable outcomes will increase. Academic programmes should benefit from people wanting to invest their time and careers in an exciting, growing, and attractive space.

While the exact targeting of government support will determine the extent of the opportunities created in different portions of the value chain, areas of existing UK strength are best placed to take advantage of a growing market.

One clear set of beneficiaries from growth in this area are **device manufacturers** – highlighted in the resilient PNT value chain as 'PNT module manufacturing'. Following on from a stimulated research and development sector, these manufacturers could have a significant advantage when it comes to the design, integration, and manufacture of PNT chipsets and modules more generally. Importantly, academic research efforts are well poised to kickstart PNT product developers in the device space, including spin outs and start-ups.

Another area that stands to benefit within the UK is **system integration**. Work in this area increasingly requires sophisticated approaches, and it is here the UK's innovation and intellectual property-based strengths should be an advantage relative to international peers. The UK is also a leader in testing and performance evaluation, and consulting across areas relevant to resilient PNT. Already and there are several early-stage companies showing great promise. More specifically, potential UK beneficiaries include both hardware and software integrators, as well as the product sales and distribution companies that facilitate their market functions. Software systems engineering companies and performance evaluation and test equipment companies also stand to benefit from an existing strong base in the UK.

Depending on to what extent the government chooses to invest in resilient PNT infrastructure R&D and construction, **PNT infrastructure providers** stand to gain accordingly. If public investment is high, then an entire industry of facilities management staffed by a technical workforce will be supported in the resilient PNT domain. The scale and form of these, along with fixed infrastructure operations companies, are highly dependent on the specific approach taken by the UK government. As previously noted, it is important to understand that infrastructure operations are generally conducted by the same entities that own the system infrastructure, and the UK has previously expressed interest in owning and operating its own PNT infrastructure.

Another facet of the UK economy that is highly dependent on the targeting of government policy is the **government** itself and linked entities. For example, public R&D organisations, including funding agencies, have budgets that are directly linked to the specifics of government focus. Existing mapping and geospatial agencies with a vested interest in UK PNT are of course also likely to benefit from increased government support for resilient PNT. More generally, government departments whose portfolio or concerns includes critical infrastructure stand to benefit from the spillovers of important resilient PNT work done elsewhere in the UK. Another set of government stakeholders are those with a focus on business development and economic growth within their area or the country more generally: this paper has sought to demonstrate the significant potential economic upside from a greater focus on resilient PNT development in the UK.

One more set of groups are the **user communities** who rely on PNT for their day-to-day activities stand to gain disproportionately from resilient PNT. It is precisely these end-users who will directly benefit from a world-leading resilient PNT push in the UK, whether they be power and utility companies aiming to ensure continuity of service or ordinary citizens benefiting from resilience in their road navigation system of choice. Other key beneficiaries of resilient PNT efforts include telecommunications network providers, and a range of transport sectors such as rail, maritime and road. Improvements across these transport sectors rely on improvements to the resilience of PNT. In rail, increased utilisation rates of the UK's existing rail network depend on understanding precisely where trains are. On the UK's roads, the nascent Autonomous Vehicles market critically depends on resilient PNT for autonomous navigation and safe travel. Finally, marine vessels and shipping ports are increasingly dependent on resilient PNT as they move towards increased autonomy in navigation and other processes.

Finally, the **public** are the final beneficiaries of PNT services. As highlighted in Figure 1, PNT underpins the modern economy and modern ways of living. Therefore, developing increased resilience in PNT ensures the continuity of the products and services that support this. In addition, future benefits can be unlocked as new and better services are developed that are only possible due to the resilience of PNT provided. One prominent example already considered in this concept paper is autonomous vehicles.

Ultimately, the world-leading skills and knowledge built in the UK's resilient PNT ecosystem because of the growth of the industry will be both scarce and marketable – on both a regional and global level. An attractive UK legal and economic environment coupled with an encouraging resilient PNT ecosystem, with consistent and programmatic government support, will help to retain talent, businesses, and ultimately economic benefits in the UK.

4 Conclusion and recommendations

This paper has identified a need for resilient PNT in the UK and internationally. This has historically been raised by government and civilian commentators, and their calls are increasing in frequency and strength as the scale and sophistication of attacks on existing PNT systems increases. Simultaneously, the reliance of modern economies on (GNSS) satellite-derived PNT signals has become fundamental, with the full extent of this reliance rarely understood outside of technical circles.

The UK has significant economic value at risk to even a temporary outage of GNSS, with the road transport, emergency, and justice services, and maritime found to be most precariously positioned. Other sectors across the economy are insufficiently prepared to face the consequences of such outages - in each sector, the most widely adopted PNT and backup systems (or lack thereof) play a vital role in minimising economic value at risk. In cases where a redundant system is readily available the magnitude of losses is far smaller. The sectors where the UK has the most value at risk from a loss of GNSS-provided PNT are precisely the sectors that lack adequate resilient backup options.

The broad alignment of the UK and other nations' vulnerabilities to PNT outages creates a strong economic incentive to develop solutions, as domestic resilience can be achieved alongside developing valuable export opportunities. It is also clear that those sectors with the largest value dependence upon GNSS are able to create a positive return on the investment if resilient PNT techniques and systems are implemented, as potential losses (financially and reputationally) are mitigated.

The unique features of different economic sectors and countries facing this problem in turn give rise to differing mitigation strategies, with the cost and effectiveness of each strategy varying by use case and business sector. In many cases research is still ongoing, with significant innovation potential still remaining. One leading strand of research thinking is to focus on the utilisation of GNSS as part of a larger system rather than the sole input. The resulting solution is often more sophisticated than simply adding one back-up source of timing information, hence the growing use of the term 'system of systems'. Such solutions are relatively immature and widely-accepted standards are yet to emerge.

Using proxy data available on the cybersecurity and timestamping markets, the current market for resilient PNT in the segments of the market deemed most aware of the risks is conservatively estimated at around £1bn per year, with a further £10bn of market potential. Based on observable trends, this market is expected to grow to over £4bn over the next 10 years, with the UK capturing 2% of market value. This description is of the business-as-usual case, where the UK government does not engage with the market via public investments and other non-financial interventions such as regulation.

As the players in the PNT market in general are not very literate on GNSS vulnerabilities, a successful UK strategy, information campaign and development programme could unlock a share of the global market for GNSS devices and augmentation services forecasted in excess of €100bn.

The UK is well placed to capture a greater share of the growing resilient PNT market, and indeed can play a vital role in increasing the global pace of growth. A high-level approximation of the return on investment for UK public spending in the resilient PNT space suggested a range of £2-£21 per £1 invested. Furthermore, taking action to create economic conditions conducive to investment in resilient PNT, as well as directly making these investments could result in significantly higher market share - perhaps up to 4% of an enlarged overall market.

Aside from public investment, supportive UK actions could include development and provision of complementary domestic (or wider) infrastructure, supporting academic and industrial research and development, creating testbeds or other infrastructure further downstream in the industry value chain, or acting as an anchor customer for resilient PNT products and services. The UK's strong track record in PNT and similar spaces suggest that resilient PNT could be an opportunity, perhaps even on the same order of magnitude as mobile phone manufacturing was for Finland. As one academic noted, discussing the economic return on Finland's strategic investments into this industry, the timely identification of a 'major growth opportunity' coupled with 'a sustained commitment to R&D' resulted in a runaway success with 'extraordinarily high' impacts on national GDP and many private sector businesses[36]. The growth potential of the wider PNT and GNSS market beyond the relatively narrow resilient PNT scope of this paper certainly support this notion.

The report closed with a discussion of the stakeholders within the UK most likely to benefit from the pursuit of a focused resilient PNT policy. Among these were multiple sections of the resilient PNT sector value chain, but most crucial are the end users who rely on PNT-derived services every day – both at the institutional level and the individual level.

This report opened by questioning whether the UK could live without a source of PNT, even temporarily. To conclude, a sensible follow-up question appears to be whether the UK can afford to let such a significant opportunity to deliver value through resilience pass by.

4.1 Recommendations

To realise the potential argued in this paper, the UK needs to develop a coherent and comprehensive resilient PNT strategy. Such a strategy could be based on a thorough Theory of Change intended to capture all the inputs, activities, outcomes, and impacts that enable the UK to achieve resilience in PNT domestically and develop competences that represent international opportunities.

To develop this strategy it is necessary to articulate its objectives. These should centre on **achieving resilience in PNT** in the UK and **enabling export opportunities**. However, it is important to allow other (perhaps secondary) objectives to be considered.

The Royal Institute of Navigation (RIN), with its deep expertise, international membership and network, is well-placed to play a key role in provision of impartial advice and in relation to bringing key stakeholders together.

The work programme for the PNT strategy development ought to include:

- Identification of potential mitigation strategies;
- Ranking of mitigation strategies in order of priority based on strategic and economic factors, including as substitutability and complementarity within a system-of-systems;
- Funding of research, development, and implementation of prioritised mitigation strategies to prove concept;
- Organisation of trade events and dissemination of information to interested allies.

[36] Walwyn, D. (2007). 'Finland and the mobile phone industry: A case study of the return on investment from government-funded research and development'